A Preliminary Natural Gas Resource Assessment of the Marcellus Shale for West Virginia using Basic Geologic Data and GIS

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Finally, I would like to make special note of the fact that this study, and numerous other studies, would not have been possible without the DOE-sponsored Eastern Gas Shale Project (EGSP) that ran from 1976 through 1992.

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I. Abstract

For West Virginia to responsibly manage its shale gas resources, a resource assessment is needed especially given the anticipated importance of shale gas over the next several decades. This study quantifies, at a preliminary level, Marcellus Shale natural gas resources for the State using a geologic-based (volumetric) approach. The distribution and geographic variability of key parameters were examined. Original gas-in-place was determined primarily using geophysical well log data from >300 wells across West Virginia and core data from >10 wells. Geological interpretation software was used to manage data and to develop stratigraphic cross-sections. Geographic information system (GIS) software and tools were used to manage data, perform calculations, produce maps, and present information.

Results and products include: 1) a conservative estimate of total original gas-in-place of 122 TCF with natural gas concentration progressively decreasing from north and north-central West Virginia to the southwest; 2) ten stratigraphic cross-sections highlighting the Marcellus Shale as well as GIS layers and maps identifying reservoir location, its geographic extent, thickness, depth, formation temperature, level of organic maturity, and original gas-in-place volumes; and 3) an up-to-date publicly-accessible web-based GIS map application, http://ims.wvgs.wvnet.edu/Mar.

The resource assessment can be refined in the future as new data are obtained. In addition, the approach can be applied to other shale or unconventional gas plays and can be extended to other geographic areas within the region.

II. Introduction

A. General Background and History

The Marcellus Shale is a geologic formation that underlies portions of seven northeastern states in the Appalachian Basin (Figure 1). The shale resource is thought to contain a large volume of natural gas and natural gas liquids. Gas drilling in the unit has accelerated recently largely because of technological advances and economic conditions. Due to the importance of the resource and activity impact, the West Virginia Geological and Economic Survey (WVGES) is examining data for the State in addition to updating and developing Marcellus-specific materials. At present, WVGES has a mix of newer and older data and materials. Much of the well data are newer while statewide maps and cross-sections are older or lacking. This project aids in that effort by examining data and developing materials for the Marcellus Shale gas play in West Virginia.

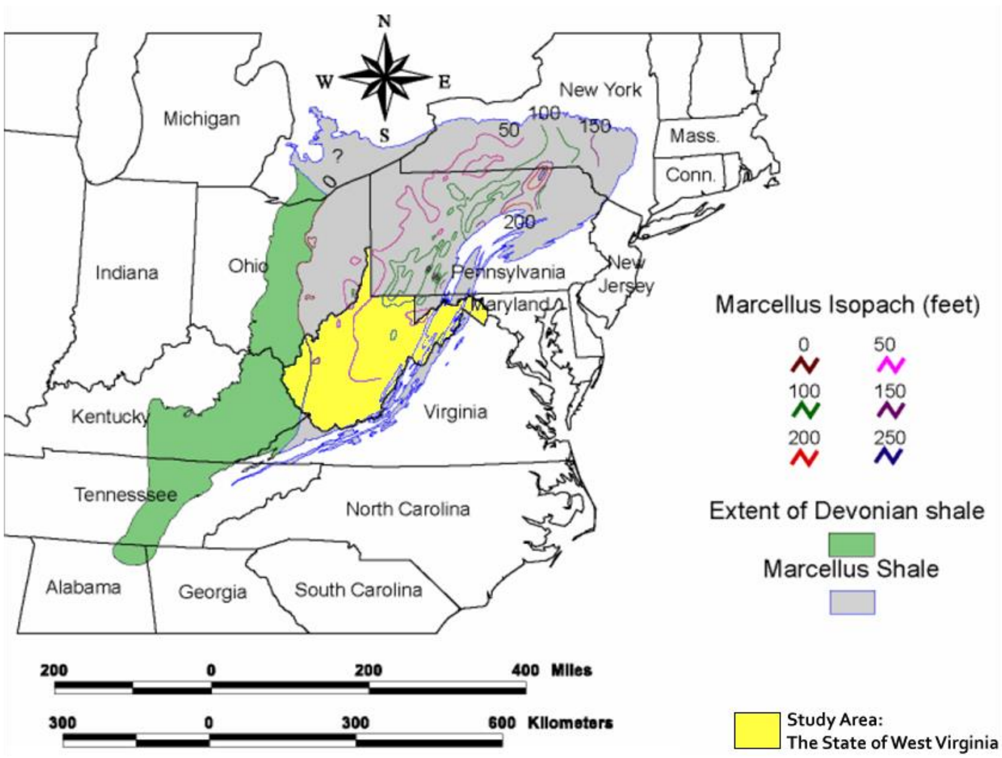


Figure 1. Map showing the approximate extent and thickness of the Marcellus Shale (modified from Milici 2005). The study area for this project is shown in yellow.

Shale gas has been produced in the basin since the late 1800s and in West Virginia since the 1930s (Boswell 1996). Until recently (~2010) however, production has been modest despite large estimates of in-place resources. Recognizing that gas shales were an under-exploited resource in the Appalachian Basin and because of the energy crises of the late 1970s, the U.S. Department of Energy (DOE) sponsored the Eastern Gas Shales Project (EGSP) from 1976 through 1992 (DOE 2007). The EGSP was designed to examine and enable realization of Appalachian shale gas resources. Much of the early work related to eastern shales focused on the Huron Shale for which the original gas-in-place estimate by the National Petroleum Council (NPC 1980) was on the order of 250 trillion cubic feet (TCF). In comparison, annual domestic gas usage has historically been approximately 20 TCF per year (EIA 2013a). The deeper and thinner Marcellus Shale was, at that time, considered a particularly speculative resource and received little attention (Figure 2).

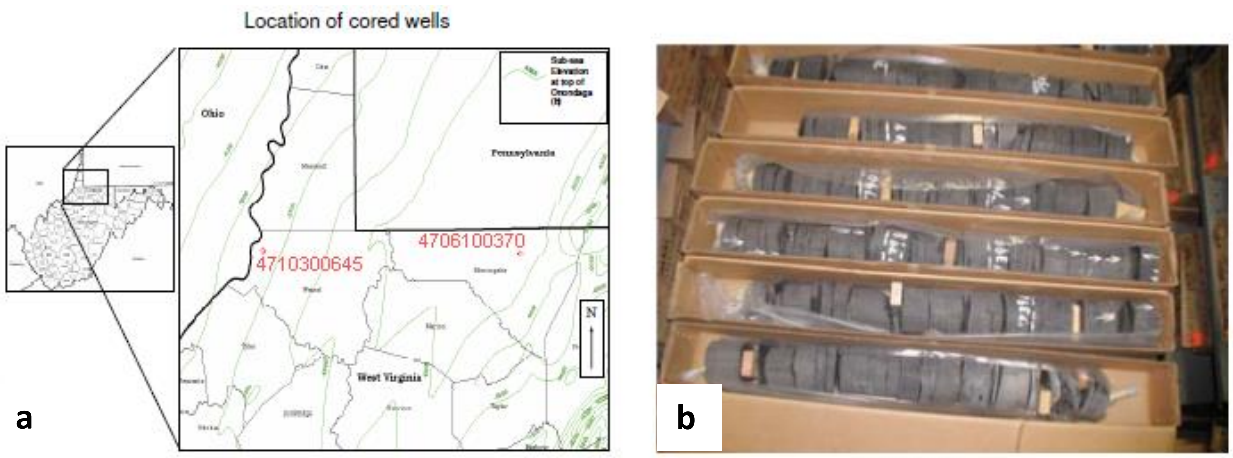


Figure 2. (a) Sampling location of the only two EGSP cores in West Virginia that contain Marcellus Shale. The cores underwent extensive analysis as part of the DOE-sponsored shale project that was initiated in 1976. Both cores are housed and managed by WVGES. Even though the cores are more than 30 years old, requests to examine or analyze the cores are still made as they are the only publicly-available Marcellus cores in the State (modified from WVGES 2008). (b) Photograph of core through the Marcellus Shale section (WVGES 2009).

Among the first EGSP studies to specifically enumerate Marcellus Shale resources were a series of reports by Kuuskraa et al. released in the early to mid-1980s. In their study of West Virginia, Kuuskraa and Wicks (1984) reported a 79.6 TCF original gas-in-place estimate for the Marcellus Shale along with recoverable volume estimates ranging from over 8.0 to over 25.9 TCF depending on the recovery technology. Notably, Kuuskraa and Wicks (1984) utilized a gas-in-place approach that allowed for the specification of potential recoverable volumes for different technology scenarios. In 2003, the United States Geological Survey (USGS) (Milici et al. 2003) estimated recoverable gas resources to be 1.93 TCF in the Marcellus Shale for the entire Appalachian Basin. The USGS estimate was viewed by some as pessimistic (Engelder and Lash 2008), particularly given the recent drilling successes in the previously poorly-producing Barnett Shale of Texas. It should be noted that the traditional USGS estimation methodology relies heavily on historic well performance rather than in-situ reservoir characteristics to estimate recoverable resources; and therefore, the approach is biased toward low estimates for unconventional reservoirs where productivity is highly sensitive to technology improvements. Engelder and Lash (2008) returned the focus to gas-in-place resources with a calculation of 500 TCF gas-in-place for the Marcellus Shale basin-wide. In 2009, Engelder provided new estimates for recoverable resources using a production-based approach. Engelder's basin-wide estimate of 489.4 TCF was significantly higher than the USGS production-based estimate partly due to newer data and the realization of improved technology in the form of horizontal or deviated drilling often coupled with hydraulic fracturing technology (Figure 3).

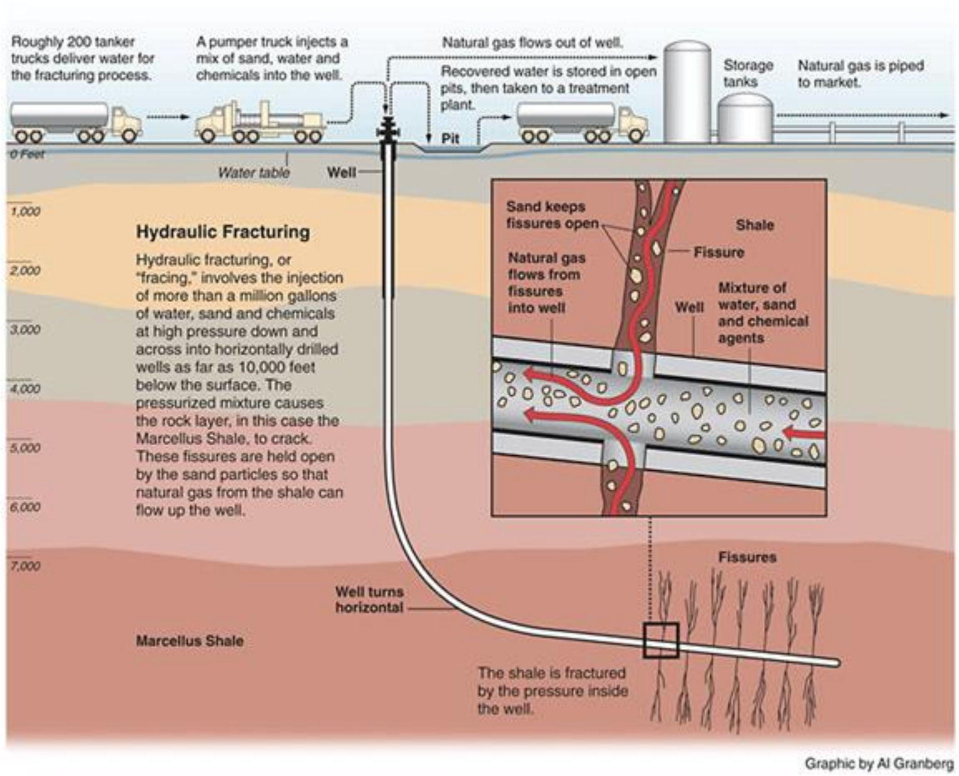


Figure 3. Schematic showing the principal technologies used to enhance Marcellus Shale productivity. In West Virginia many early Marcellus Shale wells were vertical; however, most Marcellus wells now are horizontal or deviated. The term *deviated* frequently is used because very few wells are truly horizontal; although, the term *horizontal* can be used loosely. Almost all Marcellus Shale wells undergo hydraulic fracturing, a method used to stimulate production from low-permeability reservoirs. The phrase *hydraulic fracturing* is often shortened to *fracking* or *fracing* (EIA 2013b).

Other recent reports include those by Navigant Consulting, Inc. (2008), the DOE (2009), and Stevens and Kuuskraa (2009). Two of the most recent estimates include those by the USGS (Coleman et al. 2011) and the U.S. Energy Information Administration (EIA 2013c). The USGS estimate is an update to their 2003 study with recoverable gas now estimated at 84.2 TCF with 3.4 billion barrels of natural gas liquids (BBNGL). The EIA updates estimates yearly for the "Annual Energy Outlook"; their current (2013) estimate is 148.4 TCF of recoverable gas with 0.9 billion barrels of recoverable oil (BBOil) for the Appalachian Basin.

A summary of Marcellus Shale gas volume estimates is shown in Table 1. Given the wide range of estimates, considerable uncertainty remains concerning the original gas-in-place resources and the volumes potentially recoverable both basin-wide and within West Virginia. Furthermore for many estimates, there has been limited transparency regarding the data and methods by which estimates were generated. For West Virginia to responsibly manage its resources, resource assessment work would be beneficial particularly given the anticipated importance of shale gas over the next several decades (Figure 4).

Table 1. Summary of Early, Recent, and Significant Marcellus Shale Natural Gas Assessments

Date	Primary References	Marcellus Shale: Original Gas-In-Place[1] TCF (Trillion Cubic Feet)		Marcellus Shale: Recoverable Gas[1] TCF (Trillion Cubic Feet)	
		Appalachian Basin	West Virginia	Appalachian Basin	West Virginia
2013	EIA	Not Reported	Not Reported	148.4 +0.9 BBOil	Not Reported
2011	Coleman et al.	Not Reported	Not Reported	84.2 +3.4 BBNGL	Not Reported
2009	Stevens and Kuuskraa	1,600	Not Reported	100-200	Not Reported
2009	Engelder	Not Reported	Not Reported	489.24[2]	77.59[2]
2009	DOE	1,500[3]	Not Reported	262[4]	Not Reported
2008	Navigant Consulting, Inc.	1,500[3]	Not Reported	34.2[4]	Not Reported
2008	Engelder and Lash	500	Not Reported	50	Not Reported
2003	Milici et al.	Not Reported	Not Reported	1.93	Not Reported
1993	Charpentier et al.	294.92	Not Reported	Not Reported	Not Reported
1992	NPC	248[5]	Not Reported	42[5]	Not Reported
1984	Kuuskraa and Wicks	Not Reported	79.6	Not Reported	8.0+-25.9+
Note: Secondary and duplicate references exist that are derived from or extensions of the primary references.					

[1]*Original gas-in-place and recoverable gas values can be determined and reported in a variety of formats. For instance, values can be determined and reported in a minimum-mean-maximum or a P95-P50-P5 format. Not all methodologies produce a range of values. For those studies that reported multiple values, the values in Table 1 are a mean or P50 value unless otherwise noted.*

[2]*Engelder (2009) states that the recoverable gas estimates are for a 50-year period.*

[3]*The DOE (2009) and Navigant Consulting, Inc. (2008) values are maximum values.*

[4]*The DOE (2009) report lists a recoverable gas value of 262 TCF from Navigant Consulting, Inc. The value refers to maximum reported technically recoverable gas rather than the mean value. The Navigant Consulting report, however, lists both maximum and mean values. It is felt that the mean value is more reasonable and in keeping with other values reported in Table 1; therefore, the mean value is listed in association with Navigant Consulting.*

[5]*Estimates are for Marcellus and Rhinestreet shales but the vast majority of the resource is assigned to the Marcellus.*

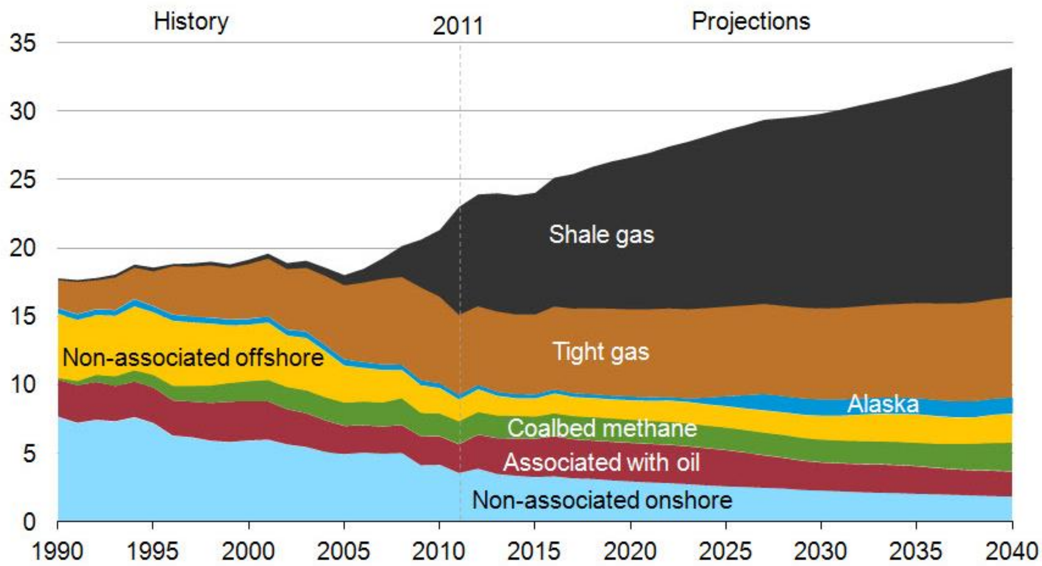


Figure 4. U.S. dry natural gas production in TCF: "The U.S. Energy Information Administration's *Annual Energy Outlook 2013 Early Release* projects U.S. natural gas production to increase from 23.0 trillion cubic feet in 2011 to 33.1 trillion cubic feet in 2040, a 44% increase. Almost all of this increase in domestic natural gas production is due to projected growth in shale gas production, which grows from 7.8 trillion cubic feet in 2011 to 16.7 trillion cubic feet in 2040." (EIA 2013b)

B. Study Purpose and Overview

This study is intended to benefit the citizens of West Virginia by aiding in resource management. Purposes are to:

- generate new geologic data from original interpretation of geophysical well logs,
- conduct a preliminary natural gas resource assessment,
- provide selected data and maps available through an up-to-date publicly-accessible web-based geographic information system (GIS) map application, and
- develop a preliminary resource assessment framework for the State to evaluate other petroleum resources

Key research questions for the project include: how much natural gas is likely to be contained in the Marcellus Shale underlying West Virginia, how is it distributed, and how do the key parameters that affect gas recoverability vary? Basic geologic and reservoir data were used to define characteristics of the Marcellus Shale and to calculate gas volumes. Data was obtained primarily from well logs, literature, and operator reports. Geological interpretation software was used to manage well log data and develop stratigraphic cross-sections. GIS software and tools were used to manage data, perform calculations, produce maps, and present information.

Approaches to estimating natural gas resource volumes generally are divided into two categories for continuous unconventional reservoirs--1) those that use production data to estimate recoverable resources directly and 2) those that use geologic data to estimate original gas-in-place to which recovery factors can be applied (Schmoker 2002) (Figure 5). Both approaches have advantages and disadvantages. For the production approach, generally advantages include the need for minimal data, the inherent inclusion of parameter variability in the data, and the ability to conduct the assessment quickly. Disadvantages include unrepresentative production data for emerging plays and the factoring of the contemporary

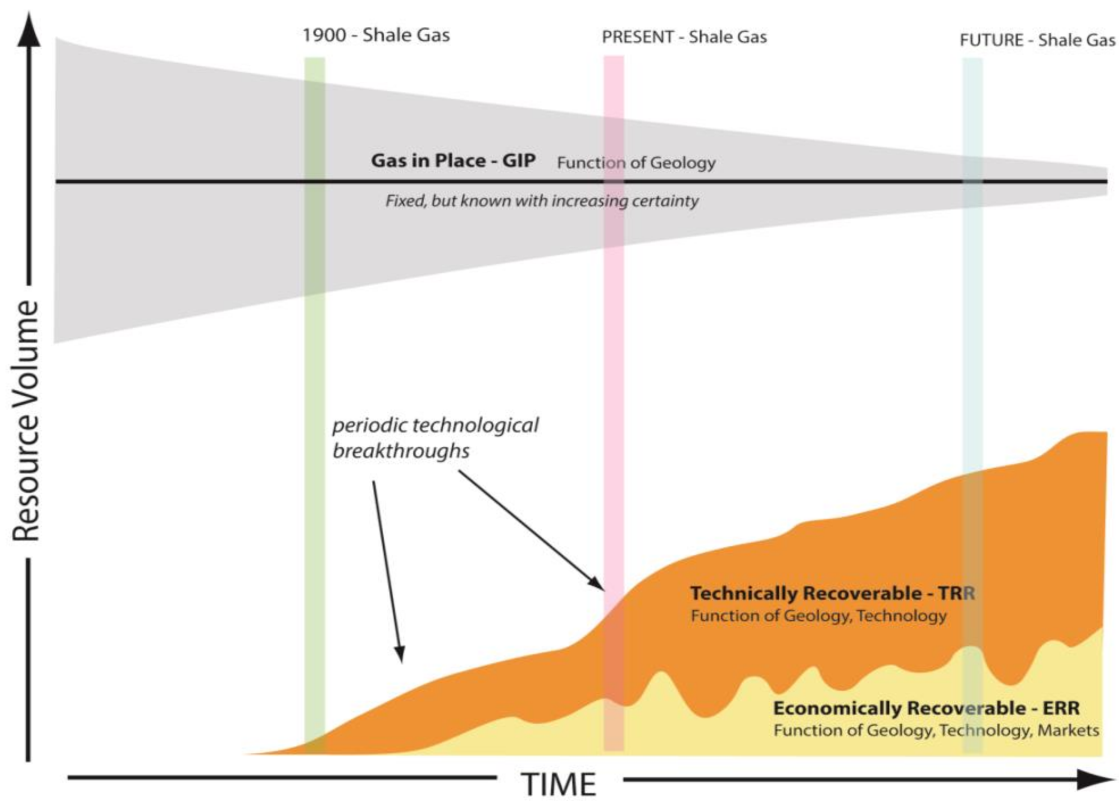


Figure 5. Resource volume versus time for original gas-in-place, technically recoverable, and economically recoverable resources specific to continuous unconventional reservoirs. Original gas-in-place is a function of geology (resource volumes are fixed and known with increasing certainty through time as more and more data are gathered). Technically recoverable resources are a function of geology and technology (resource volumes tend to increase dramatically with time due to advances in technology and application of technology). Economically recoverable resources are a function of geology, technology, and economics (resource volumes tend to fluctuate but increase slightly through time) (Boswell 2013).

technology and economic situation into the result (Charpentier and Cook, 2012). A key disadvantage of the production approach is that it will likely underestimate resources when based on early well results as per-well productivity will likely increase as technology improves. For the geologic approach, advantages of developing in-place estimates include an improved understanding of the geologic conditions as well as the ability to examine various scenarios related to technology and economics (Figure 6). Disadvantages include the likelihood that all required data are not available from public sources, that the greatest public interest is in recoverable resources rather than original in-place estimates, and that data processing is time-consuming. Ultimately, positive aspects of both approaches can be combined to conduct a more comprehensive examination of resources.

Here the geologic approach for resource quantification was used. Original gas-in-place was determined using primarily well logs and core data. Well log data from more than 300 wells across the State and core data from more than 10 wells were used to investigate the geology.

