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

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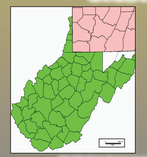
ABSTRACT

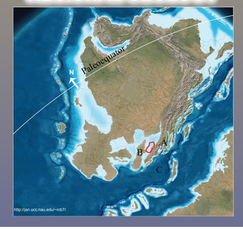
In the Appalachian basin, the Middle Devonian organic-rich shale interval, including the Marcellus Shale, is an important target for exploration. This unconventional gas reservoir is widespread across the basin and has the potential to produce large volumes of gas (estimated to have 1,307 trillion cubic 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 fluid content and then compared across the study area. In addition, the 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 new techniques to identify potential pay 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 corrected water saturations. These techniques of identifying lithology and potential gas in the Marcellus can be extremely useful in identifying exploration targets and where to fracture stimulate in a wellbore.

STUDY AREA



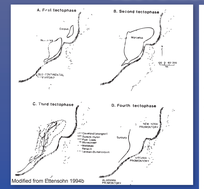
The study area encompasses of the state of West Virginia and southwest Pennsylvania. It is located in the geological province of the Central Appalachian Basin and covers an area of approximately 23500mi2 (60865 km2)

REGIONAL GEOLOGY



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 Rheic 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.

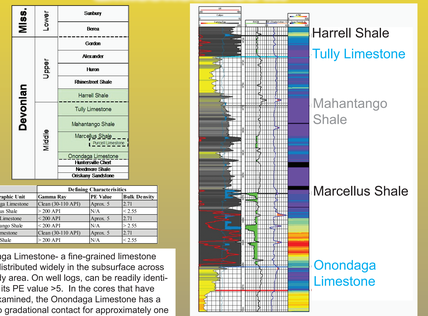
TECTONICS



Modified from Ettensohn 1994b

There are a number of published works dealing with the tectonics of the Acadian Orogeny, but the majority focus on the Upper Devonian and Lower Mississippian units. A tectophase is defined as a tectonic pulse associated with an orogeny that results in the migration of the peripheral bulge away from the foreland basin, increasing surficial loading and deepening the basin proper (Ettensohn 1994b). These tectophases are theoretically tied directly to black shale deposition.

LITHOSTRATIGRAPHY



Defining Characteristics			
Stratigraphic Unit	Gamma Ray	PE Value	Bulk Density
Onondaga Limestone	Clean (lls<10 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 (lls<10 API)	Aprox. 5	2.71
Harrell Shale	>200 API	N/A	> 2.55

Onondaga Limestone- 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 >5. 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.

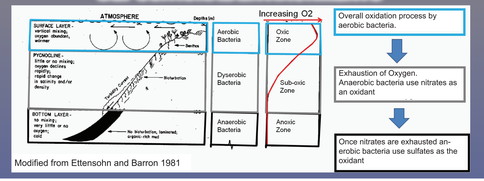
Marcellus Shale- in core and outcrop it is predominantly gray-black to black thinly laminated non-calcareous fissile pyritic organic-rich shale. In the subsurface the Marcellus is defined as having a gamma ray value of greater than 200 API and a bulk density of less than 2.55 g/cc. The Marcellus does have a formal limestone member, which is the Purcell Limestone. It is a fine-grained limestone that outcrops to the east of the study area. In the subsurface, the Purcell can be readily identified by the PE tool and has an irregular distribution in thickness.

Mahantango Shale- The Mahantango outcrops in eastern West Virginia and central Pennsylvania. In eastern West Virginia it is a calcareous gray shale with occasional thin limestone beds. In central Pennsylvania the Mahantango increases in depositional complexity and contains multiple limestone, sand, and shale units. Its log signature in the subsurface has a gradational contact with the underlying Marcellus and the overlying Tully Limestone. The Mahantango can be 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.

Tully Limestone- In the study area, the Tully 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 clean gamma ray signature and the PE curve.