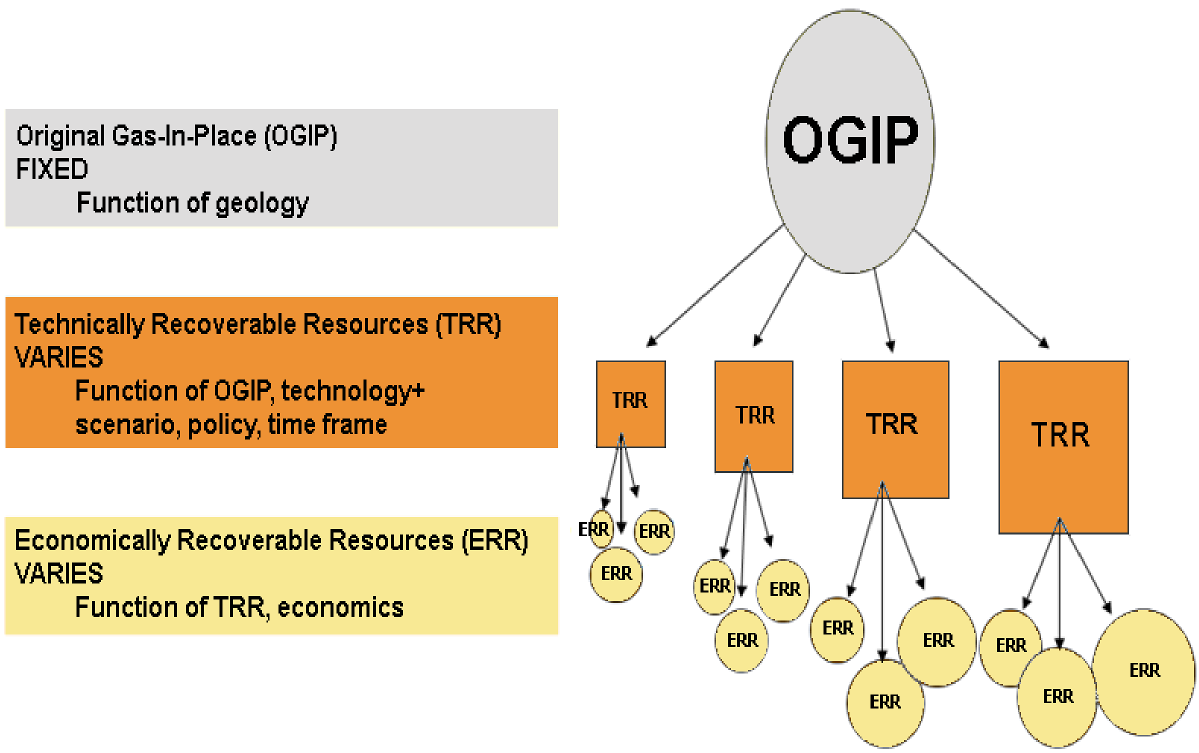


Figure 6. Original gas-in-place is essentially a fixed value to which multiple factors can be applied to estimate both technically and economically recoverable resources. By using the geologic approach to estimate original gas-in-place and the production approach to estimate recovery factors, it may be possible to capture the variety and evolution of recovery factors (modified from Boswell 2005).

III. Methodology

A. Overview

The primary task of the project was to determine in-place hydrocarbon resources in the Marcellus Shale. Although condensate and natural gas liquids commonly are associated with natural gas for the Marcellus Shale, condensate and natural gas liquids are in a gaseous state within the reservoir (Range Resources 2013). Therefore, all calculation and procedures assume only gas. The basic equation to calculate total original gas-in-place (GIP_{total}) is:

$$\mathbf{GIP_{total} = GIP_{free} + GIP_{adsrb}} \text{ (modified from Crain 2013a).} \quad (1)$$

To derive the required parameters, additional equations and a substantial amount of data was necessary. The derivation of each parameter is described in more detail. Calculations were performed, generally, at the well level for every one-half foot of thickness within the well. Data then were gridded to interpolate between wells and extrapolate beyond wells.

1. Free Gas-In-Place (GIP_{free})

Free gas-in-place is gas contained in pores and fractures. Free gas-in-place was determined using equations 2 through 5. Data for the equations were obtained largely from WVGES and IHS, Inc. well logs, published core-based maps, published core and sample-based data, and operator reports.

$$\mathbf{GIP_{free} = (\phi_{eff} * (1 - S_w) * (1\text{-}Q_{nc}) * H_{fm} * A_r * 4.356 * 10^{-5}) / B_g} \quad (2)$$

GIP_{free} = free gas volume per grid cell (Bcf)
ϕ_{eff} = effective porosity (fractional)
S_w = water saturation (fractional)
Q_{nc} = non-combustible gas (fractional)
H_{fm} = reservoir thickness (feet)
A_r = reservoir area (acres)
B_g = gas formation volume factor (fractional) (modified from Crain 2013a)

$$\mathbf{\phi_{eff} = ((\phi_n - (V_{sh} * \phi_{nsh}) - (V_{ker} * \phi_{nker})) + (\phi_d - (V_{sh} * \phi_{dsh}) - (V_{ker} * ((2650 - \rho_{ker}) / 1650)))) / 2} \quad (3)$$

ϕ_{eff} = effective porosity (fractional)
ϕ_n = neutron porosity (fractional)
V_{sh} = shale volume (fractional)
ϕ_{nsh} = shale neutron porosity (fractional)
V_{ker} = kerogen volume fraction (unitless)
ϕ_{nker} = kerogen neutron porosity (fractional)
ϕ_d = density porosity (fractional)
ϕ_{dsh} = shale density porosity (fractional)
ρ_{ker} = kerogen density (g/cc) (modified from Crain 2013a, Crain 2013b)

$$S_w = (((((1 - V_{sh}) * A * (R_W@FT) / (\phi_{eff}^{M})) * V_{sh} / (2 * R_{sh}))^2 + (((1 - V_{sh}) * A * (R_W@FT) / (\phi_{eff}^{M})) / R_{fmd}))^{0.5} - (((1 - V_{sh}) * A * (R_W@FT) / (\phi_{eff}^{M})) * V_{sh} / (2 * R_{sh})))^{(2/N)} \quad (4)$$

S_w = water saturation (fractional)
V_{sh} = shale volume (fractional)
A = tortuosity exponent (fractional)
R_w = formation water resistivity (ohm-m)
ϕ_{eff} = effective porosity (fractional)
M = cementation exponent (fractional)
R_{sh} = shale resistivity (ohm-m)
R_{fmd} = formation resistivity, deep reading (ohm-m)
N = saturation exponent (fractional) (modified from Crain 2013c)

$$B_g = (P_s * (T_f + 460)) / (P_{fm} * (T_s + 460)) * Z_f \quad (5)$$

B_g = gas formation volume factor (fractional)
P_s = surface pressure (psi)
T_f = formation temperature (^oF)
P_{fm} = formation pressure (psi)
T_s = surface temperature (^oF)
Z_f = gas compressibility factor (fractional) (modified from Crain 2013a)

2. Adsorbed Gas-In-Place (GIP_{adsrb})

Adsorbed gas-in-place is gas that is sorbed to the surface of the kerogen (Lewis et al. 2004). Adsorbed gas-in-place was determined using equations 6 and 7. Data were obtained from published core analysis results, published core-based maps, and well logs.

$$GIP_{adsrb} = G_c * \rho_{fm} * H_{fm} * A_r * 1.3597*10^{-6} \quad (6)$$

GIP_{adsrb} = gas in place (Bcf)
G_c = gas content (scf/ton)
ρ_{fm} = formation density (g/cc)
H_{fm} = reservoir thickness (feet)
A_r = spacing unit area (acres) (modified from Crain 2013a)

$$G_c = TOC * G_p \quad (7)$$

G_c = gas content (scf/ton)
TOC = total organic carbon (weight percent)
G_p = gas parameter (modified from Crain 2013a)

B. Data Sources

Table 2 provides a summary of the data and sources that were used to estimate natural gas resources for the Marcellus Shale in West Virginia using a geologic approach.

Table 2a. Data Items and General Data Source(s) for Free Gas-In-Place
(*Parameters are given in order as described in "Methodology Overview"; data items shown in bold are primary values being calculated)*

Data Item	General Data Source(s)
Free Gas-In-Place (GIP_{free})	calculate (equation 2)
Effective Porosity (ϕ_{eff})	calculate (equation 3)
Water Saturation (S_w)	calculate (equation 4)
Non-combustible Gas (Q_{nc})	assume 0.01
Reservoir Thickness (H_{fm})	well logs[1,2], cross-sections[1,3], map[1], reports[1]
Reservoir Area (A)	well logs[1,2], cross-sections[1,3], maps[1,3], reports[1]
Gas Formation Volume Factor (B_g)	calculate (equation 5)
Effective Porosity (ϕ_{eff})	calculate (equation 3)
Neutron Porosity (ϕ_n)	well logs[1,2]
Shale Volume (V_{sh})	literature[4]
Shale Neutron Porosity (ϕ_{nsh})	well logs[1,2]
Kerogen Volume (V_{ker})	literature[4], calculate
Kerogen Neutron Porosity (ϕ_{nker})	assume 0.65[5]
Density Porosity (ϕ_d)	well logs[1,2]
Shale Density Porosity (ϕ_{dsh})	well logs[1,2]
Kerogen Density (ρ_{ker})	assume 1.30[5]
Water Saturation (S_w)	calculate (equation 4)
Shale Volume (V_{sh})	literature[4]
Tortuosity Exponent (A)	assume 1.0
Formation Water Resistivity (R_w)	well logs[1,2]
Effective Porosity (ϕ_{eff})	calculate (equation 3)
Cementation Exponent (M)	assume 1.7
Shale Resistivity (R_{sh})	well logs[1,2]
Formation Resistivity (R_{fmd})	well logs[1,2]
Saturation Exponent (N)	assume 1.7
Gas Formation Volume Factor (B_g)	calculate (equation 5)
Surface Pressure (P_s)	assume 14.7
Formation Temperature (T_f)	well logs[1]
Formation Pressure (P_{fm})	calculate
Surface Temperature (T_s)	assume 50
Gas Compressibility Factor (Z_f)	assume 0.9 to 1.0

Table 2b. Data Items and General Data Source(s) for Adsorbed Gas-In-Place
(Parameters are given in order as described in "Methodology Overview"; data items shown in bold are primary values being calculated)

Data Item	**General Data Source(s)**
Adsorbed Gas-In-Place (GIP_{adsrb})	calculate (equation 6)
Gas Content (G_c)	calculate (equation 7)
Formation Density (ρ_{fm})	well logs[1,2]
Reservoir Thickness (H_{fm})	well logs[1,2], cross-sections[1,3], map[1], reports[1]
Spacing Unit Area (A_r)	well logs[1,2], cross-sections[1,3], maps[1,3], reports[1]
Gas Content (G_c)	literature[6], calculate
Total Organic Carbon (TOC)	literature[4]
Gas Parameter (G_p)	calculate, assume

Table 2c. General Data Source Translations for Table 2a and Table 2b

General Data Source Translations
[1]*West Virginia Geological and Economic Survey (WVGES)* [2]*IHS, Inc.* [3]*United States Geological Survey (USGS)* [4]*Black Shale Lithofacies Prediction and Distribution Pattern Analysis of Middle Devonian Marcellus Shale in the Appalachian Basin, Northeastern U.S.A. (Wang 2012)* [5]*Crain's Petrophysical Handbook (Crain 2013a)* [6]*Technically Recoverable Devonian Shale Gas in West Virginia (Kuuskraa and Wicks 1984)*

C. Role of GIS

The role of GIS in the resource assessment project was to:

- capture, store, and retrieve data including that from well logs and cores along with all supplemental data required for calculations;
- manipulate and analyze data by performing calculations, generating layers, and examining geographic patterns; and
- integrate and present data through maps and web-based GIS map applications

Specific tasks using GIS were to:

- identify wells meeting study criteria (ArcMap and a web-based GIS map application);
- manage well and core or sample-based attribute data (ArcMap);
- query well data (ArcMap);
- perform calculations related to depth, thickness, level of organic maturity (LOM), pressure, temperature, and original gas-in-place (ArcMap);
- generate spatial data layers including: depth, thickness, LOM, pressure, temperature, original gas-in-place, high organic content, and ratio of adsorbed to free gas (ArcMap with Geostatistical Analyst);
- estimate values for wells lacking data (ArcMap);
- develop maps (ArcMap);
- examine data and edit as needed (ArcMap); and
- present data (ArcMap and web-based GIS map applications)

D. Approach Overview

1. **Well Selection**
    a. **WVGES Database Search**
    b. **ArcMap Project**
    c. **Representative Well Sample**
2. **Well Log Correlation**
3. **Well Log Interpretation and Data Extraction**
    a. **Reservoir Thickness**
    b. **Reservoir Extent**
    c. **Porosity**
    d. **Water Saturation**
4. **Supplemental Data Derivation**
    a. **Level of Organic Maturity**
    b. **Total Organic Carbon**
    c. **Volume of Shale**
    d. **Pressure Gradient**
    e. **Temperature**
5. **Data Processing**
    a. **Porosity, Adjusted**
    b. **Water Saturation, Adjusted**
    c. **Formation Volume Factor**
    d. **Free Gas**
    e. **Adsorbed Gas**
6. **Data Correction and Refinement**

E. Approach Details — Data Collection and Manipulation Procedure

1. Well Selection

a) WVGES Database Search

The WVGES enterprise-level Oil and Gas Database was searched for all wells that have logs penetrating the Marcellus Shale. Specifically, the Oil and Gas Database was searched using the default WVGES Oil and Gas ArcMap Project (.mxd) that is connected to Oracle data tables as well as to Arc Spatial Database Engine (SDE). A simple query statement was written and executed for the "Owner & Completion" layer within ArcMap to obtain the initial set of wells, i.e. those wells that penetrate the Marcellus Shale and have a scanned well log (Figure 7).

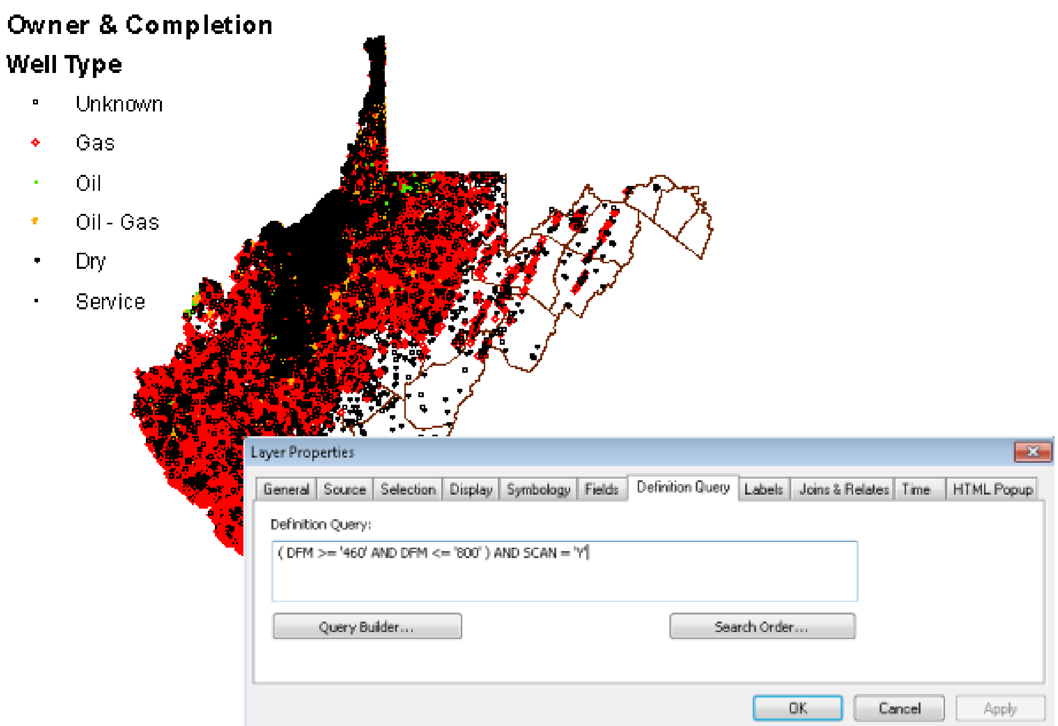


Figure 7. Location of all wells in the WVGES Oil and Gas Database along with query used to identify wells useful for this study. The map was generated using the default WVGES Oil and Gas ArcMap Project. Wells are symbolized by well type (see legend). A simple query statement was used to obtain the initial set of wells — i.e. those that penetrate the Marcellus Shale and have a scanned well log.

b) ArcMap Project

Data from Step 1a were loaded into an *individual* ArcMap Project created for the Marcellus Resource Assessment study. Selected data were retained for each well (including API number, geographic location, well log availability, etc.) and used to create an updated map showing the distribution of well logs that penetrate the Marcellus Shale. Figure 8 shows only the wells that penetrate the Marcellus that also have gamma ray, porosity, and resistivity logs. Some wells also have temperature logs. The ArcMap Project was developed into a draft resource assessment tool in the form of a web-based GIS map application (http://ims.wvgs.wvnet.edu/MarcellusResourceAssessment2) so that the project data could be shared easily among researchers and other interested parties as well as be available at WVGES and through the web (Figure 8).

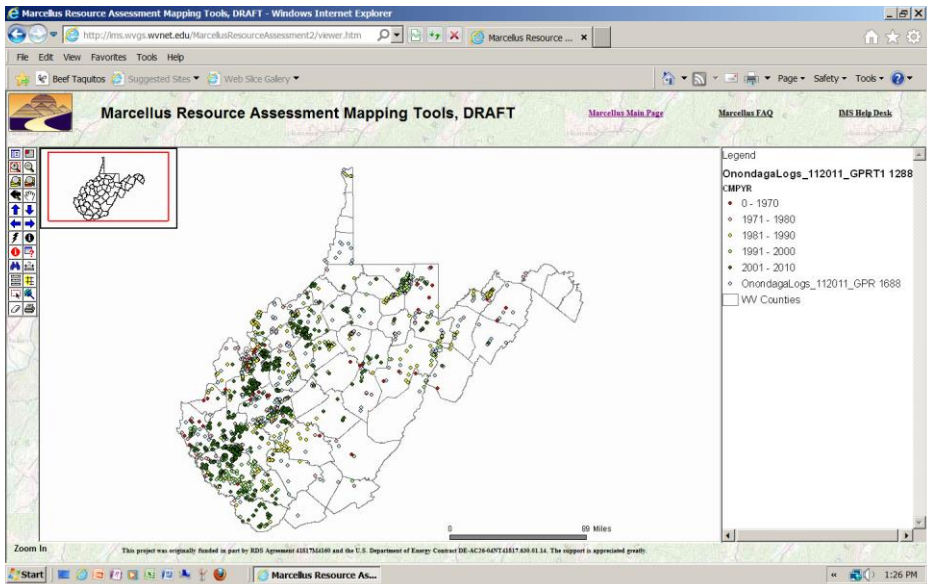


Figure 8. Screenshot of the web-based GIS map application was developed for the project to enable access to data at WVGES and through the web. Circles on the map represent gas and oil wells and show the distribution of all wells for which WVGES has logs that penetrate the Marcellus Shale and that have at minimum gamma ray, porosity, and resistivity logs. For those wells that also have a temperature log, circle color represents age as follows: red (1970 or before), pink (1971 to 1980), yellow (1981 to 1990), light green (1991 to 2000), and dark green (2001 to 2010). The assumption was made that newer data were preferable. Data circa fall 2011.

c) Representative Well Sample

To achieve a dataset of workable size and appropriate distribution throughout the State, wells were selected as randomly as possible but based on: 1) Marcellus penetration, 2) geographic distribution, 3) well log availability and legibility, 4) well orientation, and 5) lack of structural complexities such as high formation dips and faults. Regarding well log availability; wells with gamma ray, porosity, and resistivity traces at the minimum were selected. In addition, wells that had a temperature trace were preferable. Also regarding log availability, wells with more recent data and digital data were preferentially selected. Only vertical wells were selected as required given the methodology. Selections were performed using the draft Marcellus Shale resource assessment tool (http://ims.wvgs.wvnet.edu/MarcellusResourceAssessment2).

The procedure was as follows. A well of interest was selected. The hyperlink tool was used to link to all scanned well log records for that well (*many wells have more than one scanned log*). If the gamma ray trace was suitable (Figure 9), the well was included and the relevant portion of the well log was used to correlate stratigraphic units and to determine the depth, thickness, and extent of each unit. The representative sample contained more than 300 wells for the reservoir characterization (approximately 30% of the total available wells) and more than 120 wells for the volumetric estimation (approximately 10% of the total). It is estimated that approximately 900 wells and 1500 well logs were reviewed to obtain the necessary data.

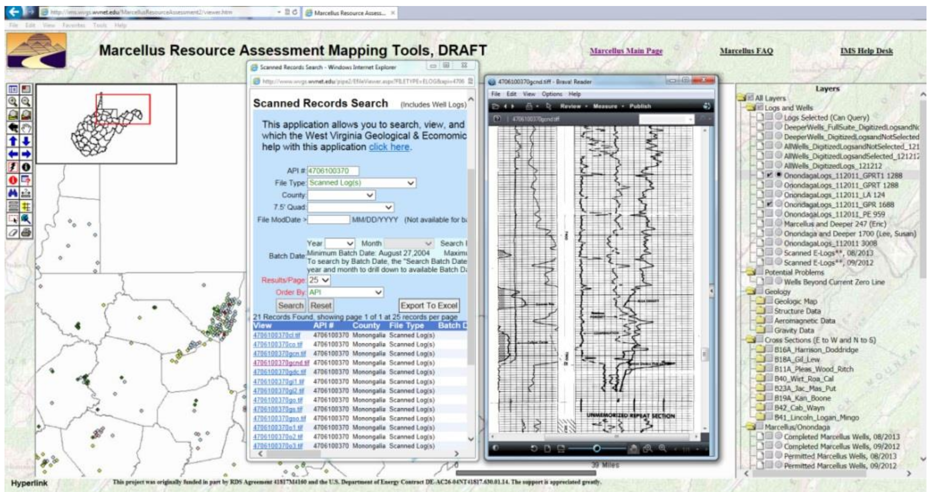


Figure 9. Screenshot of the web-based GIS map application (draft resource assessment tool). One can click on a well of interest that links to a scanned records page. When the application links to the records page, it sends along the API number for the well and the data that the user is interested in. The list of well logs can then be reviewed by opening files in a .tif reader. Some wells have many scanned well logs. For instance, Monongalia County 370 (4706100370), shown above, has 21 scanned well logs. Not all logs were useful for the project so the most likely candidates were selected based on filename which provides an indication of the log traces contained in the scanned well log file.

2. Well Log Correlation

Stratigraphic units were identified on well logs and correlated between wells, checked, and re-correlated as needed using standard techniques (Figure 10, Appendix C). The correlation of well logs was necessary to extract data about the Marcellus Shale and pertinent overlying and underlying stratigraphic units. Correlation of the logs was essential as it formed one of the primary foundations of the study.