Harrell Shale- The Harrell is a black organic, fissile shale that is similar to the Marcellus in lithology and possibly its depositional environment. 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

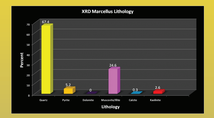
DEPOSITIONAL ENVIRONMENTS



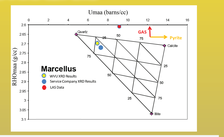
Modified from Ettensohn and Barron 1981

The units in question for this study are thought to have been deposited in a stratified water column. There would have been 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 occur, the environment must have three things; a large influx of organic matter, low circulation, and low sediment input. The excess of organic material that is input into the system would first be oxidized by the aerobic bacteria in the oxic zone, thus using most of the oxygen in the water column to degrade the organic matter. However, if there is a large amount of organic matter in the system, the majority of it would not be degraded by the aerobic bacteria and be incorporated into the sub-oxic zone. In the sub-oxic zone, most of the oxygen has been used as an oxidant to degrade the organic matter, therefore the anaerobic bacteria must then use nitrates as an oxidant. In addition to the increase consumption by the bacteria, anaerobic bacteria degrade organic matter much slower than aerobic bacteria, which can allow for organic matter to move through the sub-oxic zone, into the anoxic zone. In the anoxic zone, all the oxygen has been consumed as well as the nitrates; therefore the anaerobic bacteria must use the remaining sulfates as an oxidant to degrade the organic matter. 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 is no longer degraded and can be incorporated into the sediment allowing for a large amount of organic matter preservation. This depositional model is taken from the modern depositional environment of the Black Sea and is consistent with bottom waters that are synchronously anoxic. Recently micro-anoxic envirnoments have been proposed, rather than synchronous anoxic bottom waters (MacQuaker, AAPG Denver Meeting 2009). These micro-anoxic environments were identified in thin section as small sequences. This would suggest that the entire basin was not synchronously anoxic, and consequently could explain rapid spatial changes in thickness and the presence of limestone members in the Marcellus.

LITHOLOGIC ANALYSIS

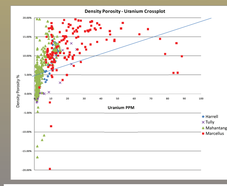


Example of X-Ray Diffraction (XRD) results for a sample from the Marcellus in the study area. This sample has a high amount of quartz (67%) and fairly low amount of clay (24%), which is characteristic of the 36 Marcellus Shale samples throughout the study area. Also it is important to identify that there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

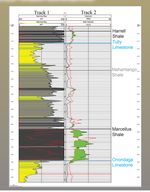


RHOma Umaa plot for a single foot of the Marcellus Shale compared to core analysis. The red and yellow squares are the XRD results for a sample that indicate the Marcellus is mostly quartz. The blue square is the LAS data for the same location in the Marcellus. It shows that the LAS data is effected by the small amount of pyrite by pulling the data to the right (high Umaa value due to the high number of electrons associated with pyrite), and the gas by pulling the data above the lithologic triangle (low RHOma due to the low density of gas. This must be taken into consideration when attempting to model the Marcellus lithology.

GAS AND PAY IDENTIFICATION

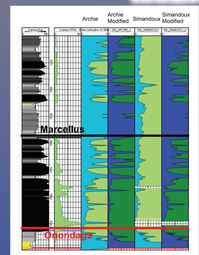


A relationship is recognized between the gamma ray and density porosity, specifically the Uranium (U) in the gamma ray tool. An increase in U correlates to an increase in TOC. The relationship between the U and density porosity shows that anything above this line can be considered gas-rich. The Marcellus has a large amount of free gas and high TOC where as the Mahantango and Harrell do not have but do have a noticeable amount of free gas. The potential for free gas not only in the Marcellus, but also the Mahantango and Harrell is significant, and could influence exploration of the entire interval.



The correlation of Uranium (U) ,density porosity, and gas-rich intervals is illustrated. When the U value exceeds the bulk density value it is highlighted in green. These highlighted areas have high potential for free and bound gas. In addition to the pay identification in the Marcellus, this new method highlights intervals with potential in the Mahantango and Harrell Shale units as well.