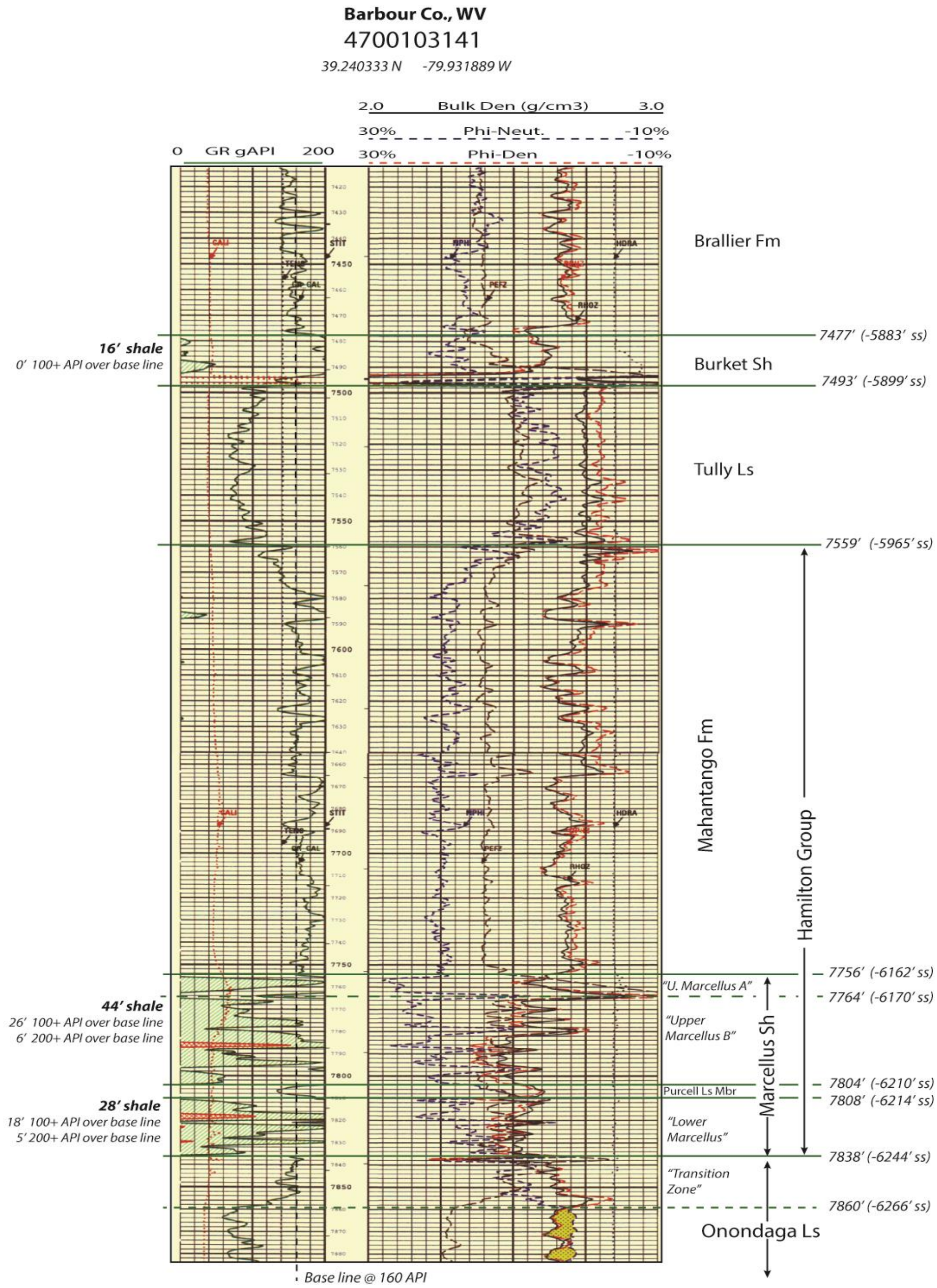


Figure 10. Portion of a modern-day well log showing the gamma ray trace on the left and porosity-related traces (i.e. bulk density, neutron porosity and density porosity) on the right. The logs must be interpreted to be of use, i.e. the text to the left and right of the image has been interpreted from the log. For this well, it has been determined from the gamma ray trace that the "Upper Marcellus" occurs at depth of 7,756 feet below the surface (6,162 feet below sea level), is 48 feet thick, contains 44 feet of shale (where gamma ray trace exceeds, to the right of, the interpreted shale baseline), and 26 feet of highly-radioactive shale (where gamma ray is 100 API units or more above the shale baseline) (per approach of Piotrowski and Harper 1979). Correlations interpreted for two additional logs from the study are shown in Appendix C.

Initially, the following stratigraphic units were correlated when present (see Appendix B for a stratigraphic chart): Cashaqua Shale Member of the Sonyea Formation, Middlesex Shale Member of the Sonyea Formation, the Geneseo Shale Member of the Genesee Formation (or Burket Shale Member of the Harrell Shale), Tully Limestone, Mahantango Formation, "Upper Marcellus-A" shale, "Upper Marcellus-B" shale, Purcell Limestone Member of the Marcellus Shale, "Lower Marcellus" shale, and Onondaga Limestone and equivalents.

Later, additional units younger than the Sonyea Formation were added for completeness to 1) add to cross-section usefulness and 2) permit easier integration into previously-existing WVGES products. The additional units include: Lower Part Huron Member of the Huron Shale, Java Formation, Angola Shale Member of the West Falls Formation, and the Rhinestreet Shale Member of the West Falls Formation. A sample stratigraphic cross-section is shown in Figure 11. See Appendix D for additional cross-sections.

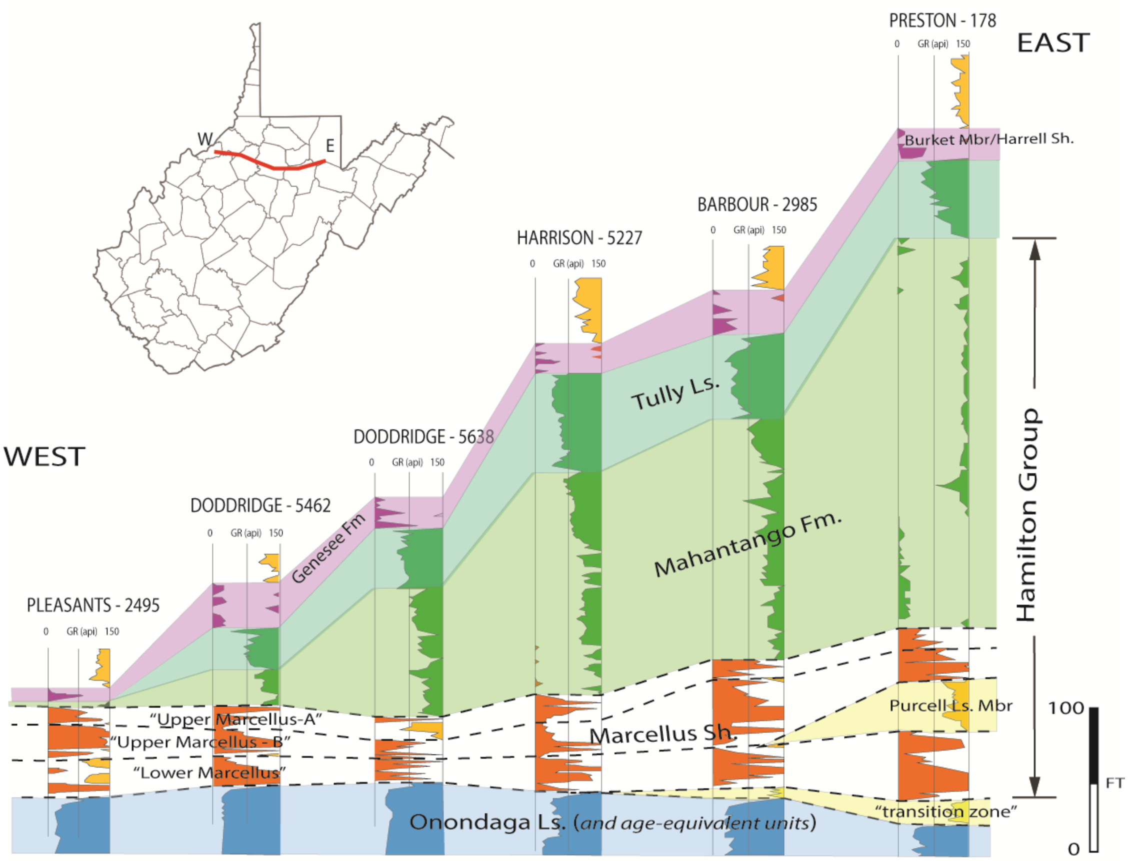


Figure 11. Stratigraphic cross-section in the north-central portion of West Virginia highlighting the Marcellus Shale in addition to overlying and underlying units. At present, there is a great deal of Marcellus Shale-related activity in the north-central region of the State especially in Harrison County. In West Virginia, the Marcellus Shale consists of the "Upper Marcellus", the Purcell Limestone Member, and the "Lower Marcellus". For the purposes of this study, the "Upper Marcellus" was divided into two units corresponding to high gamma-ray lobes observed in certain parts of the State. High gamma-ray values are indicators of zones high in total organic carbon.

3. Well Log Interpretation and Data Extraction

From the original interpretation of more than 300 well logs (Figure 12a); depth and thickness of up to 16 stratigraphic units were determined for each well including five units associated with the Marcellus Shale. From such, the statewide extent of each unit was determined. In addition, the thickness of the two most highly-radioactive zones within the Marcellus was identified at four different levels to track exactly how radioactive and thus how highly-organic the units are. This study provides WVGES with basic Marcellus-specific data that it lacked. In addition to depth and thickness, porosity and water saturation data were extracted from WVGES or IHS, Inc. well logs (Figure 12b).

Data were extracted or interpreted from well logs in various formats. Paper logs, scanned log images, depth-registered scanned log images, and digital log data were used. For the most part, paper logs were used to obtain thickness and depth data (Figure 10). Later in the project, depth-registered scanned log images and digital log data were used to refine the thickness and depth data. Digital log data were used to calculate porosity and water saturation data at one-half foot intervals. All well log data were normalized.

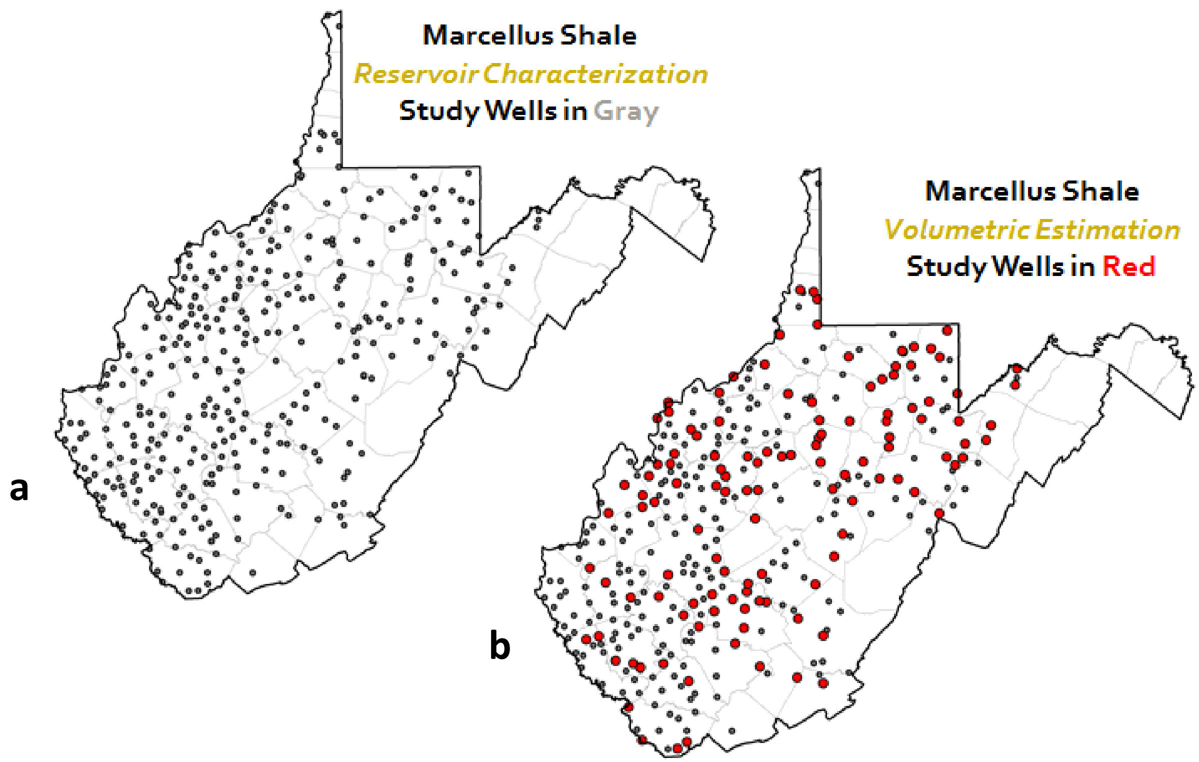


Figure 12. Location of wells used in the preliminary natural gas resource assessment. The (a) upper map shows the wells that were used for geologic or reservoir characterization while the (b) lower map shows the wells that were used in estimating original gas-in-place.

a) Reservoir Thickness

Reservoir thickness was determined by interpreting gamma ray well logs (Figure 10). Details for the Marcellus Shale not available previously at WVGES were collected by recording data for the "Upper Marcellus", Purcell Limestone Member, and "Lower Marcellus". Published cross-sections and maps available from WVGES and the USGS were reviewed and considered in making interpretations. In addition, selected operator-provided well completion reports were used to verify well log data. Stratigraphic cross-sections, showing reservoir thickness and depth data across the State, are shown in Appendix D.

b) Reservoir Area

Given the reservoir thickness interpretations, the areal extent of the Marcellus Shale reservoir becomes evident. Previously published limits in the western and southern parts of the State were somewhat uncertain. Data extracted from well logs were used to define the reservoir extent. Published maps and cross-sections available from WVGES and the USGS were reviewed and considered in making interpretations. In addition, selected operator-provided well completion reports also were reviewed and considered.

c) Porosity

Porosity is one of the most important but elusive parameters required for shale resource assessment. For non-shale units, generally porosity is interpreted directly from a porosity well log with relatively minor adjustments required. For shale units, however, major adjustments must be made because the logging tool records porosity + kerogen as porosity. In addition, porosity must be corrected for the volume of shale (V_{sh}). Core data are needed to determine the volume of kerogen (V_{ker}) and V_{sh} and make these adjustments. Public access to cores and core data is very limited with the majority being retained by private companies. Only two cores and associated data are available for the Marcellus Shale in West Virginia. The cores were collected as part of the DOE research program on eastern gas shales between 1976 and 1992 (DOE 2007). For this project though, appropriate summary core data were available for an additional 9 cores as part of a doctoral dissertation by Wang (2012). Although the core data used by Wang were proprietary, the summary data were detailed and sufficient. For this project, porosity-related logs used along with the core data included bulk density, density porosity, and neutron porosity as available.

d) Water Saturation

Like porosity, water saturation is also very difficult to determine from well logs for shale units. And, generally, water saturation will be questionable if only density porosity logs are used for porosity input. In addition to porosity, resistivity log data are required. As with porosity, water saturation must be corrected for the V_{sh} and corrected again for V_{ker}.

4. Supplemental Data Derivation

a) Level of Organic Maturity

Level of organic maturity (LOM) was determined from vitrinite reflectance data taken from cores and cuttings analyzed by the USGS and WVGES. These cores and cuttings were obtained from oil and gas wells. The vitrinite reflectance data are contained in a USGS report, "Thermal Maturity Patterns (CAI and %Ro) in the Ordovician and Devonian Rocks of the Appalachian Basin in West Virginia" (Repetski et al. 2005). The organic maturity was estimated from vitrinite reflectance by using a figure displaying the relationship between the two entities (Figure 13, Crain 2013d). Data were imported into ArcMap and a layer was generated using Geostatistical Analyst. From that, LOM was assigned to the study wells.

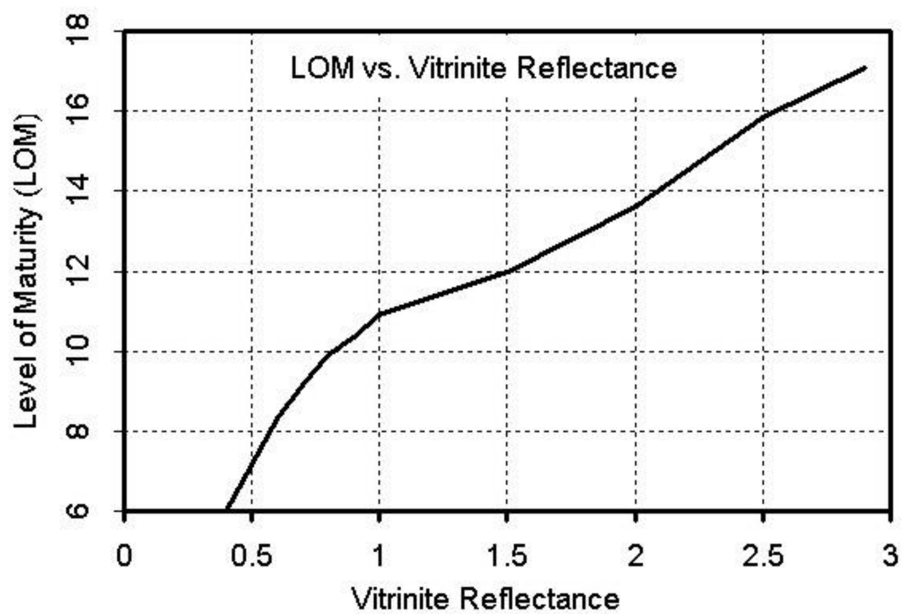


Figure 13. Relationship between vitrinite reflectance and LOM. Crain states that some petrophysicists do not accept the graph and would prefer to use regression analysis (Crain 2013d).

b) Volume of Shale

The volume of shale (V_{sh}) was estimated for the "Upper Marcellus" and "Lower Marcellus" by combining a series of facies maps included in Wang (2012). Wang's maps are based on proprietary data from 18 cores with 9 from West Virginia.

c) Total Organic Carbon

As with V_{sh}, total organic carbon (TOC) was estimated for the "Upper Marcellus" and "Lower Marcellus" by examination of a series of facies maps included in Wang (2012).

d) *Pressure Gradient*

Pressure data were obtained from operator reports received by WVGES via WVDEP (West Virginia Department of Environmental Protection). Pressure data are reported at surface conditions and thus provide a conservative estimate. For this study, only wells with completion zones in the Marcellus Shale, Purcell Limestone, and/or Hamilton Group were used. Data were imported into ArcMap and reported pressure gradients for rock pressure were calculated by dividing reported rock pressure by depth. A layer was generated given the input pressure gradient data using Geostatistical Analyst from ArcMap. From that, the pressure gradients were assigned to study wells.

e) *Temperature*

Temperature data were interpreted from well logs received by WVGES via WVDEP. The initial set of wells was a subset of the study wells because not all study wells had temperature logs. Temperature data were imported into ArcMap and temperature gradient were calculated by subtracting surface temperature from formation temperature and dividing by depth. A layer of temperature gradients was made using Geostatistical Analyst. Temperature gradient values were determined using the gradient layer for wells without data. Data were converted back to formation temperature using surface temperature and depth.

5. Data Processing

a) *Porosity, Adjusted*

Porosity log data were used to calculate effective porosity. A bulk density log is almost always available and was used to calculate density porosity if a density porosity log was unavailable. Density porosity was calculated from bulk density given a grain and fluid density. Density porosity and neutron porosity then were averaged, as is the normal convention, to determine porosity. If both density and neutron porosity logs were not available, the available data were used. Porosity was corrected for the V_{sh} as extracted from maps based on Wang (2012). Porosity was further corrected for V_{ker} assuming a linear relationship based on the TOC maps extrapolated from Wang (2012). Porosity data were normalized using a baseline method and processed in one-half foot intervals. Porosity was conservatively assumed to be 3% based on the range of the data in the dataset if processing yielded an unreasonable result such as a negative number.

b) *Water Saturation, Adjusted*

Data from the porosity log(s) and resistivity log were used to calculate water saturation. Generally, the deepest reading on the resistivity log was selected. A modified version of the Simandoux equation was used with A=1, M=1.7, and N=1.7 to correct for the V_{sh} (as extrapolated from Wang, 2012). Water saturation was further corrected for the V_{ker} assuming a linear relationship based on the TOC maps extrapolated from Wang (2012). Porosity and resistivity data were normalized using a baseline method and processed for every one-half foot interval. Water saturation was set to be 1 (100%) if data processing yielded a value greater than 1.

c) Formation Volume Factor

The formation volume factor (FVF) converts gas volumes present in the reservoir to surface temperature and pressure conditions. FVF also incorporates gas compressibility. When multiple gases are present, this calculation can be complex; therefore, to simplify the calculation, gas was assumed to be 99% methane and 1% indeterminate gas for this study. In actuality, based on gas composition analysis of four Marcellus Shale wells; Bullin and Krouskop (2008) indicate that methane, ethane, and propane account for 98.8 to 99.6% of the gas in the reservoir while carbon dioxide and nitrogen account for 0.4 to 1.2% of the gas in the reservoir. Although the assumption of 1% indeterminate gas is reasonable for the Marcellus Shale, the significance of ethane and propane in determining the formation volume factor should be investigated for any future work.

d) Free Gas

Free gas was calculated from porosity, water saturation, non-combustible gas, reservoir thickness, and formation volume factor for every one-half foot interval and then summed for each zone of interest for each well (equation 2). For this preliminary study, the zones of interest were the “Upper Marcellus-A”, “Upper Marcellus-B”, and the “Lower Marcellus”. The derivation of each required parameter is described in detail above. In general, most data were obtained through the original interpretation of well logs with adjustments made to data as necessary using core data extracted from literature.

e) Adsorbed Gas

Adsorbed gas was calculated given gas content (G_c) adjusted for pressure, formation density, and reservoir thickness for each zone of interest for each well (equation 6). For this preliminary study, the zones of interest were the “Upper Marcellus-A”, “Upper Marcellus-B”, and the “Lower Marcellus”. The derivation of each parameter is described above. In general, most data were extracted from literature with Wang (2012) and Kuuskraa and Wicks (1984) being the primary sources. Data were also obtained through the original interpretation of well logs.

6. Data Correction and Refinement

For the most part, stratigraphic cross-sections and maps were used to identify reservoir thickness, depth, and extent issues. Cross-sections and maps were reviewed, in general, for abnormal transitions; data adjustments were made as necessary. In addition, some rather simple data checks were performed such as those related to depth.

IV. Results and Discussion

A number of layers and maps were derived to obtain supplemental data required for the resource assessment. In addition, various maps and layers summarizing the results of the assessment were developed.

Given the study methodology, the level of organic maturity (LOM) may be used, along with other parameters, to calculate free and adsorbed gas. More specifically, LOM is used to estimate total organic carbon (TOC) using density or neutron porosity and resistivity well logs. The LOM map shown in Figure 14 was derived from vitrinite reflectance data, which were obtained from the USGS (2005). The map shows that the Marcellus Shale is more thermally mature (pink) in the eastern part of West Virginia becoming less mature in the western part of the State (green) in accordance with the changing depth of burial. LOM conveys the extent to which organic matter is converted to hydrocarbons and also impacts the type of resource — more thermally mature areas would be likely to contain natural gas whereas less mature areas are likely to contain natural gas liquids or possibly oil. The TOC data derived from the LOM data was compared to the TOC data from Wang (2012). When there was a difference, the data extrapolated from Wang's dissertation was used preferentially.

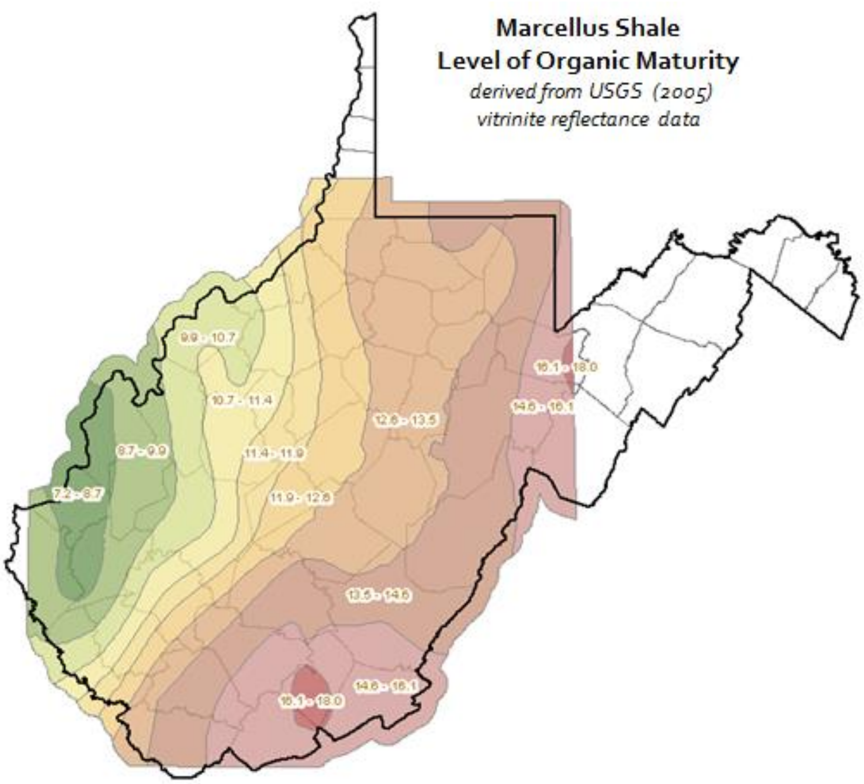


Figure 14. LOM within the Marcellus Shale. LOM is derived from vitrinite reflectance data which are obtained from cores and cuttings. LOM is used along with density porosity and resistivity well log data to estimate TOC.

TOC is used to estimate the volume of kerogen (V_{ker}) which in turn is used to adjust porosity and water saturation values. TOC is also used to estimate gas content (G_c). The "Upper Marcellus" and "Lower Marcellus" TOC summary maps are shown in Figure 15. Both maps show somewhat similar patterns of distribution along with similar percentages of TOC. The TOC concentration is highest in the center of the State becoming less concentrated toward the west and east. Reduced TOC to the east is likely a function of increased dilution of organic matter during sedimentation by increased influx of clastic material within the more landward portion of the basin. Reduced TOC to the west may be more a function of reduced organic matter production further offshore and also potentially reduced organic matter preservation with shallowing water depth on the western margin of the basin.

a

b

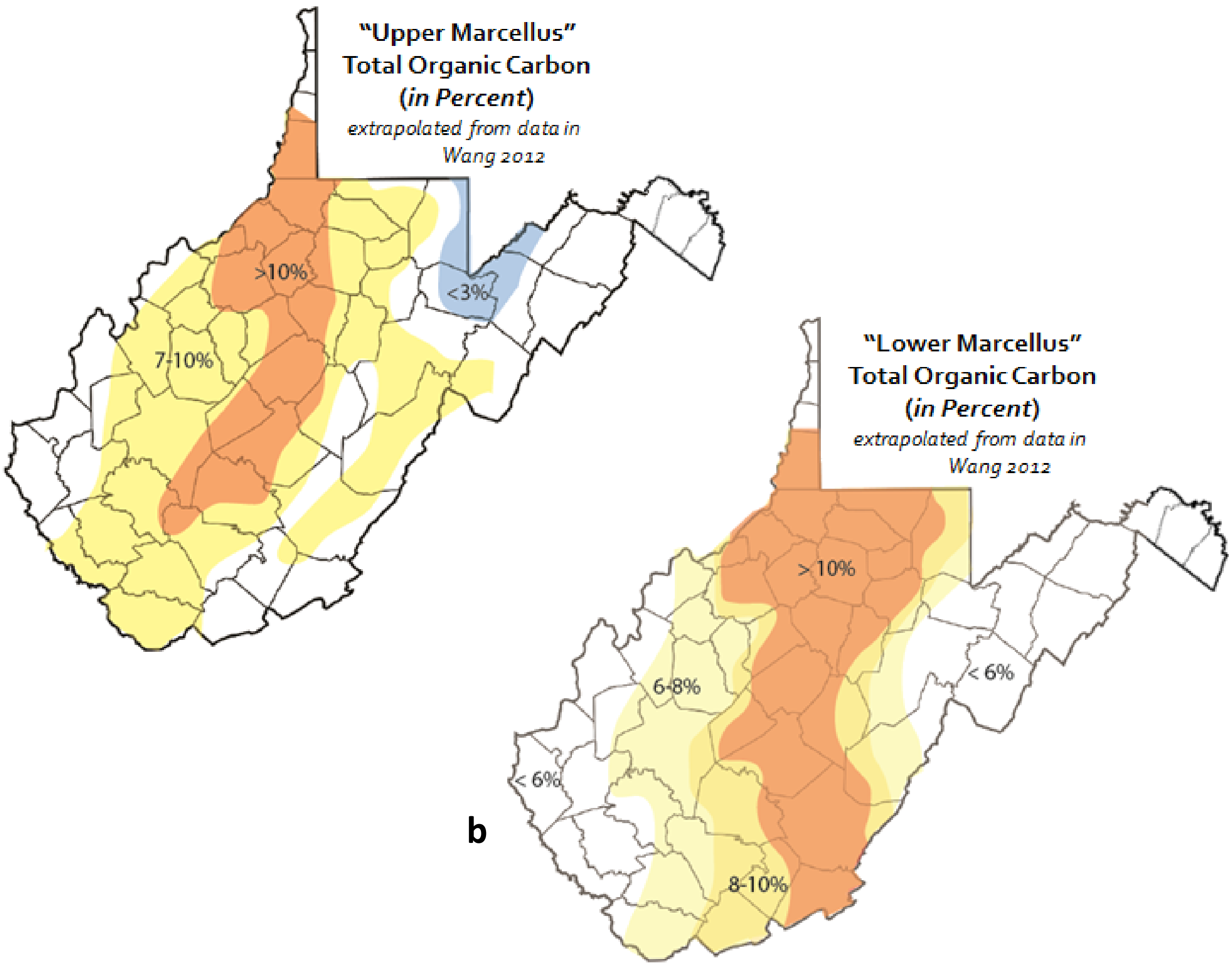


Figure 15. TOC concentration for the (a) "Upper Marcellus" and (b) "Lower Marcellus" shale. In this case, TOC were derived from core data (Wang 2012). TOC is used to estimate V_{ker} and G_c.

The volume of shale (V_{sh}) reflects the abundance of clay minerals and is required, along with V_{ker}, to make adjustments to porosity and water saturation values extracted from the well logs. Those data are used, along with other parameters, to calculate free gas. The “Upper Marcellus” and “Lower Marcellus” V_{sh} summary maps shown in Figure 16 were derived from a series of maps contained in a doctoral dissertation by Wang (2012). By examining the maps, it is apparent that clay minerals are more common in the “Upper Marcellus”. It is also apparent that the “Upper Marcellus” is clay-rich on the western and eastern edges of the State becoming poorer in clay toward the center. The “Lower Marcellus” appears to be clay-rich on the western part of the West Virginia becoming decreasingly clay-rich to the east. The amount and distribution of clay is directly related to the depositional environment.

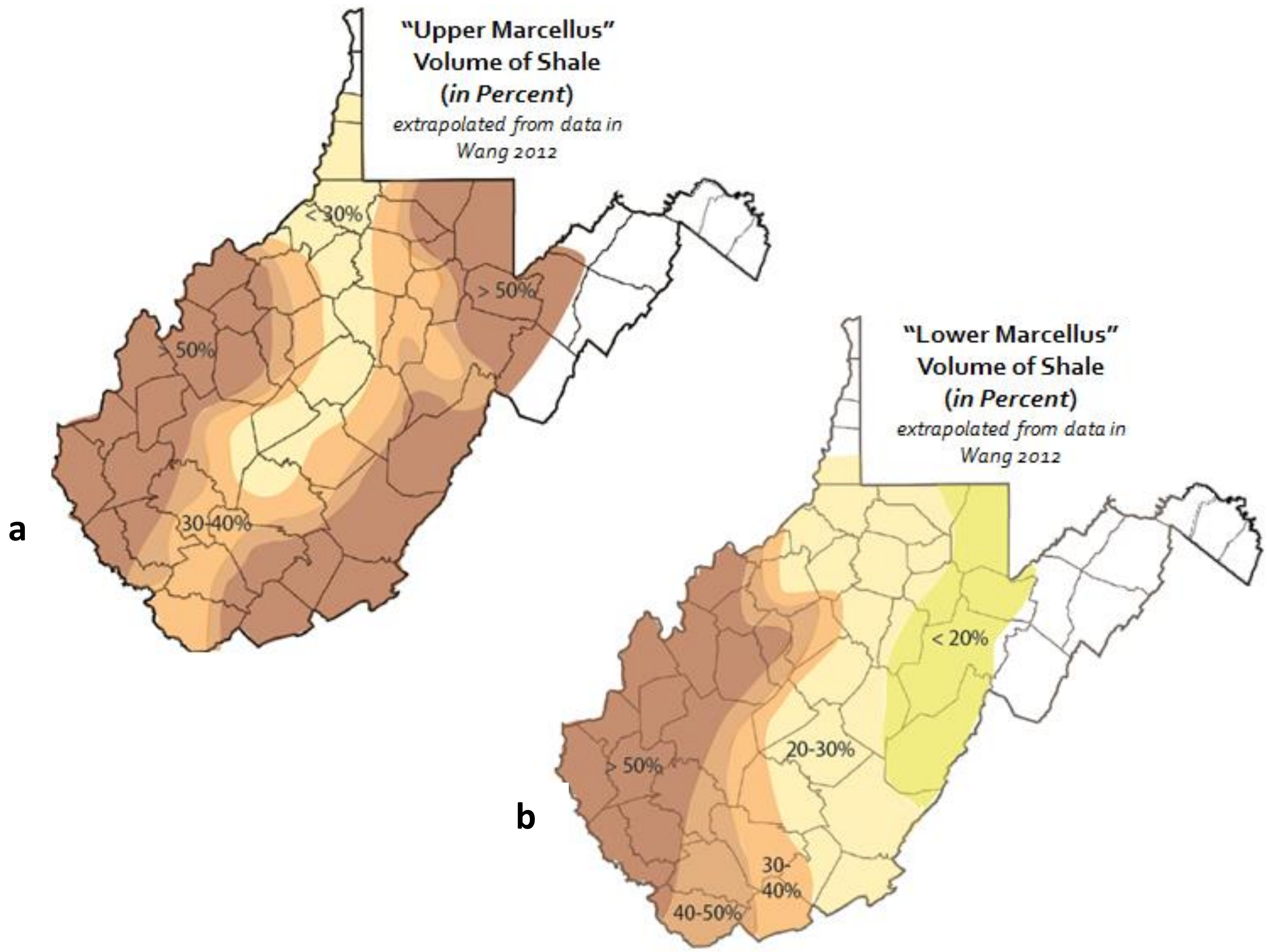


Figure 16. V_{sh} for the (a) “Upper Marcellus” and (b) “Lower Marcellus” shale. V_{sh} is derived from core data and is used to make adjustments to porosity and water saturation data.

Pressure data are used to calculate both free and adsorbed gas-in-place. The equations are sensitive to pressure gradient thus making it an important parameter. The data were reported by oil and gas operators to WVGES via WVDEP. At present, there is known to be an issue — data appear to be most commonly reported at surface conditions rather than subsurface conditions specific to the Marcellus Shale. Higher pressures, corresponding to reservoir conditions, would increase the reserve estimate. Several solutions have been proposed to estimate formation pressure including: 1) use of bottomhole pressure data to develop an empirical relationship, 2) use the Cullender and Smith (1956) estimation method, 3) use mud weight data, 4) use formation breakdown pressure data, and/or 5) use any pressure data contained in WVDEP "WW-6B" document (*see "Future Work" for additional details)*. The pressure at the surface in Figure 17a shows normal pressure areas in yellow with over-pressured areas to the north (red) and under-pressured areas to the south (blue). Previous work has shown that the over-pressured area (and hence normal-pressured area also) likely extends further to the south (Wrightstone 2009). Over-pressured areas will have higher volumes of free gas.

Formation temperature data are used to determine free gas-in-place. Data for this study were taken from temperature well logs. Figure 17b shows higher formation temperature in red and lower in blue. The formation temperature decreases from east to west across West Virginia primarily due to the decreasing depth of the Marcellus Shale.

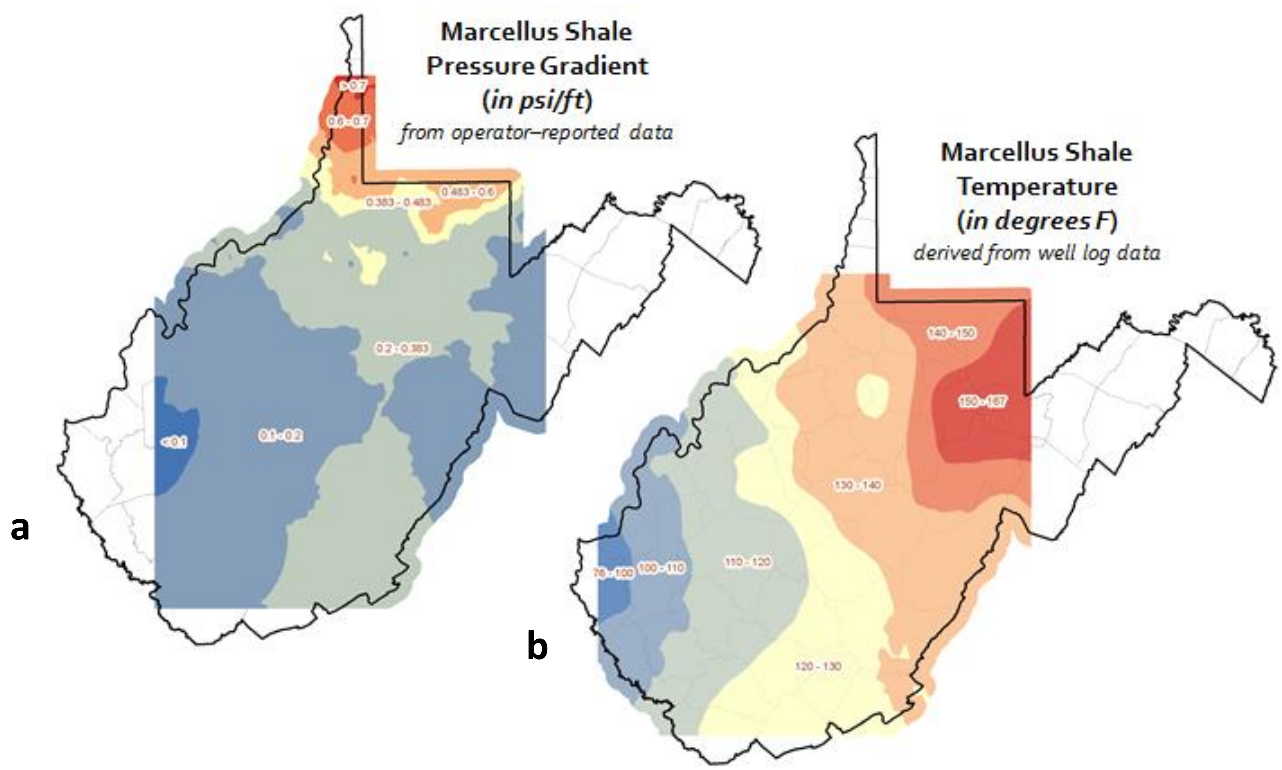


Figure 17. (a) Pressure gradient as derived from operator-reported data. Over-pressured areas are shown in red while under-pressured are shown in blue. Calculations are sensitive to pressure gradient variations. (b) Formation temperature as derived from temperature well log data. Higher temperatures are shown in red while lower temperatures are shown in blue.

Thickness data as shown in Figure 18a are used in calculating free and adsorbed gas-in-place. Figure 18a displays the thickness of the “Upper Marcellus” and “Lower Marcellus” *only*, which would be that portion of the Marcellus Shale that is highest in organic content; and therefore, most significant for estimating natural gas resources. The thickness data were obtained by evaluating well logs. The map shows the Marcellus, generally, is thickest in the eastern part of West Virginia (pink) becoming progressively thinner toward the western part (green). The thickness of the Marcellus is directly related to the depositional environment and structural history.

The map in Figure 18b, also derived from well logs, shows what proportion of “Upper Marcellus” and “Lower Marcellus” thickness is highly radioactive. Radioactivity is an indicator of organic content. The highest concentration of organic material is shown through the center of the State (pink) becoming progressively less toward the east and west (green). Interestingly, data from the map correspond to data from the TOC maps shown in Figure 15 even though the input datasets were different and derived independently from each other.

a

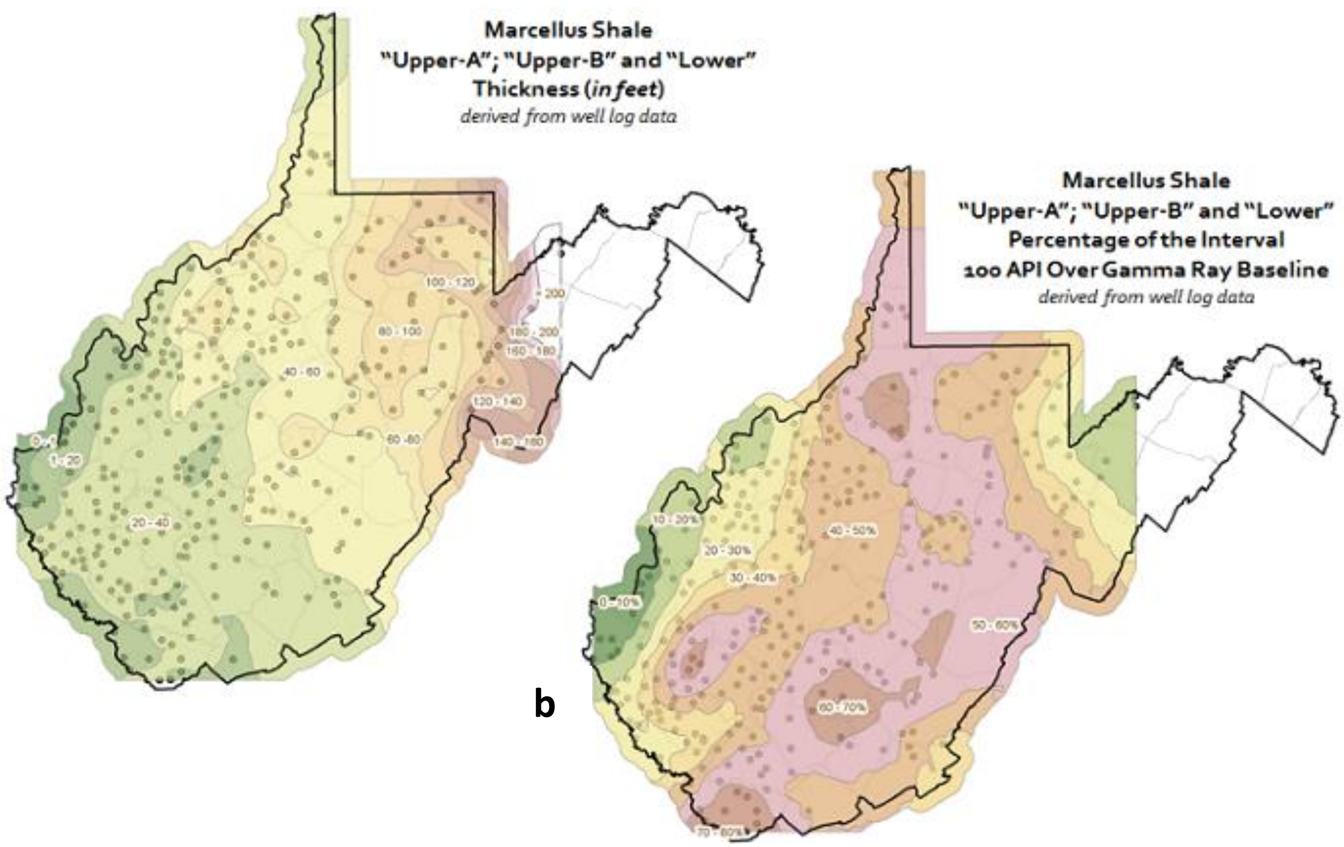


Figure 18. (a) Thickness of the “Upper Marcellus” and “Lower Marcellus” as derived from well log data. Thicker areas are shown in pink while thinner areas are shown in green. (b) Proportion of the “Upper Marcellus” and “Lower Marcellus” thickness that is highly radioactive; and therefore presumably, higher in natural gas resources.

Original gas-in-place estimates for the “Upper Marcellus” (both study units) and “Lower Marcellus” are shown in Figure 19. The maps display both free and adsorbed gas-in-place. Higher original gas-in-place volumes are shown in the north-central part of West Virginia (dark orange) with gas concentration decreasing to the south and west (light orange). This decrease to the south is a reflection of both decreasing unit thickness as well as decreasing depth (and therefore decreasing pressure). The layers are combined into an overall summary map for the Marcellus Shale in Figure 20.

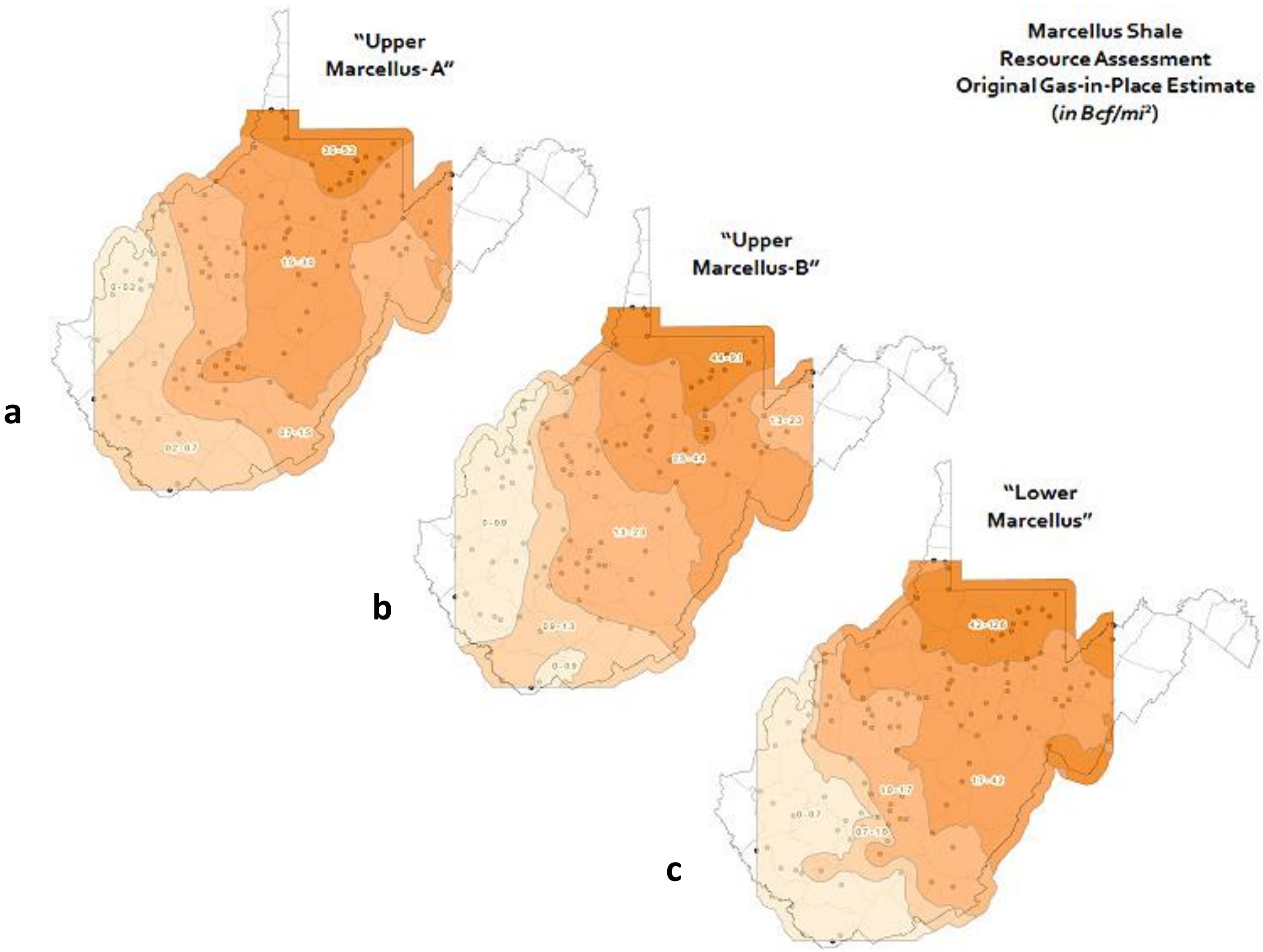


Figure 19. Original gas-in-place per unit area for the (a) “Upper Marcellus-A”, (b) “Upper Marcellus-B”, and (c) “Lower Marcellus” derived using a geologic approach for the resource assessment. Natural gas concentration is highest in the north-central part of the West Virginia (dark orange). Gas concentration decreases across the State toward the south and west.

Figure 20 shows the original gas-in-place estimates per unit area for the Marcellus Shale ("Upper Marcellus" and "Lower Marcellus" *only*). As with the individual "Upper Marcellus" and "Lower Marcellus" maps in Figure 19, the map displays both free and adsorbed gas-in-place. Higher original gas-in-place volumes are shown in the north-central part of West Virginia (dark red) with gas concentration decreasing to the south and west (pink). Higher concentrations in the north-central part of the State are due, in part, to greater reservoir thickness and higher pressure.

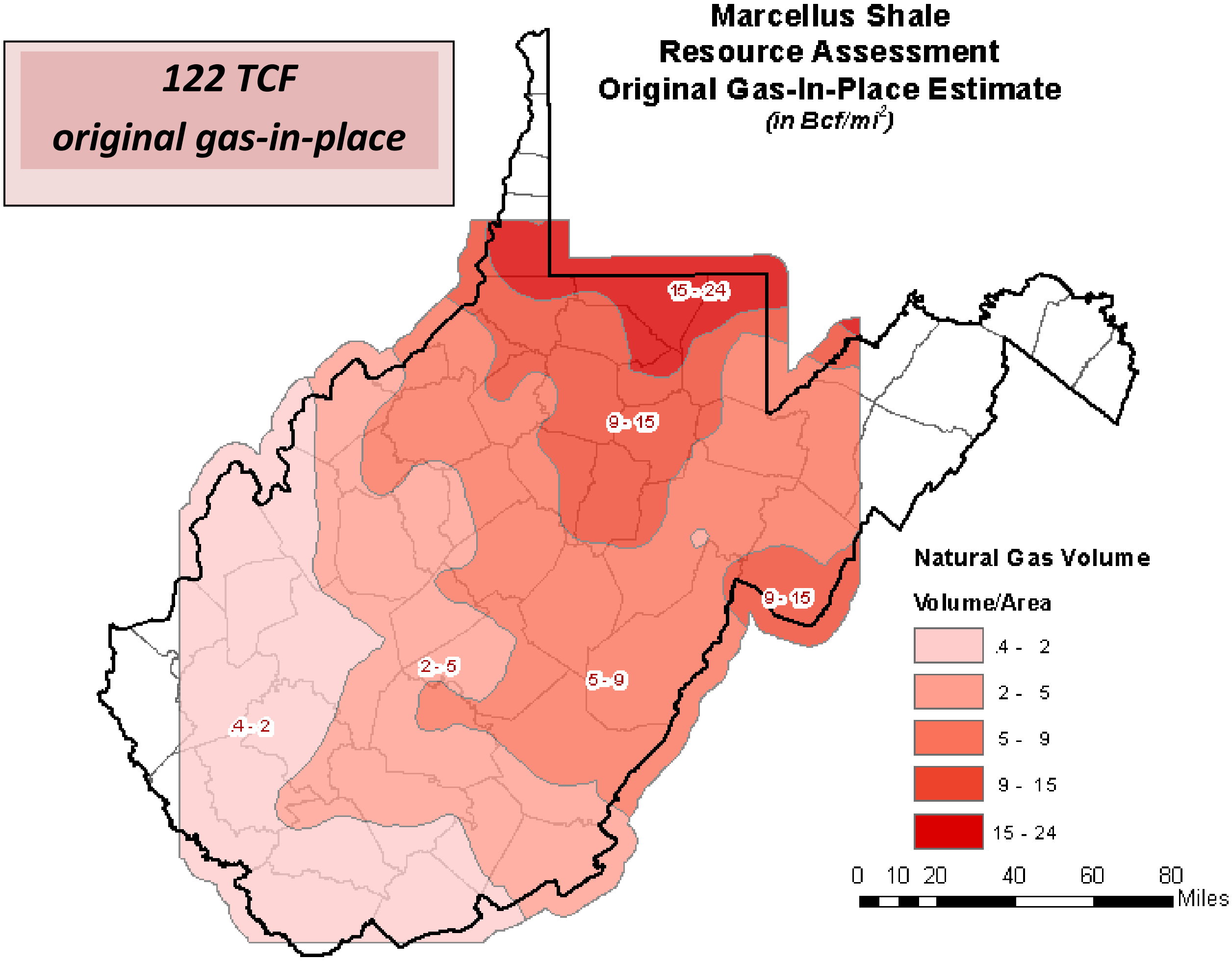


Figure 20. Original gas-in-place per unit area for the Marcellus Shale ("Upper Marcellus" and "Lower Marcellus" only). Natural gas concentration is highest in the north-central part of the State in the dark red area. The map translates to an overall preliminary original gas-in-place estimate of 122 TCF for West Virginia. Determining recoverable and remaining recoverable gas from original gas-in-place is the focus of future work.

The data depicted in Figure 20 translates to an overall preliminary estimate for original gas-in-place of 122 TCF for West Virginia. A "deterministic" methodology was used for the study — a single most likely value for each parameter for each well in the study was determined; and thus, the results are expressed as a single best estimate. Other study methodologies assign statistical probably functions providing a range of values around a mean. The estimate of 122 TCF is expected to increase with further study, most notably with finalization of the pressure data. In the only other known similar study specific to West Virginia, Kuuskraa and Wicks (1984) reported a 79.6 TCF original gas-in-place estimate. This study, because it was undertaken almost 30 years later, includes data not available to Kuuskraa and Wicks. It should be noted that original gas-in-place is not the same as recoverable gas or remaining recoverable gas.

Dozens of additional layers and maps have been, and can be, generated as the result of data developed from this study. With the exception of the original gas-in-place maps, the maps (Figures 14 through 18) address basic reservoir data. However, many additional specialty maps can be produced; for example, a map showing the ratio of adsorbed gas to free gas (Figure 21). In the light green areas, the ratio of adsorbed to free gas is approximately one. In the dark green area, the amount of free gas is higher. In the pink and yellow areas, the amount of adsorbed gas is higher.

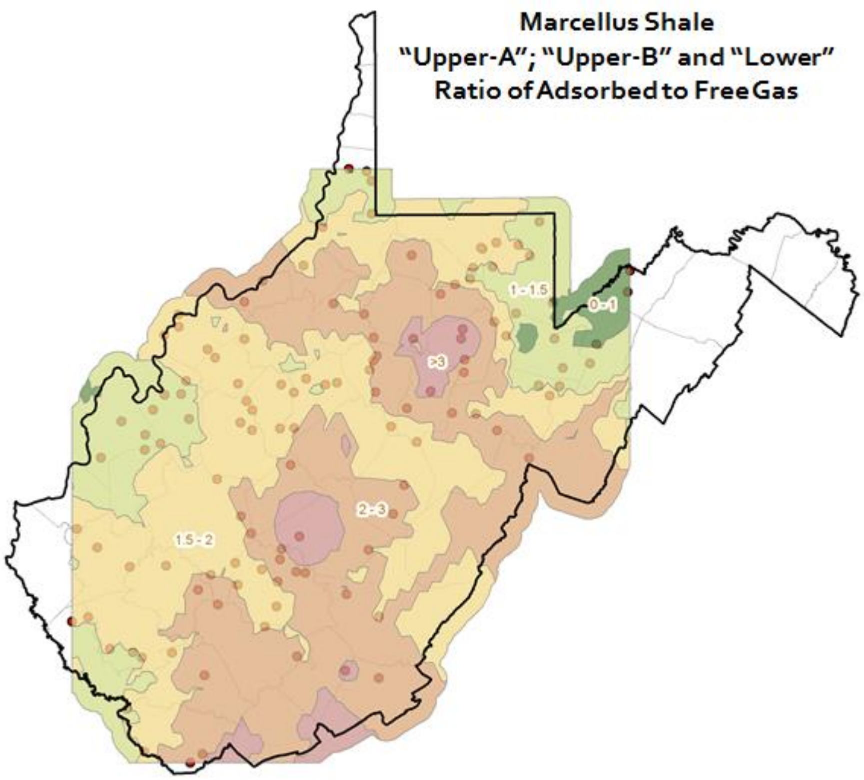


Figure 21. Ratio of adsorbed to free gas for the "Upper Marcellus" and "Lower Marcellus". The free and adsorbed gas are in nearly equal proportions in the light green area. Free gas exceeds adsorbed gas in the dark green area while adsorbed gas exceeds free gas in the pink and yellow areas.

V. Conclusions

The primary purpose of the project was to conduct a preliminary natural gas resource assessment of the Marcellus Shale for West Virginia using basic geologic data and GIS. The project was also designed to meet a number of other purposes including to: generate new geologic data from original interpretation of geophysical well logs; develop maps and stratigraphic cross-section sections; provide an up-to-date publicly-accessible web-based GIS map application; and develop a preliminary resource assessment framework for the State to evaluate other petroleum resources.

As is the case with many GIS-based studies, data acquisition and processing took a great deal of time and effort. Data processing mechanics need to be modified to streamline the overall procedure. It is interesting to note that in a recent Marcellus Shale conference brochure, the keynote speech was to address “geospatial technologies and how they assisted in the discovery and exploitation of the Marcellus Shale in the region” (EnerGIS 2013). Unfortunately, the State tends to lag behind industry when it comes to technology especially in this particular circumstance. However, it is important for the State to examine its own resources and this set of GIS-based products will assist WVGES in further evaluation of the Marcellus Shale and other emerging resources.

- **Preliminary Natural Gas Resource Assessment**

  This study used a geologic approach to estimate original gas-in-place resources for the Marcellus Shale for West Virginia. The preliminary estimate was determined to be 122 TCF original gas-in-place. In the only other known similar study specific to West Virginia, Kuuskraa and Wicks (1984) reported a 79.6 TCF original gas-in-place estimate.

  The estimate produced from this study can be refined in the future as new data are obtained. Data processing mechanics will need to be modified to some extent to streamline the overall procedure. Although results from the study are reasonable, adjustment to the pressure data is a necessary improvement but somewhat complex. Adjusting the pressure data from surface to subsurface values will increase the original gas-in-place estimate. However, the estimate of 122 TCF could be viewed as being in the conservative range of estimates. It is anticipated that the general pattern of gas distribution will remain approximately the same because the general pattern of pressure data is not expected to change.

- **Geologic Data from Original Interpretation of Geophysical Well Logs**

  A significant amount of new data was developed as the result of the study through original interpretation of well logs. Stratigraphic unit depths and thicknesses were determined and recorded for up to 16 different units for more than 300 wells. In addition, the zone and thickness of highly-radioactive shale were recorded for the “Upper Marcellus” and “Lower Marcellus” at up to four different levels — gamma ray over baseline, gamma ray 100 API over baseline, gamma ray 200 API over baseline, and gamma ray 300 API over baseline. Presumably, the higher levels of radioactivity imply higher levels of organic content and thus, in turn, imply the greater possibility of higher levels of natural gas resources. In addition to the stratigraphic data, porosity and resistivity data were interpreted and recorded for up to five different units at one-half foot intervals for more than 100 wells. Temperature data were recorded for 86 wells. These data were used to generate original gas-in-place maps and estimate original gas-in-place resources.

In addition, the new geologic data were used to define and refine the aerial extent of the Marcellus Shale in the State. The stratigraphic data were used to make 10 stratigraphic cross-sections that span West Virginia. The data were also used to make various stratigraphic maps, almost all of which did not exist previously. The only WVGES Marcellus-specific map that existed previously is shown in Figure 22a. The map was developed in 1980. An updated version of the map, using data developed from this study, is shown in Figure 22b. This map shows broad agreement with the pre-existing interpretation in terms of unit thickness throughout much of the State; however, the western limit of the Marcellus Shale (the “zero line”) is significantly refined as is the southern limit. The information is useful because WVGES has received operator reports indicating Marcellus Shale exists in areas where the unit was previously interpreted to not exist.

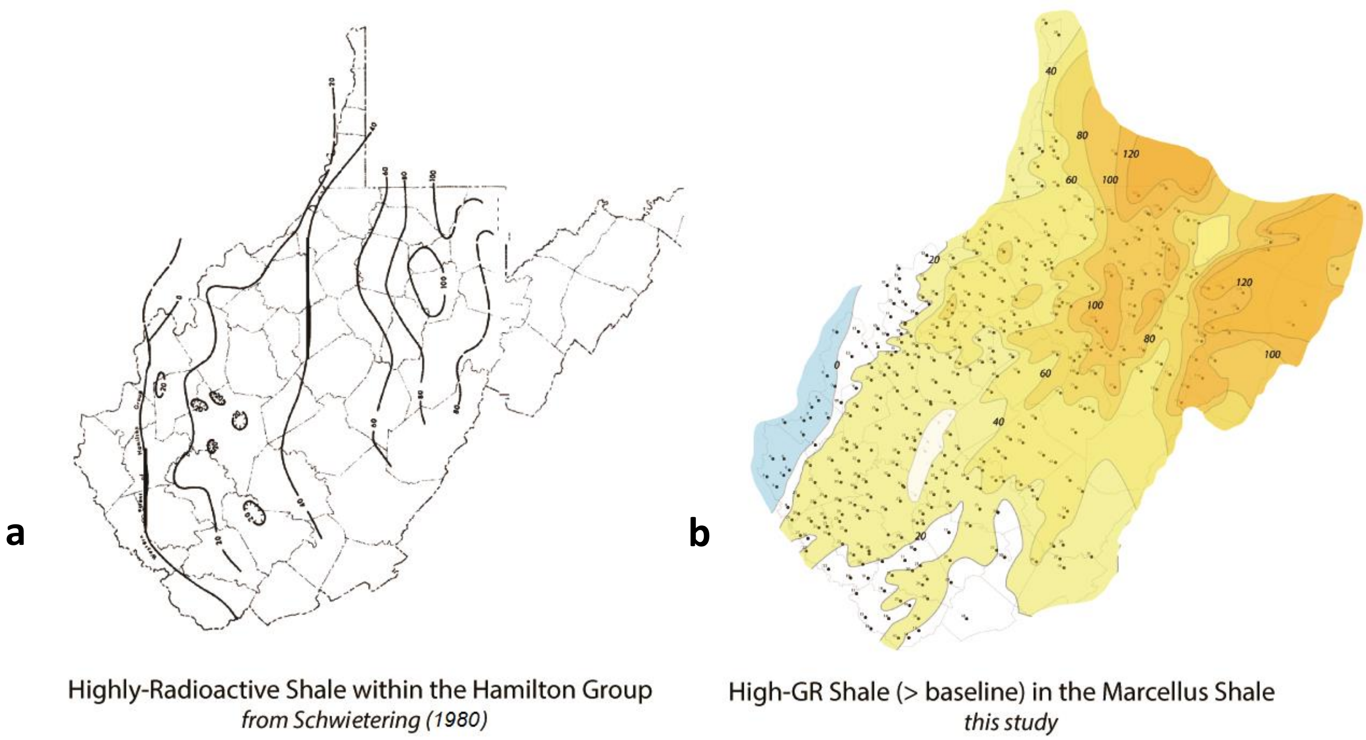


Figure 22. (a) Highly-radioactive shale within the Hamilton Group (equal to Marcellus Shale) circa 1980. The map shows the Marcellus thinning westward. (b) Map updated with data developed during this study showing the highly-radioactive portion of the Marcellus Shale. The Marcellus thins from east (dark orange) to west (white) and does not exist in the western-most part of the State (blue).

- **Data, Maps, and Stratigraphic Cross-Sections**
  All data, maps, and stratigraphic cross-sections developed as the result of the project are available for in-house use and research at WVGES. The data, maps, and cross-sections create a framework from which the State can further examine the Marcellus Shale. Data in the form of GIS layers and maps include: Marcellus Shale gross thickness, reservoir high gamma-ray thickness, reservoir depth, LOM, TOC, V_{sh}, formation temperature, gas ratio, and original gas-in-place. The stratigraphic cross-sections include 10 sections that span West Virginia — four in the north-to-south

direction and six in the west-to-east direction. Selected data and materials will be made available for public use.

- **Publicly-Accessible Web-Based GIS Map Application**
An up-to-date, publicly-accessible, web-based GIS map application has been developed and is available (http://ims.wvgs.wvnet.edu/Mar). The current application was developed using ArcIMS; a newer version is being developed using ArcGIS Server and a draft is available (http://www.wvgs.wvnet.edu/gis/marcellus/index7.html). The current version of the application was updated most recently in August 2013. After this study is finalized, data and maps will undergo peer review. At that time, selected data (GIS layers) will be added to the map application. Stratigraphic cross-sections will be made accessible through the application as well.

- **Preliminary Resource Assessment Framework to Evaluate Other Petroleum Resources**
Shale: A geologic-based resource assessment takes a tremendous amount of data and *can potentially* also take a tremendous amount of time depending largely on the availability and format of data as well as the availability of data processing tools. A geologic-based ***shale*** resource assessment can be a particularly difficult task if using public data *only* because core data are necessary and such data are a rarity. Even with core data, a geologic-based shale resource assessment is challenging as hydrocarbon storage and production from shales is not yet thoroughly understood. Future studies could be improved by obtaining reservoir pressure data directly from the operator or applying an acceptable method for determining reservoir pressure. Future studies also could be improved with additional data from core related to: 1) porosity; 2) V_{sh}, V_{ker}, and TOC; and 3) G_c and TOC-G_c functions. Although it was not an issue for the Marcellus Shale (Range Resources 2013); for some shale plays, dry and wet gas would need to be addressed. Assuming that publicly available data and the knowledge base increase through time such a task will become easier and yield more reliable results in the future.

Because of the work performed for the Marcellus Shale study, a resource assessment could be conducted fairly readily for at least two other shales assuming the appropriate core data are publicly available. The two shales are the Geneseo Shale Member of the Genesee Formation (or Burket Shale Member of the Harrell Shale) and the Rhinestreet Shale Member of the West Falls Formation. Necessary core data may be available from the EGSP. Seven cores were collected in West Virginia during the EGSP and may penetrate the Geneseo (Burket) and Rhinestreet, where they are present, as they are shallower than the Marcellus Shale (only two cores penetrated the Marcellus) (WVGES 2008). It should be noted that using a geologic-based resource assessment approach would not be appropriate at present for the Utica Shale in West Virginia due to the lack of Utica Shale wells and data.

Other Unconventional Petroleum Resources: Given the work that was performed for the Marcellus Shale resource assessment, it would be a fairly simple task to modify the approach and apply it to tight or low-permeability gas sands, such as the Upper Devonian siltstones recently discussed by Eckert et al. (2013). These resource assessments would not require core data as there is no need to consider adsorbed gas and no need to make adjustments to porosity and water saturation values related to V_{ker}.

VI. Future Work

Future considerations, work, and research have been categorized as shorter and longer term.

A. Shorter Term

- Finalize stratigraphic cross-sections. Cross-sections provide a framework from which a general understanding of the Marcellus Shale can be established and advanced. Four north-to-south and six west-to-east cross-sections that span the State have been developed.

- Adjust pressure data. Pressure data being used for the study are those reported by oil and gas operators to WVDEP. The data then are subsequently delivered from WVDEP to WVGES. At present, there are known to be issues with the pressure data — data appear to be most commonly reported at surface conditions rather than subsurface conditions specific to the Marcellus Shale. Potential solutions that have been suggested or otherwise identified are as follows.

    - Identify those wells with bottomhole pressure data, *which is thought to exist but be rather limited*, and develop an empirical relationship. Then apply the empirical relationship to all surface data to develop a pressure map or layer specific to the Marcellus Shale.

    - Use the Cullender-Smith method to calculate formation pressure data from surface pressure data (Cullender and Smith 1956). The method is considered to be too simplistic especially for multi-phase wells and some Marcellus Shale wells likely fall into that category. Necessary data are available.

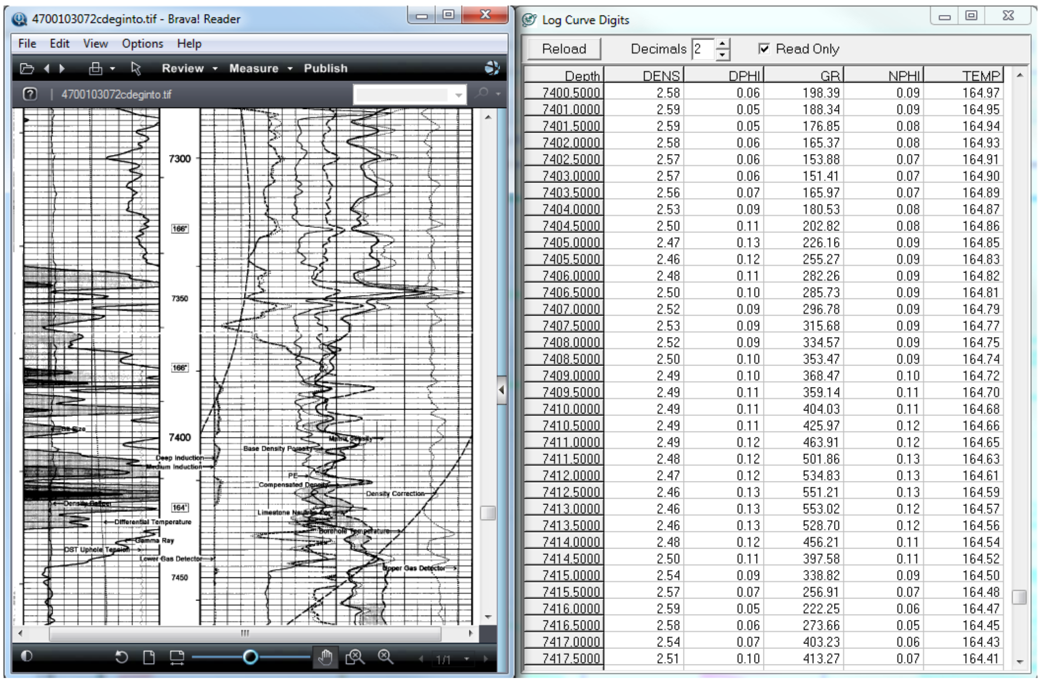
    - Use mud weight reported on any well logs to which WVGES has access. Mud weight is critical in keeping the well under control; and therefore, is directly related to formation pressure. At present, however, WVGES receives very few mud logs.

    - Use breakdown pressure as reported on records received by WVGES from the operator to estimate formation pressure from breakdown pressure.

    - Use pressure data contained in "WW-6B", a newer type of document that WVGES is starting to receive from operators via WVDEP. At least one of the documents received recently contained pressure gradient data for the Marcellus Shale and it has been suggested that all "WW-6B" documents should be reviewed for relevant data.

- Adjust existing well data based on refined correlations and refined pressure data. Currently, well data related to stratigraphic unit (formation) tops are undergoing internal review at WVGES; data will be adjusted as necessary. Any refined stratigraphic data along with the refined pressure data will need to be incorporated into the project.

- Incorporate additional well data. Most of the WVGES well log data is available as scanned images. Although such data are useful, digital data are far more useful for data analysis and in performing calculations (Figure 23). For this preliminary study, digital data for 123 wells were processed with very encouraging results. Because additional digital data are available, it would be beneficial to incorporate the data into the study. Also, WVGES receives new well logs regularly and a sample of wells in bordering states might prove helpful.



Depth	DENS	DPHI	GR	NPHI	TEMP
7400.5000	2.58	0.06	198.39	0.09	164.97
7401.0000	2.59	0.05	188.34	0.09	164.95
7401.5000	2.59	0.05	176.85	0.08	164.94
7402.0000	2.58	0.06	165.37	0.08	164.93
7402.5000	2.57	0.06	153.88	0.07	164.91
7403.0000	2.57	0.06	151.41	0.07	164.90
7403.5000	2.56	0.07	165.97	0.07	164.89
7404.0000	2.53	0.09	180.53	0.08	164.87
7404.5000	2.50	0.11	202.82	0.08	164.86
7405.0000	2.47	0.13	226.16	0.09	164.85
7405.5000	2.46	0.12	255.27	0.09	164.83
7406.0000	2.48	0.11	282.26	0.09	164.82
7406.5000	2.50	0.10	285.73	0.09	164.81
7407.0000	2.52	0.09	296.78	0.09	164.79
7407.5000	2.53	0.09	315.68	0.09	164.77
7408.0000	2.52	0.09	334.57	0.09	164.75
7408.5000	2.50	0.10	353.47	0.09	164.74
7409.0000	2.49	0.10	368.47	0.10	164.72
7409.5000	2.49	0.11	359.14	0.11	164.70
7410.0000	2.49	0.11	404.03	0.11	164.68
7410.5000	2.49	0.11	425.97	0.12	164.66
7411.0000	2.49	0.12	463.91	0.12	164.65
7411.5000	2.48	0.12	501.86	0.13	164.63
7412.0000	2.47	0.12	534.83	0.13	164.61
7412.5000	2.46	0.13	551.21	0.13	164.59
7413.0000	2.46	0.13	553.02	0.12	164.57
7413.5000	2.46	0.13	528.70	0.12	164.56
7414.0000	2.48	0.12	456.21	0.11	164.54
7414.5000	2.50	0.11	397.58	0.11	164.52
7415.0000	2.54	0.09	338.82	0.09	164.50
7415.5000	2.57	0.07	256.91	0.07	164.48
7416.0000	2.59	0.05	222.25	0.06	164.47
7416.5000	2.58	0.06	273.66	0.05	164.45
7417.0000	2.54	0.07	403.23	0.06	164.43
7417.5000	2.51	0.10	413.27	0.07	164.41

Figure 23. Screenshot of a scanned well log image on the left and digitized well log data on the right. Digitized well log data are very useful for analyzing data and performing calculations. However it is very time-consuming and difficult, especially for Marcellus Shale data because image data tend to overlap, to convert data in scanned form to digital form.

- Recalibrate G_c to reflect changes in reservoir pressure.

- Investigate gas composition for the Marcellus Shale and the impact of gas composition on the formation volume factor.

- Refine volume estimates. Current volume estimates, though thought to be reasonable, would need to be refined in light of adjusted pressure data, updated stratigraphic data, additional well data, recalibrations to core, and a modified formation volume factor.

- Investigate recovery factors by comparing original gas-in-place estimates to production data. Recovery factors would be dependent on a number of parameters including but not limited to geology or reservoir characteristics, well spacing, well orientation (vertical or deviated well) or well orientation related to current stress fields, prevailing engineering technology, infrastructure, and economics. It may possible to capture the variety and evolution of recovery factors as new technologies are utilized in the basin such as reduced cluster spacing and reduced fracture stage length.

- Estimate ***current recoverable*** natural gas volumes using the recovery factors that are developed.

- Estimate ***future recoverable*** resources given a variety of anticipated conditions and scenarios.

- Estimate ***remaining recoverable*** resources by subtracting produced volumes from original gas-in-place volumes.

- Estimate volumes of co-produced liquids from production data.

- Conduct sensitivity analysis.

- Input V_{sh} and TOC maps into GIS format. The V_{sh} and TOC maps were hand-drawn based on data obtained from a dissertation by Wang (2012) that, among other items, contains a series of facies maps for the Marcellus Shale. Wang's maps were combined to obtain summary "Upper Marcellus" and "Lower Marcellus" V_{sh} and TOC maps for the study. The resulting summary maps could be made GIS compatible.

- Finalize maps including reservoir location, extent, thickness, and depth; formation temperature and pressure; LOM; and original, current recoverable, and remaining recoverable gas-in-place volumes.

- Integrate new data developed as the result of the project into the centralized WVGES Oil and Gas Database as possible and appropriate. Data would likely include stratigraphic data such as unit name and depth and well log data such as porosity and water saturation values. *Note: Any numerical data obtained directly from IHS, Inc. are to be held confidential or, in other words, the data can be used by WVGES but not released to other entities or the public.*

- Add additional maps and features to the publicly accessible Marcellus Shale web-based GIS map application. Add access to maps including: reservoir location, geographic extent, thickness, depth; formation temperature and pressure; and LOM. Add access to stratigraphic cross-sections.

- Maintain and improve the publicly accessible Marcellus Shale web-based GIS map application. The current application is available at: http://ims.wvgs.wvnet.edu/Mar; the future application draft is available at: http://www.wvgs.wvnet.edu/gis/marcellus/index7.html (Figure 24).

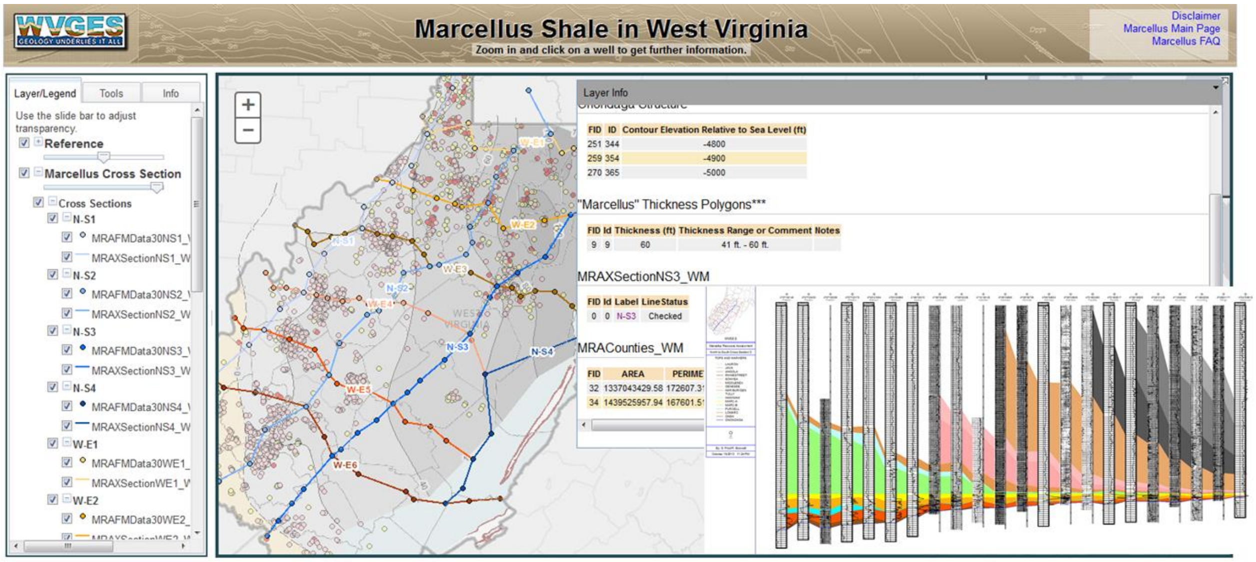


Figure 24. Screenshot showing a draft of the future version of the publicly-accessible Marcellus Shale web-based GIS map application. The current version of the application was developed using ESRI ArcIMS technology; the future version is being developed using ESRI ArcGIS Server technology.

B. Longer Term

- Investigate the possibility of using irregularly-shaped grids for GIS-based calculations because that might be more appropriate given irregularly-spaced well data.

- Build additional GIS-based tools so that future shale and non-shale resource assessments for the State can be conducted somewhat readily using a standard methodology.

- Investigate porosity, V_{sh} and V_{ker}, as well as G_c and TOC functions further because none are thoroughly understood — almost all aspects of shale reservoir research, exploration, development, and production is in its infancy. Porosity, V_{sh} and V_{ker}, as well as G_c and TOC functions play an important role in the determination of resources.

- Extend the resource assessment geographically to include other or all states that have Marcellus Shale resources.

- Explore conflict management (i.e. consider water, roads, pipeline access/capacity, right-of-ways, residential conflict, utility access and usage issues, etc.).

- Use the data and results from the study to conduct cost-benefit analyses specific to the Marcellus Shale (i.e. consider all aspects of the energy system — economy, environment, etc.).

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VIII. Appendix

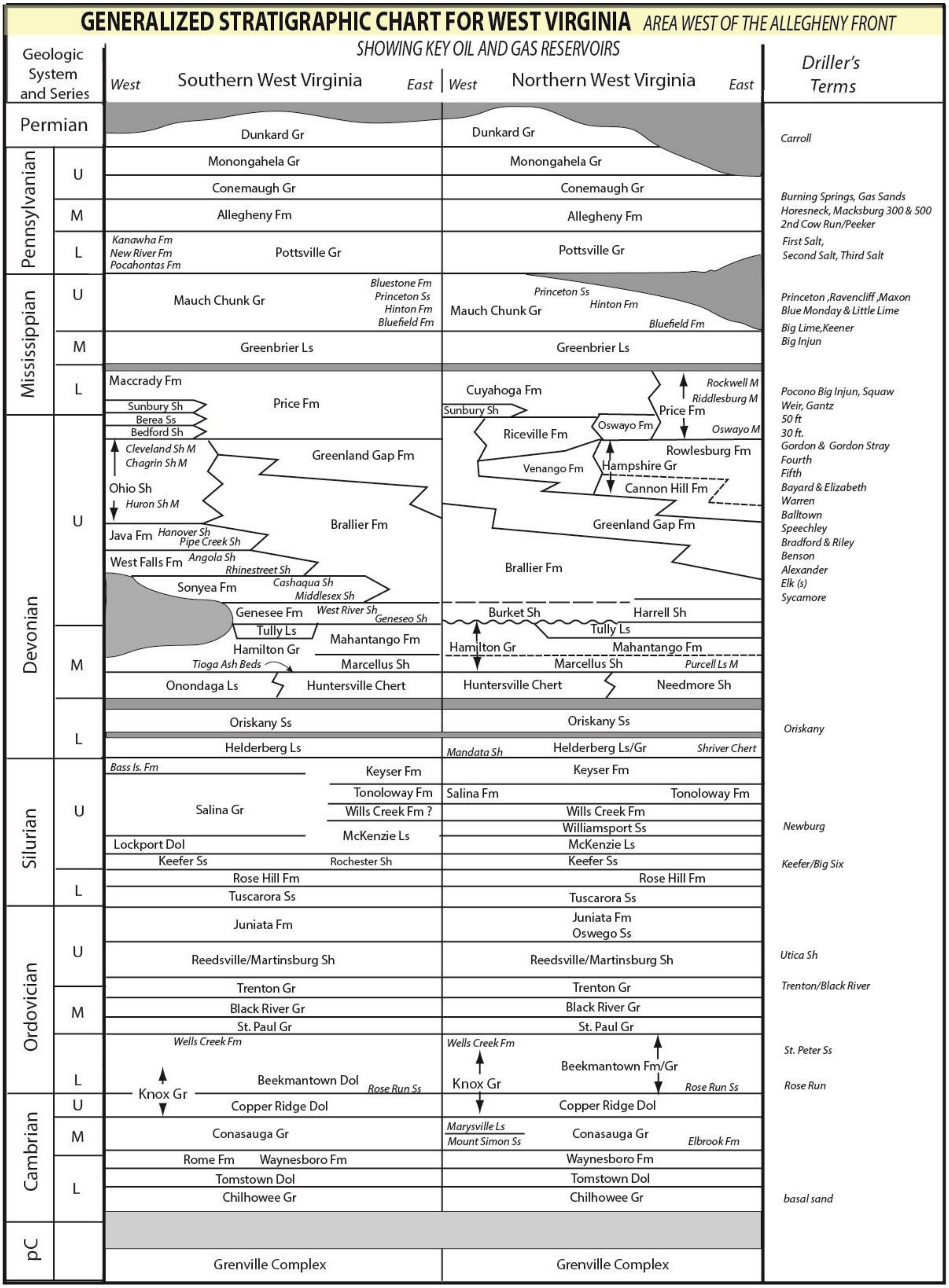
A. Abbreviation List

(in alphabetical order)

Abbreviation	Abbreviation Translation
AAPG	American Association of Petroleum Geologists
AGS	Appalachian Geological Society
API	American Petroleum Institute
Bcf	Billion Cubic Feet
BBNGL	Billion Barrels of Natural Gas Liquids
BBOil	Billion Barrels of Oil
BTU	British Thermal Units
cc	cubic centimeters
DOE	United States Department of Energy
EIA	United States Energy Information Administration
EGSP	Eastern Gas Shale Project
F	Fahrenheit
g	grams
G_c	Gas Content
GIP_{adsrb}	Original Adsorbed Gas-In-Place
GIP_{free}	Original Free Gas-In-Place
GIP_{total}	Total Original Gas-In-Place
GIS	Geographic Information System
LOM	Level of Organic Maturity
m	Meters
NETL	National Energy Technology Laboratory
NPC	National Petroleum Council
psi	Pounds per Square Inch
scf	Standard Cubic Foot
SDE	Spatial Database Engine
TCF	Trillion Cubic Feet
TOC	Total Organic Carbon
USGS	United States Geological Survey
V_{ker}	Volume of Kerogen
V_{sh}	Volume of Shale
WVDEP	West Virginia Department of Environmental Protection
WVGES	West Virginia Geological and Economic Survey

B. Stratigraphic Chart

A generalized stratigraphic chart for West Virginia shows key oil and gas reservoirs for southern and northern West Virginia in the area west of the Allegheny Front. Common driller's terms are also shown. The Marcellus Shale can be seen midway down the figure in the Middle Devonian portion of the chart.

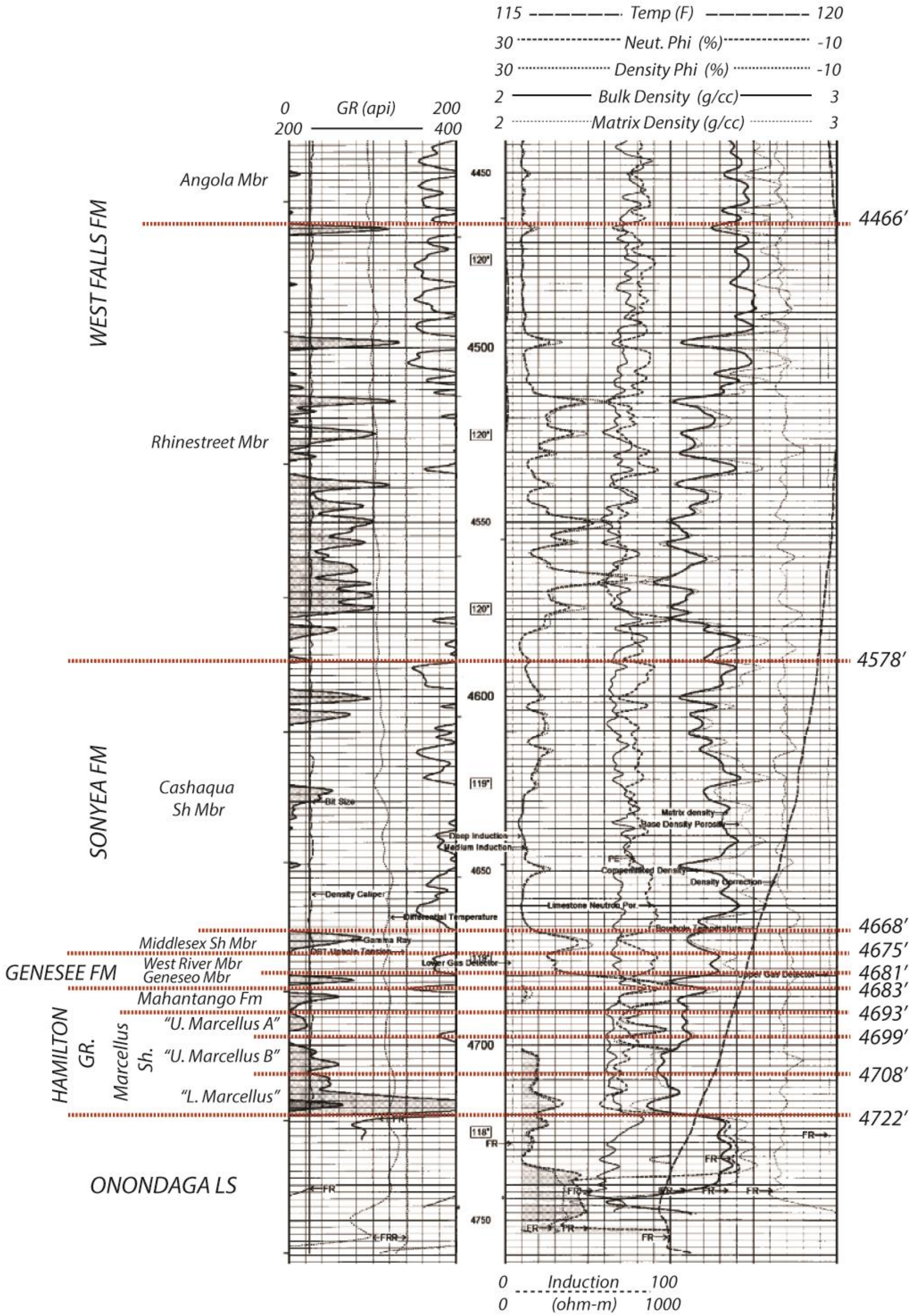

GENERALIZED STRATIGRAPHIC CHART FOR WEST VIRGINIA AREA WEST OF THE ALLEGHENY FRONT
SHOWING KEY OIL AND GAS RESERVOIRS
Geologic System and Series
West Southern West Virginia East
West Northern West Virginia East
Driller's Terms
Permian
Pennsylvanian
Mississippian
Devonian
Silurian
Ordovician
Cambrian
pC
U
M
L
Dunkard Gr
Monongahela Gr
Conemaugh Gr
Allegheny Fm
Kanawha Fm
New River Fm
Pocahontas Fm
Pottsville Gr
Mauch Chunk Gr
Bluestone Fm
Princeton Ss
Hinton Fm
Bluefield Fm
Greenbrier Ls
Maccrady Fm
Price Fm
Sunbury Sh
Berea Ss
Bedford Sh
Cuyahoga Fm
Rockwell M
Riddlesburg M
Oswayo Fm
Oswayo M
Riceville Fm
Rowlesburg Fm
Venango Fm
Hampshire Gr
Cannon Hill Fm
Cleveland Sh M
Chagrin Sh M
Ohio Sh
Huron Sh M
Greenland Gap Fm
Brallier Fm
Java Fm
Hanover Sh
Pipe Creek Sh
West Falls Fm
Angola Sh
Rhinestreet Sh
Sonyea Fm
Cashaqua Sh
Middlesex Sh
Genesee Fm
West River Sh
Geneseo Sh
Burket Sh
Harrell Sh
Tully Ls
Mahantango Fm
Hamilton Gr
Tioga Ash Beds
Marcellus Sh
Purcell Ls M
Onondaga Ls
Huntersville Chert
Needmore Sh
Oriskany Ss
Helderberg Ls
Mandata Sh
Helderberg Ls/Gr
Shriver Chert
Bass Is. Fm
Keyser Fm
Tonoloway Fm
Salina Gr
Salina Fm
Wills Creek Fm ?
Wills Creek Fm
Williamsport Ss
Lockport Dol
McKenzie Ls
Keefer Ss
Rochester Sh
Rose Hill Fm
Tuscarora Ss
Juniata Fm
Oswego Ss
Reedsville/Martinsburg Sh
Trenton Gr
Black River Gr
St. Paul Gr
Wells Creek Fm
Beekmantown Dol
Beekmantown Fm/Gr
Rose Run Ss
Knox Gr
Copper Ridge Dol
Conasauga Gr
Marysville Ls
Mount Simon Ss
Elbrook Fm
Rome Fm
Waynesboro Fm
Tomstown Dol
Chilhowee Gr
Grenville Complex
Carroll
Burning Springs, Gas Sands
Horesneck, Macksburg 300 & 500
2nd Cow Run/Peeker
First Salt,
Second Salt, Third Salt
Princeton ,Ravencliff ,Maxon
Blue Monday & Little Lime
Big Lime,Keener
Big Injun
Pocono Big Injun, Squaw
Weir, Gantz
50 ft
30 ft.
Gordon & Gordon Stray
Fourth
Fifth
Bayard & Elizabeth
Warren
Balltown
Speechley
Bradford & Riley
Benson
Alexander
Elk (s)
Sycamore
Oriskany
Newburg
Keefer/Big Six
Utica Sh
Trenton/Black River
St. Peter Ss
Rose Run
basal sand

C. Geophysical Well Log Interpretation, Selected Samples

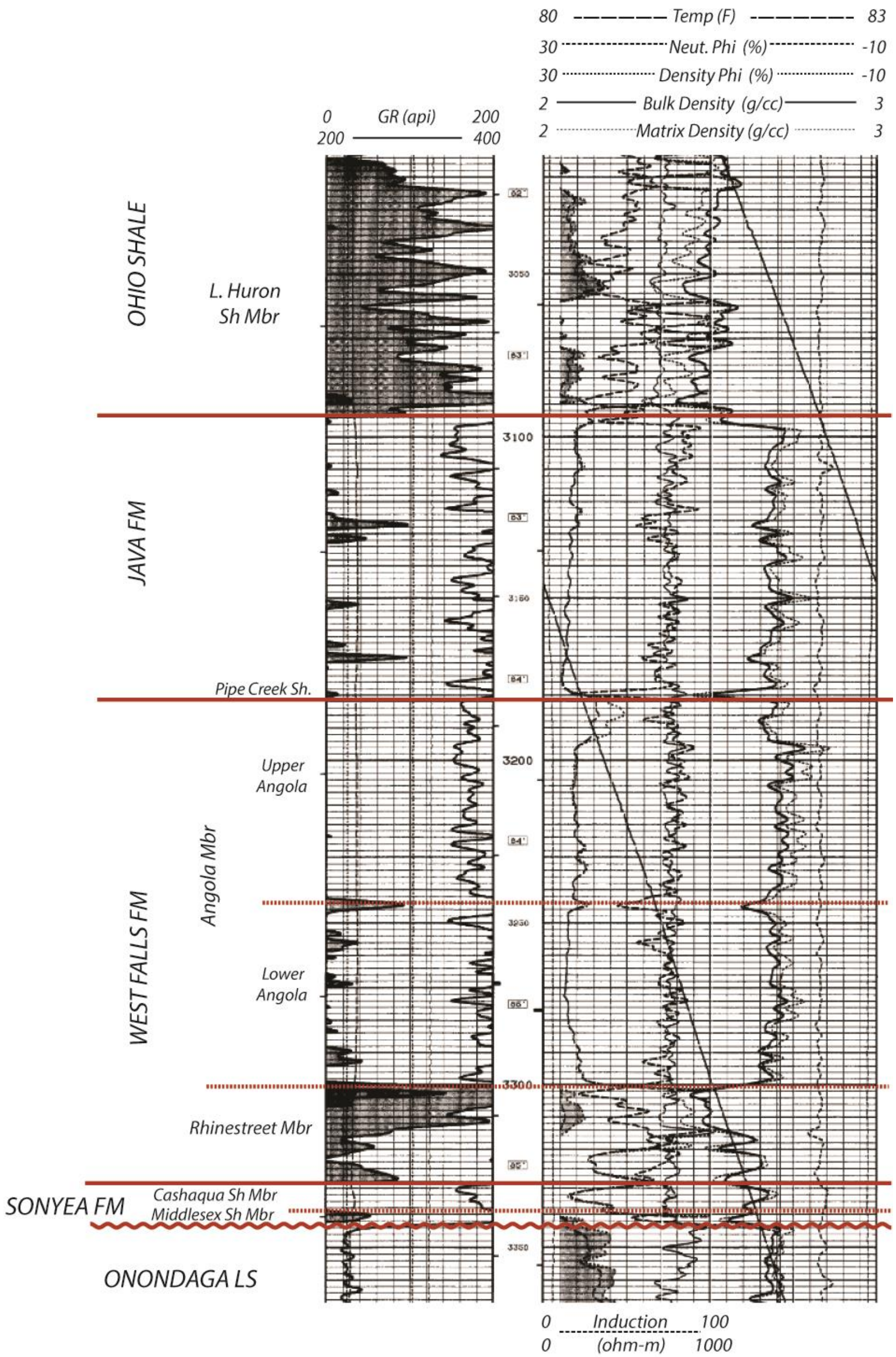
A gamma ray well log, at minimum, was printed out for each well using a consistent vertical or depth-based scale for all wells. Stratigraphic units for each well were interpreted and stratigraphic units between wells were correlated using standard techniques. Interpretations and correlations were checked using various tools including stratigraphic cross-sections and maps. Wells were then re-interpreted and re-correlated as needed given inconsistencies or issues as seen in the cross-sections and maps. Later in the project, depth-registered scanned log images and digital log data were used in Petra to further refine thickness and depth data as interpreted from the paper logs.

Shown below are interpretations of two gamma ray well logs. Over the past few years, reports received from operators have highlighted the need for WVGES to review and update any Marcellus-specific materials as well as to generate newer materials. At present the ***only*** WVGES-published Marcellus Shale map, other than Marcellus wells, is from 1980 (Schwietering) (Figure 22a). One of the questions about the Marcellus Shale is exactly where the western limit is. The two well logs shown below are near the western limit — one to the east of the western limit (Putnam County) and one to the west of the western limit (Wayne County). Based on the WVGES and DOE interpretations, it was determined that the Putnam County well contains Marcellus Shale but the Wayne County well does not (everything shown in red on the well log images is interpreted and is new data for WVGES).

Putnam Co.
4707901463
Lat 39.498089 N Lon -81.814842 W



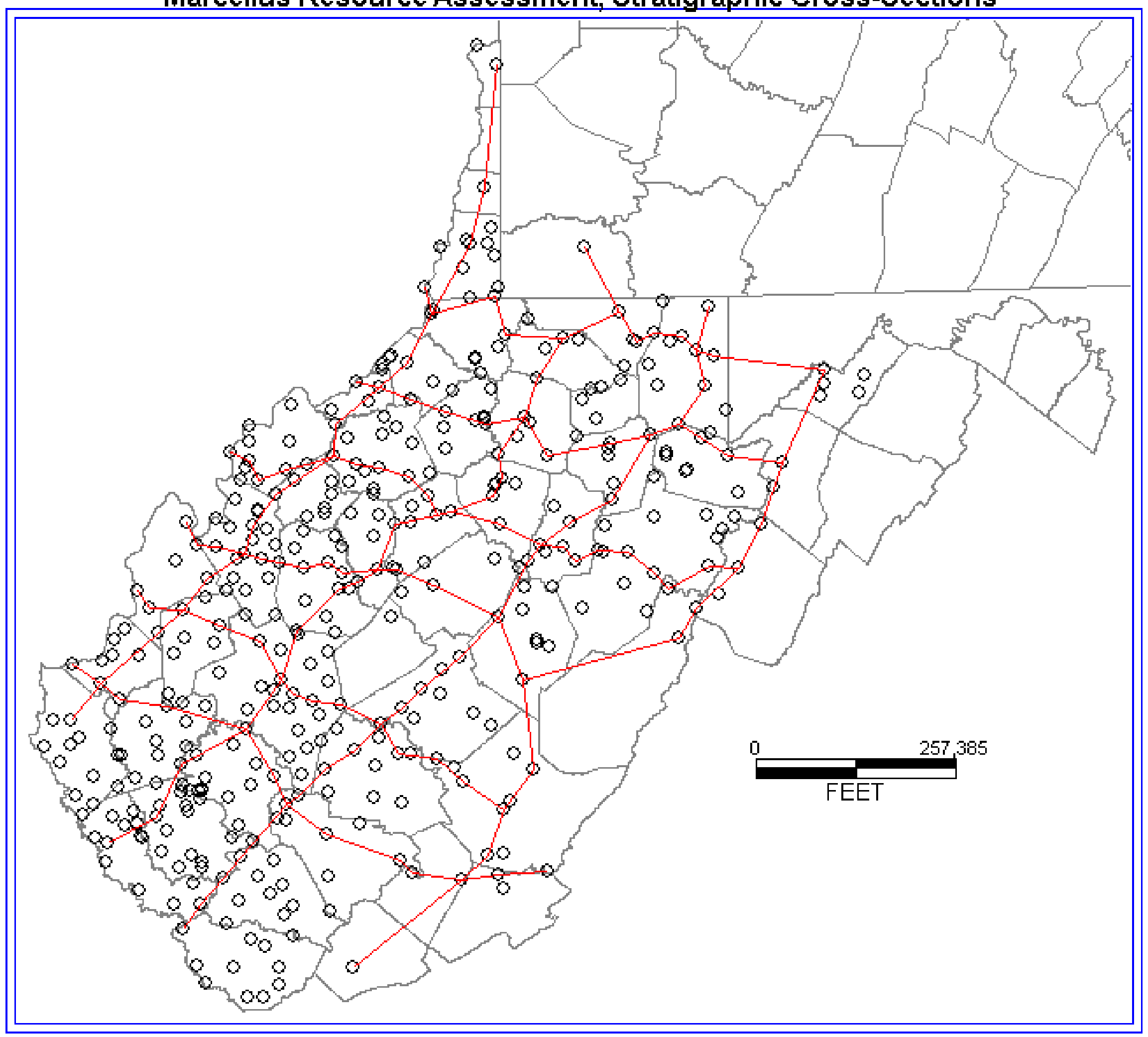
Wayne Co.
4709902044
Lat 39.09115 N Lon -82.47711 W

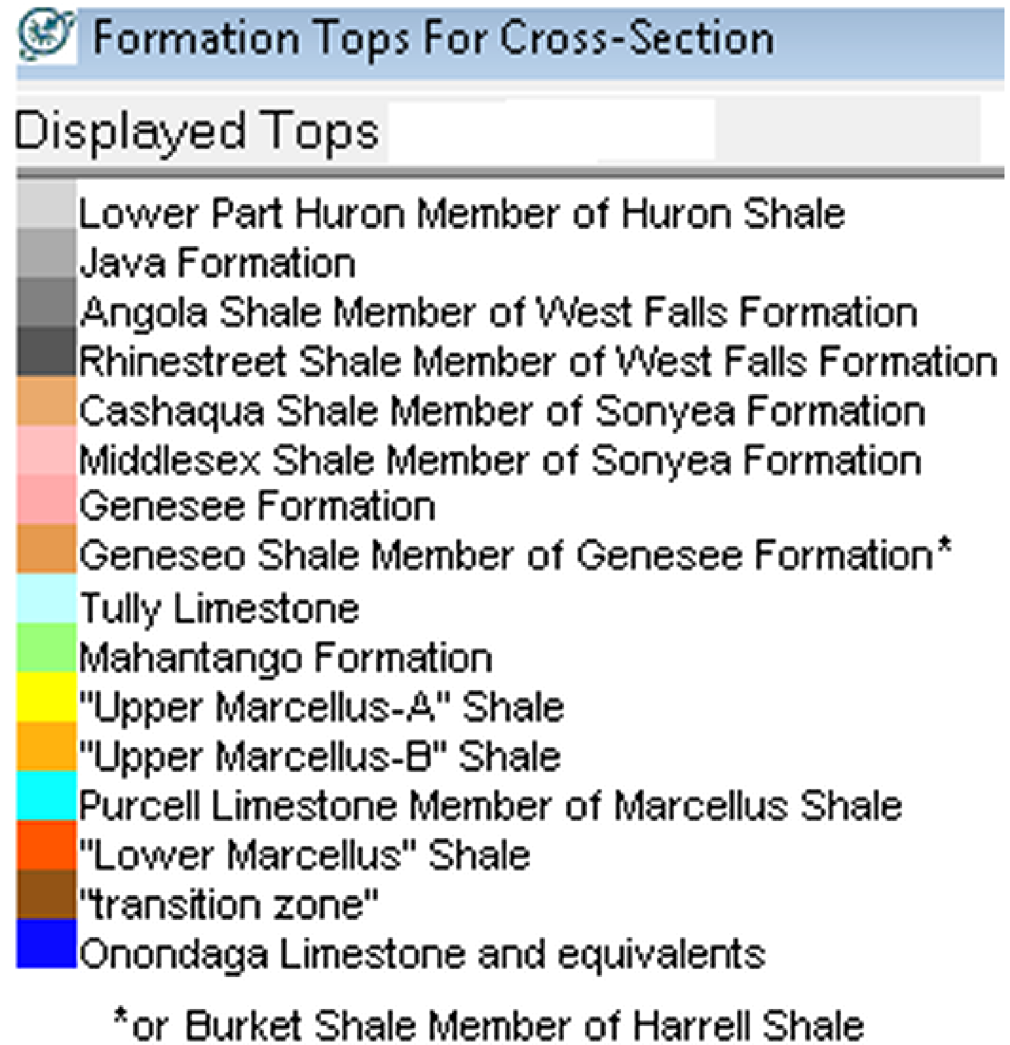


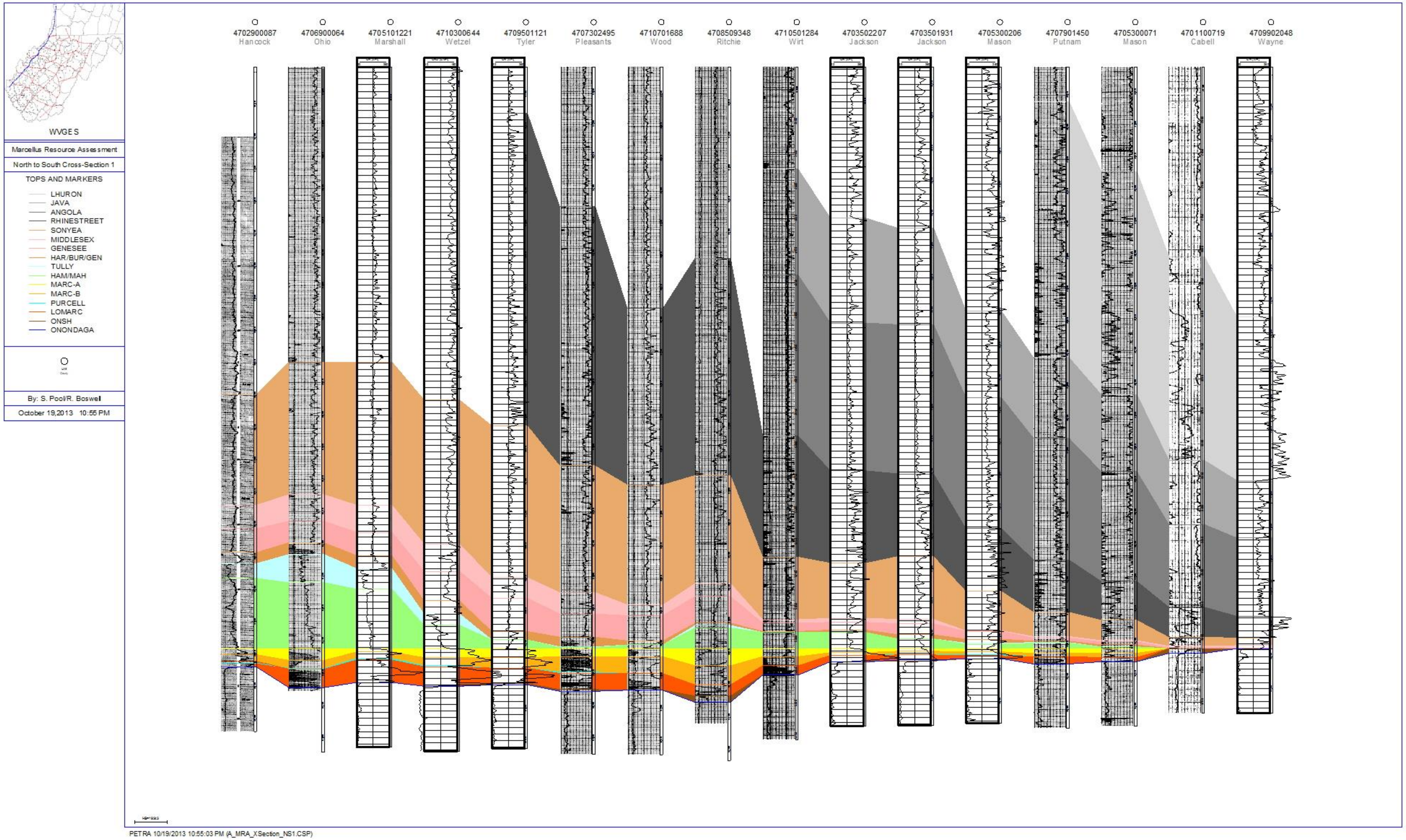
D. Stratigraphic Cross-Sections

Cross-sections showing the stratigraphy of the Marcellus Shale and other pertinent units above and below the Marcellus Shale have been assembled. Four north-to-south and six west-to-east cross-sections have been developed to show the depth, thickness, and distribution of the units as well as the relationship between units. Cross-sections lines are shown in red on the map while a color guide and associated stratigraphic units are shown in the legend (both images were taken from Petra). Draft cross-sections are included below and, when finalized, will be made accessible through the GIS map application.

Marcellus Resource Assessment, Stratigraphic Cross-Sections






WVGES
Marcellus Resource Assessment
North to South Cross-Section 1
TOPS AND MARKERS
LHURON
JAVA
ANGOLA
RHINESTREET
SONYEA
MIDDLESEX
GENESEE
HAR/BUR/GEN
TULLY
HAM/MAH
MARC-A
MARC-B
PURCELL
LOMARC
ONSH
ONONDAGA
By: S. Pool/R. Boswell
October 19,2013 10:55 PM
4702900087
Hancock
4706900064
Ohio
4705101221
Marshall
4710300644
Wetzel
4709501121
Tyler
4707302495
Pleasants
4710701688
Wood
4708509348
Ritchie
4710501284
Wirt
4703502207
Jackson
4703501931
Jackson
4705300206
Mason
4707901450
Putnam
4705300071
Mason
4701100719
Cabell
4709902048
Wayne
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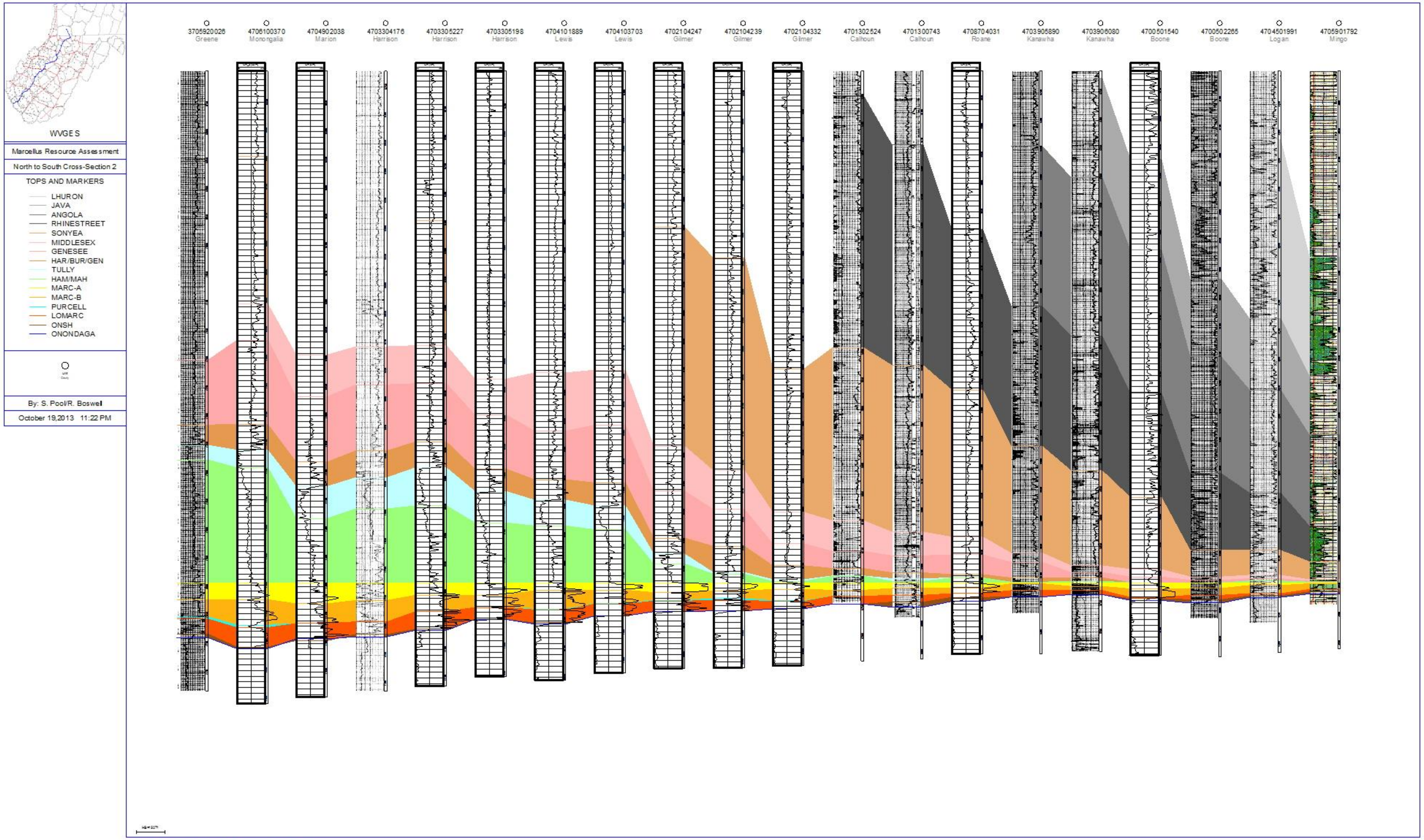

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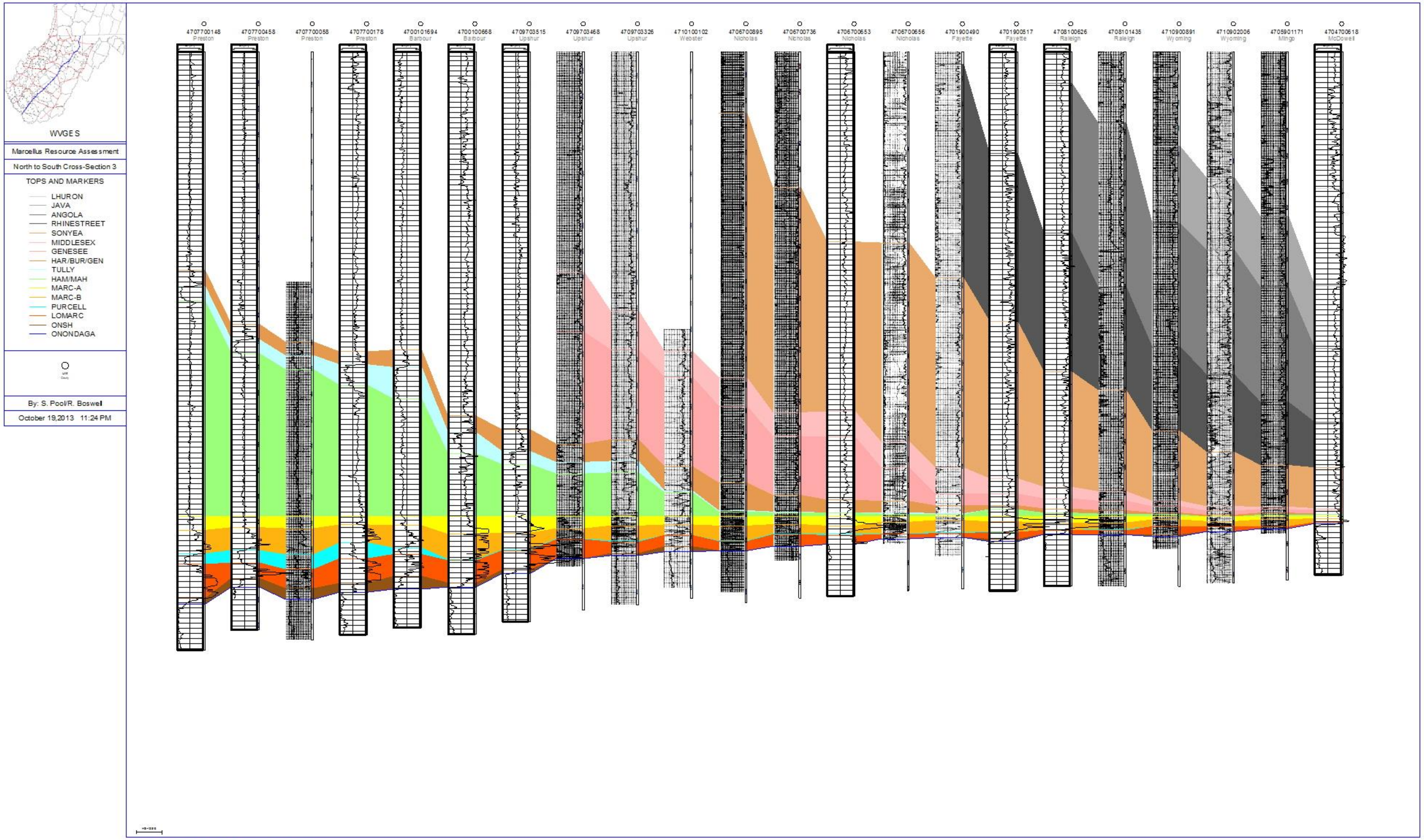

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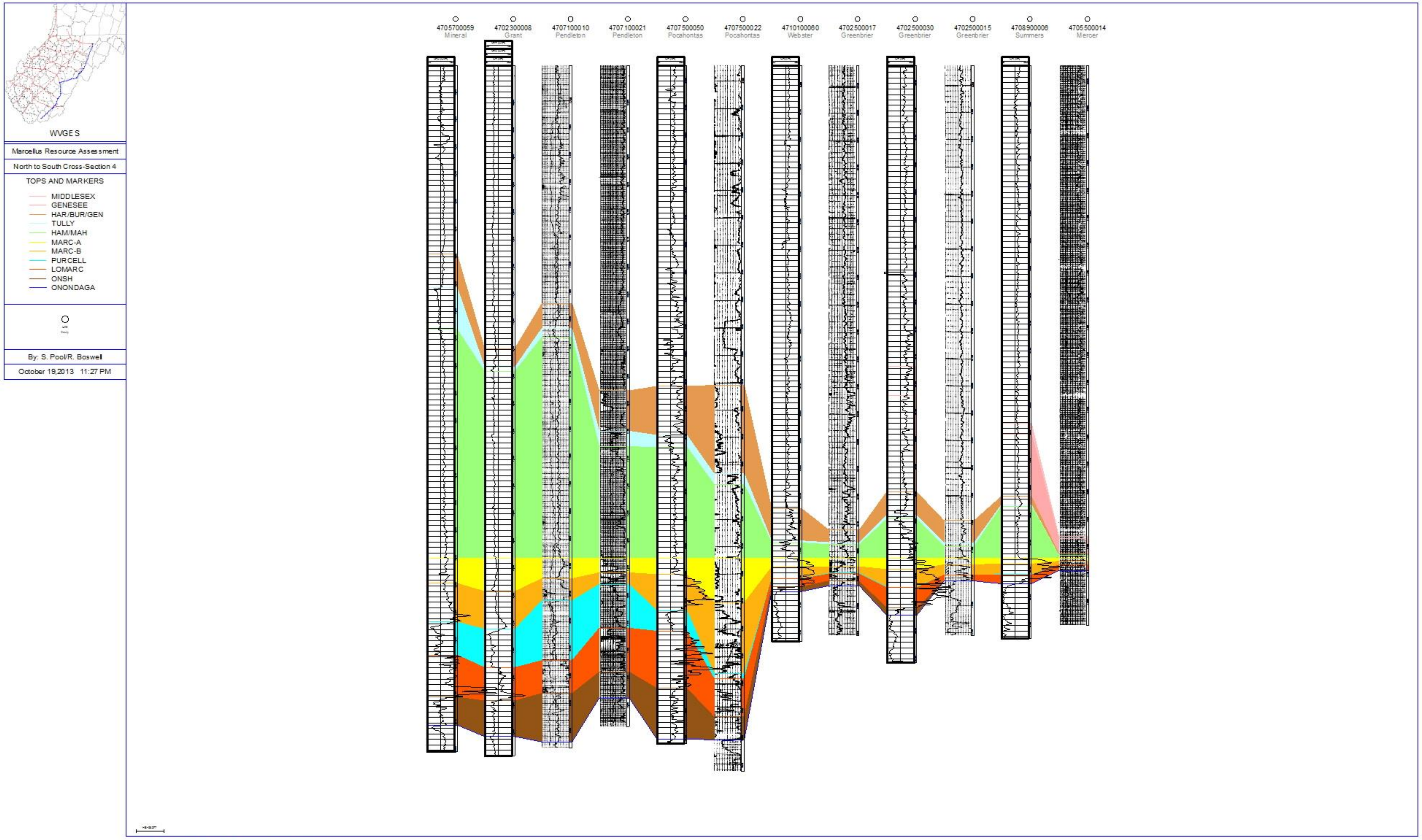
WVGES
Marcellus Resource Assessment
North to South Cross-Section 4
TOPS AND MARKERS
MIDDLESEX
GENESEE
HAR/BUR/GEN
TULLY
HAM/MAH
MARC-A
MARC-B
PURCELL
LOMARC
ONSH
ONONDAGA
By: S. Pool/R. Boswell
October 19,2013 11:27 PM
4705700059
Mineral
4702300008
Grant
4707100010
Pendleton
4707100021
Pendleton
4707500050
Pocahontas
4707500022
Pocahontas
4710100060
Webster
4702500017
Greenbrier
4702500030
Greenbrier
4702500015
Greenbrier
4708900006
Summers
4705500014
Mercer
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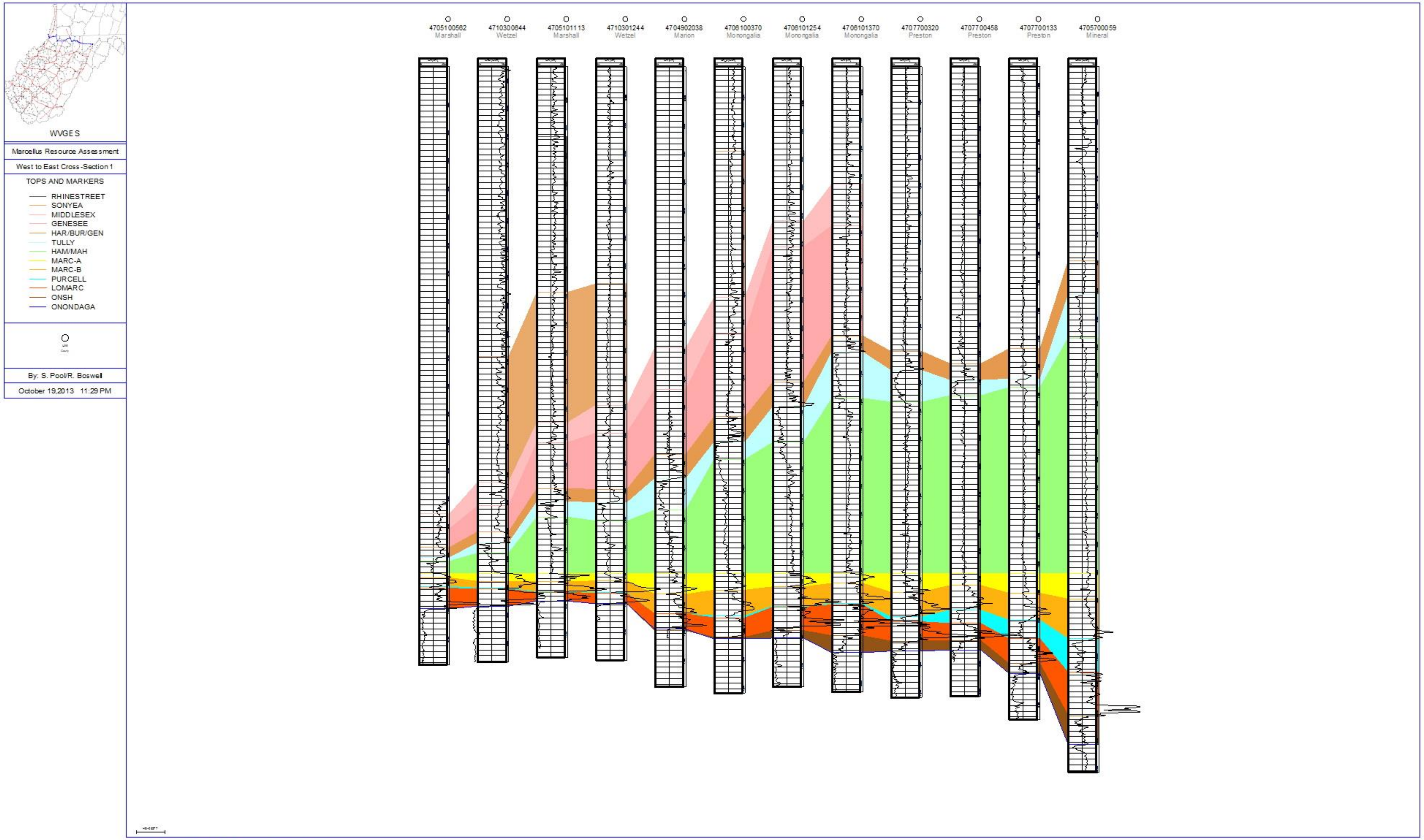

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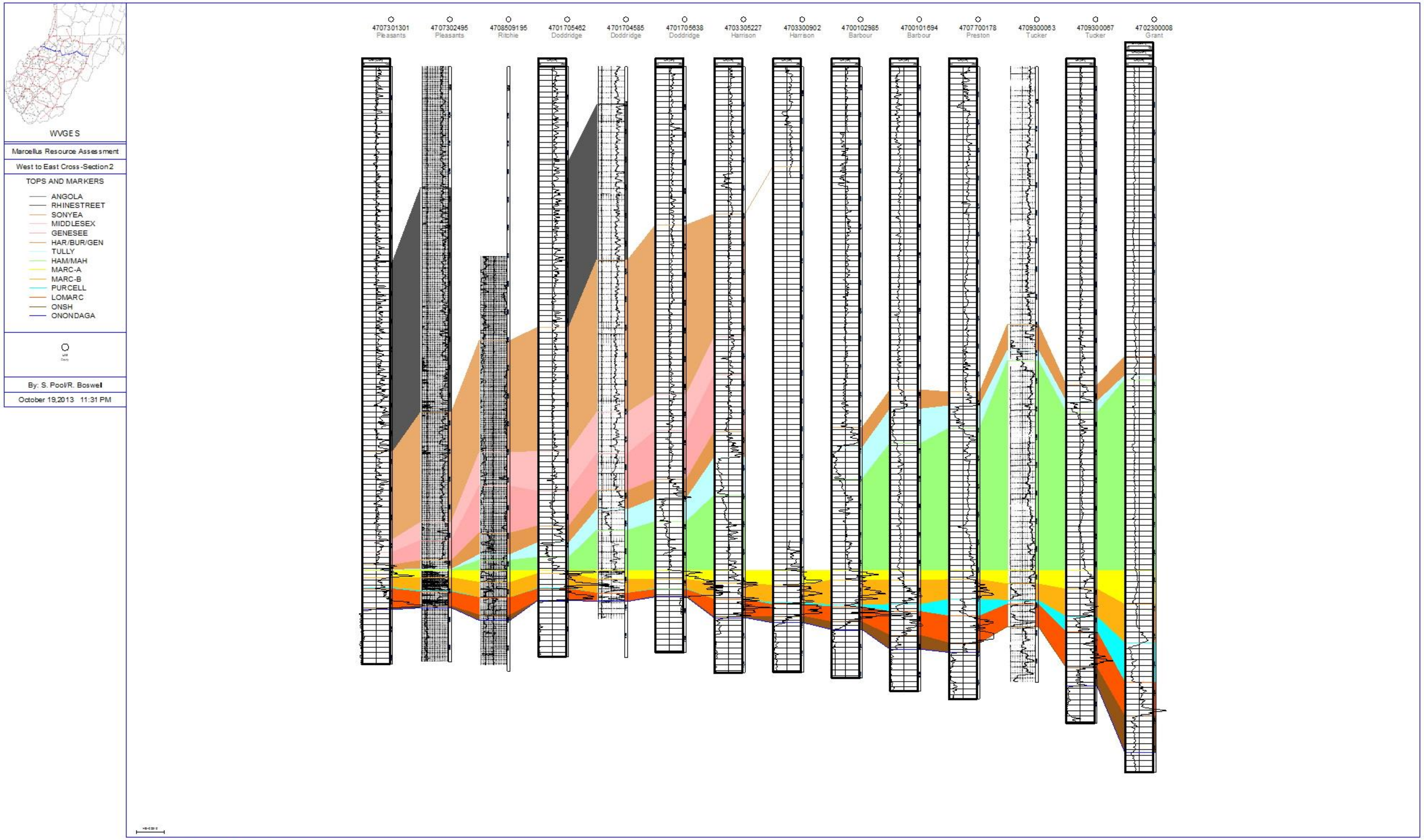

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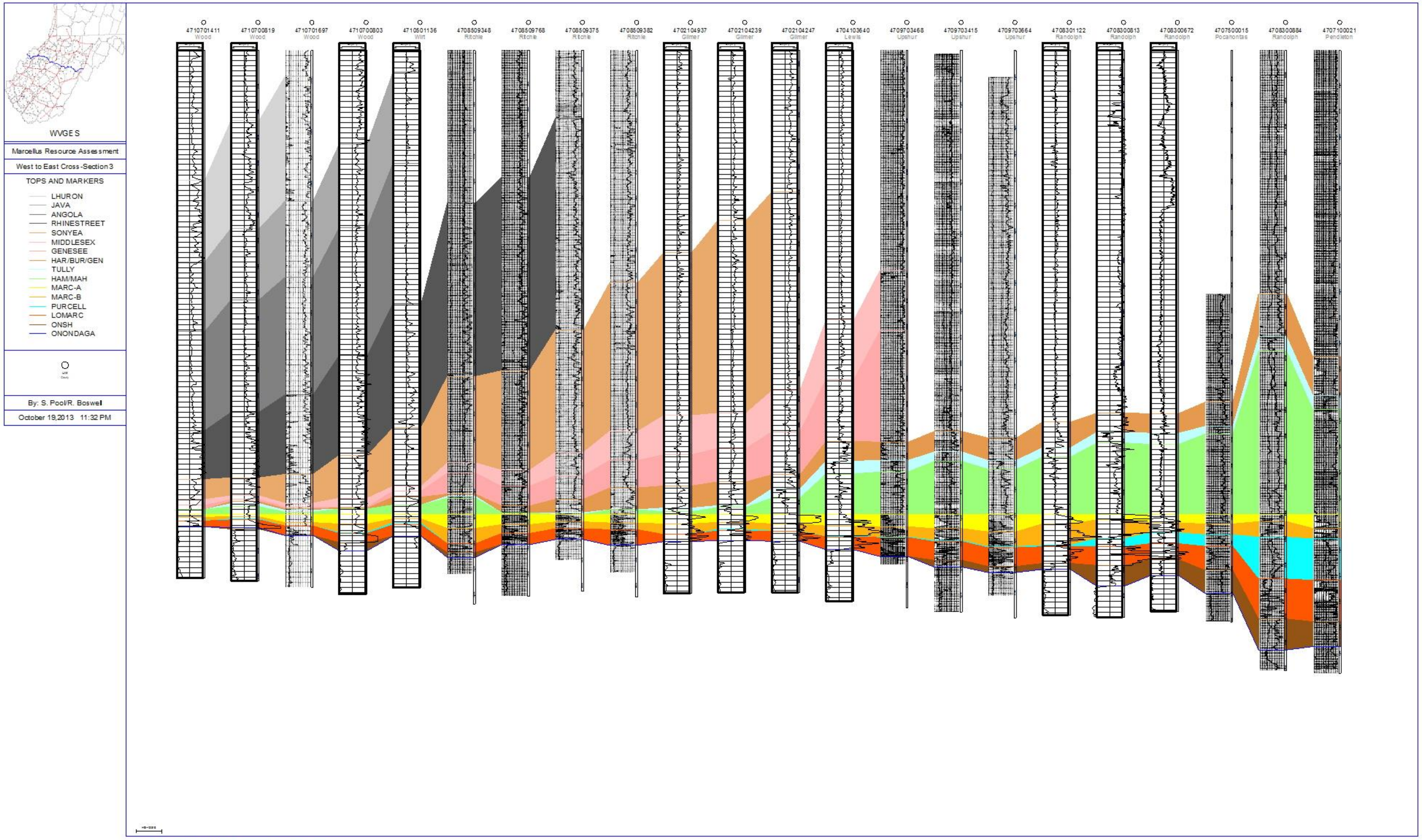
4710701411
Wood
4710700819
Wood
4710701697
Wood
4710700803
Wood
4710501136
Wirt
4708509348
Ritchie
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Ritchie
4708509375
Ritchie
4708509382
Ritchie
4702104937
Gilmer
4702104239
Gilmer
4702104247
Gilmer
4704103640
Lewis
4709703468
Upshur
4709703415
Upshur
4709703664
Upshur
4708301122
Randolph
4708300813
Randolph
4708300672
Randolph
4707500015
Pocahontas
4708300884
Randolph
4707100021
Pendleton
WVGES
Marcellus Resource Assessment
West to East Cross-Section 3
TOPS AND MARKERS
LHURON
JAVA
ANGOLA
RHINESTREET
SONYEA
MIDDLESEX
GENESEE
HAR/BUR/GEN
TULLY
HAM/MAH
MARC-A
MARC-B
PURCELL
LOMARC
ONSH
ONONDAGA
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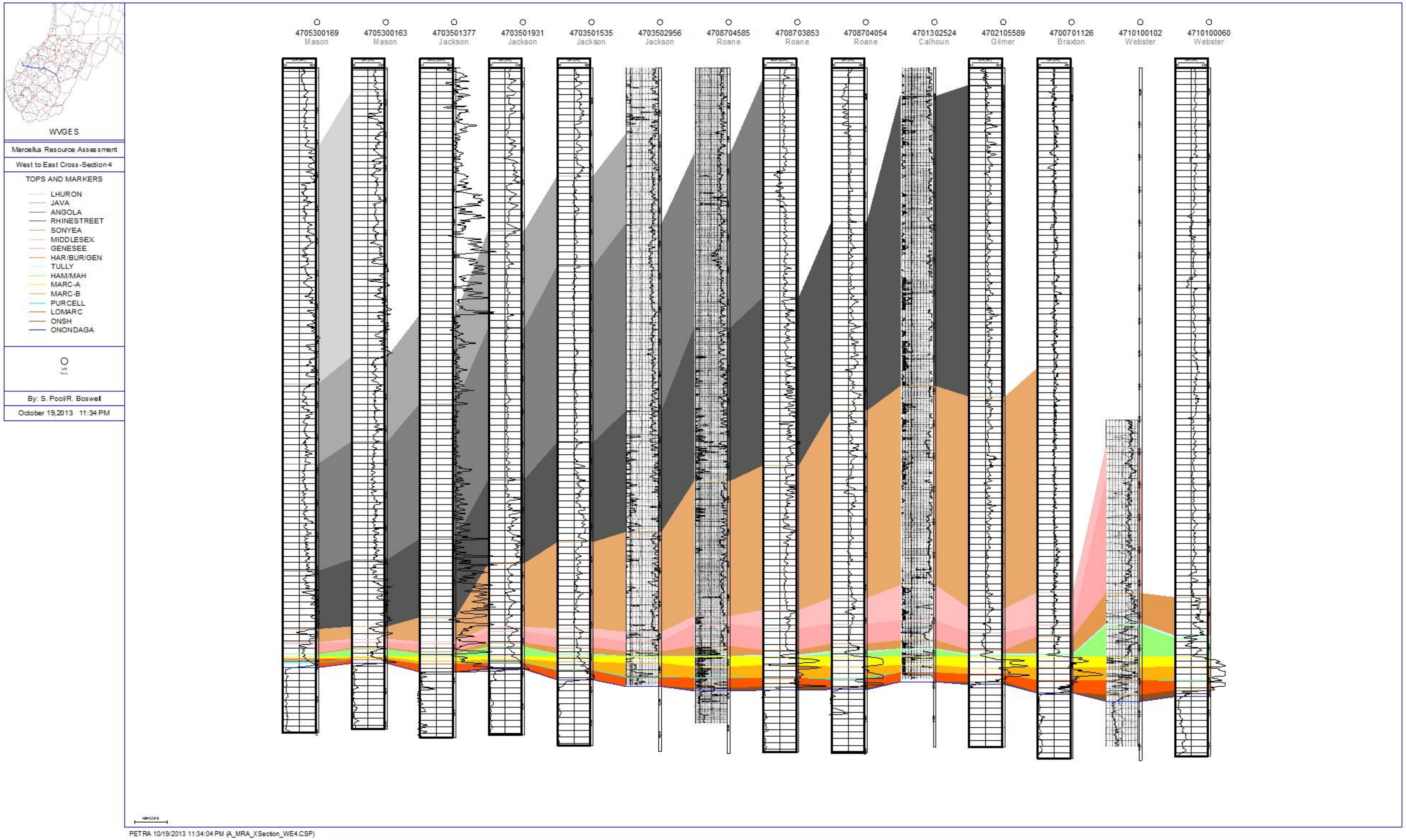

WVGES
Marcellus Resource Assessment
West to East Cross-Section 4
TOPS AND MARKERS
LHURON
JAVA
ANGOLA
RHINESTREET
SONYEA
MIDDLESEX
GENESEE
HAR/BUR/GEN
TULLY
HAM/MAH
MARC-A
MARC-B
PURCELL
LOMARC
ONSH
ONONDAGA
By: S. Pool/R. Boswell
October 19,2013 11:34 PM
4705300169
Mason
4705300163
Mason
4703501377
Jackson
4703501931
Jackson
4703501535
Jackson
4703502956
Jackson
4708704585
Roane
4708703853
Roane
4708704054
Roane
4701302524
Calhoun
4702105589
Gilmer
4700701126
Braxton
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Webster
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Webster
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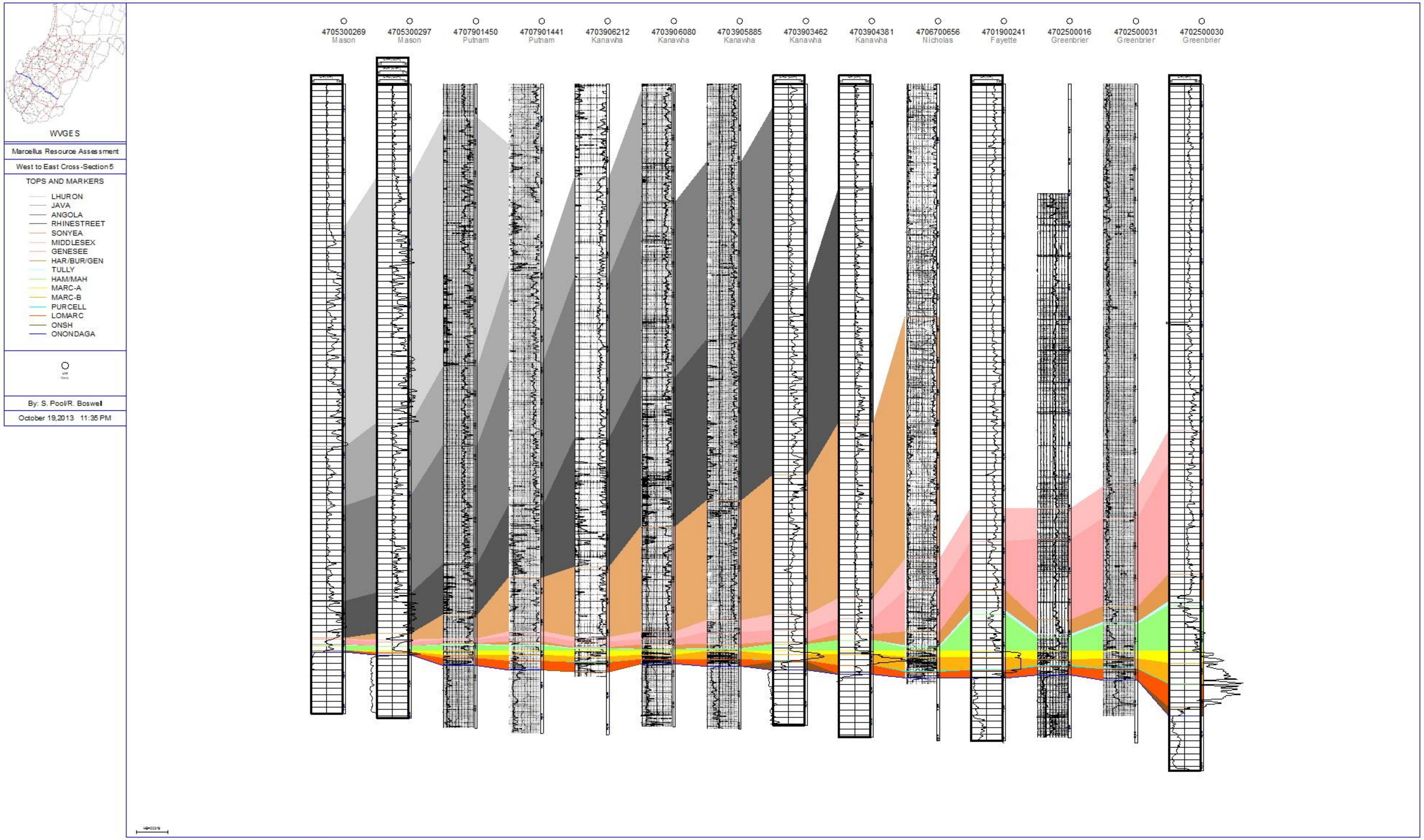

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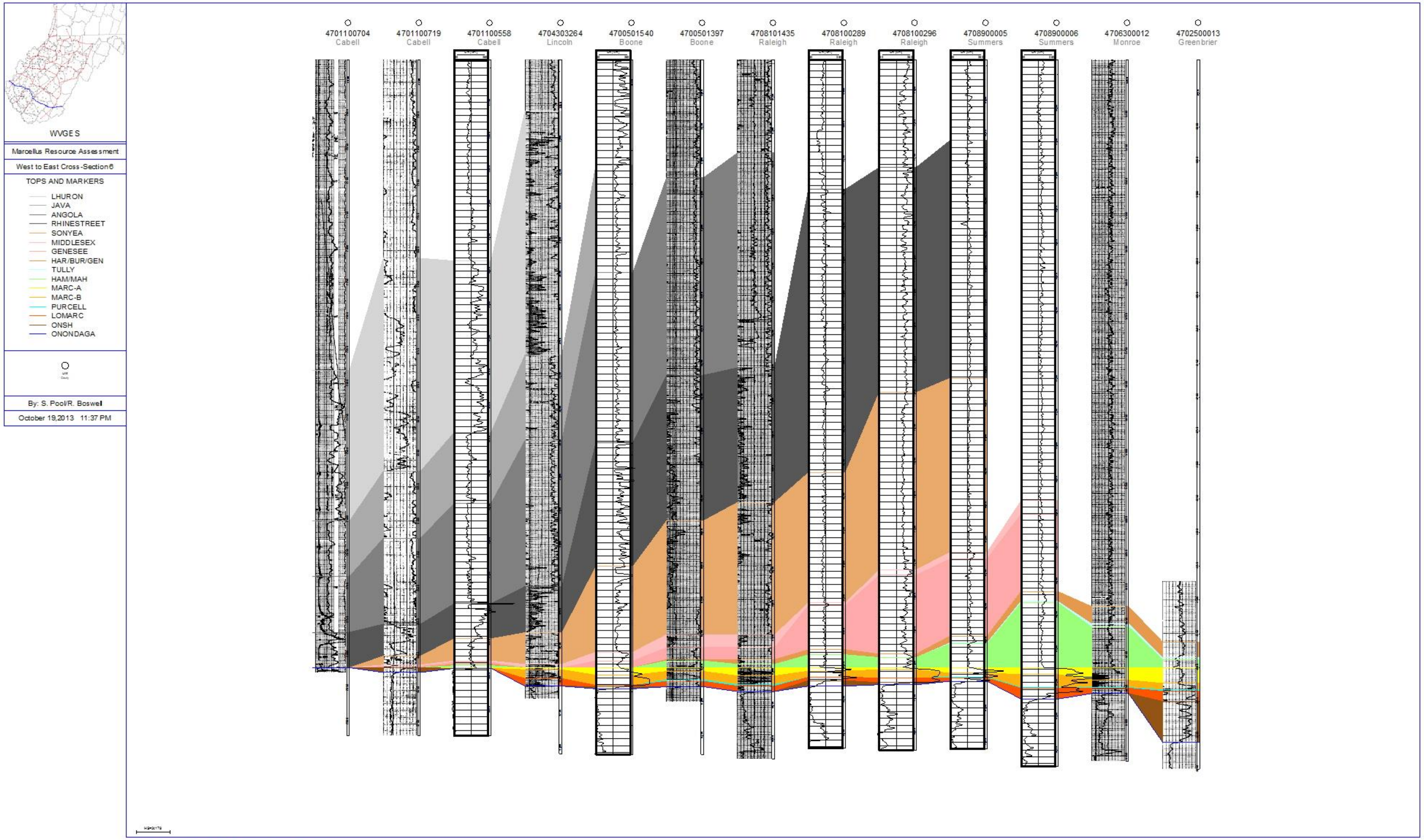

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