WATER SATURATIONS



The Uranium (U) content can be incorporated into other pay calculations. The water saturation for the Marcellus is typically calculated by using the Archie equation (Equation 1) or the Simandoux shale correction for the Archie equation (Equation 3). The Archie is a more conservative equation that was originally derived to be used in sandstones. The equation does not take into account shale particles that suppress resistivity or the measured tortuosity of shale. Archie overestimates water satuations in shale and since Uranium is directly tied to free and bound gas, it can be incorporated into the Archie equation as seen in Equation 2. Another equation used is the Simandoux shale correction for Archie. The Simandoux equation was derived specifically for sandy-shaly units to compensate for bound water by using a Vshale ratio from the gamma ray tool. When the Simandoux correction is applied to shales, it overestimates gas content. Considering the Uranium is tied to the gas in shale the Vuran ratio was substituted for a Vshale ratio (Equation 4). The Vuran ratio is calculated by subtracting the shale value minus the U divided by the shale minus the sand. The change of this ratio helps to identify areas in the shale that will have a higher potential for free and bound gas.

Equation 1

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

Equation 2

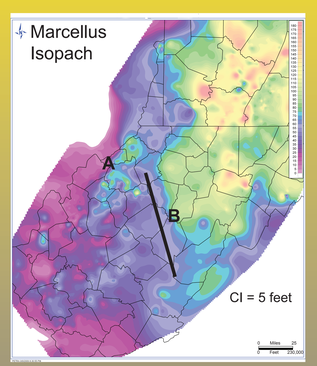
$$S_{WU} = \left(\frac{R_w * a}{\phi^m * Rt * U_{log}}\right)^{\frac{1}{n}}$$

Equation 3

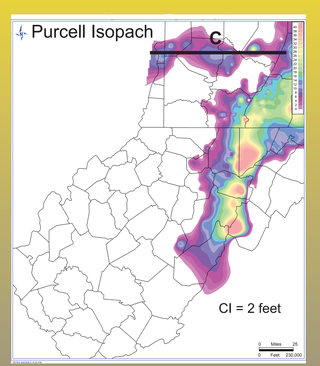
$$S_w = \sqrt{\left(\frac{V_{sh}}{R_{sh}}\right)^2 * 4 * \left(\frac{\phi^m}{\left(a^*R_w\right)\left(1-V_{sh}\right)}\right)\frac{1}{Rt}} - \frac{V_{sh}}{R_{sh}} \Rightarrow V_{sh} = \frac{GR - Sand}{Shale - Sand}$$

Equation 4

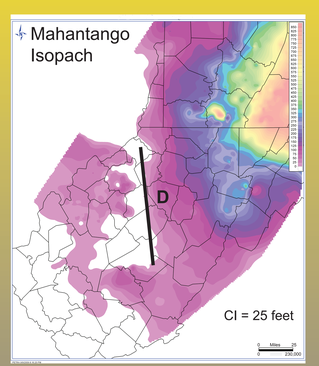
$$S_{WU} = \sqrt{\left(\frac{V_{uran}}{R_{uran}}\right)^2 * 4 * \left(\frac{\phi^m}{\left(a^*R_w\right)\left(1-V_{uran}\right)}\right)\frac{1}{Rt}} - \frac{V_{uran}}{R_{uran}} \Rightarrow V_{uran} = \frac{U_{log} - U_{sand}}{U_{sh} - U_{sd}}$$



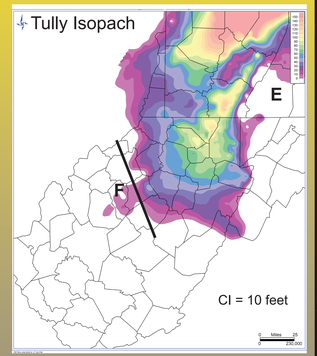
Isopach of the Marcellus Shale illustrating changes in thickness. The warmer colors illustrate thicker deposits and the cooler colors are thinner. The Marcellus Shale is decreasing in thickness significantly to the southwest. The anomalous thick (A) that trends southwest to northeast is located at the west-bounding limb of the Rome Trough structure. This thick suggests that the Rome Trough structure was active during the deposition of the Marcellus Shale. Also, there is a significant change in thickness in the central area of the Map in WV where the Marcellus sharply decreases from 100ft (30.4m) to 60ft (18.3m) or less (B). This change in thickness is trending from northwest to southeast and appears to have influenced the deposition of the Marcellus and its overlying units.



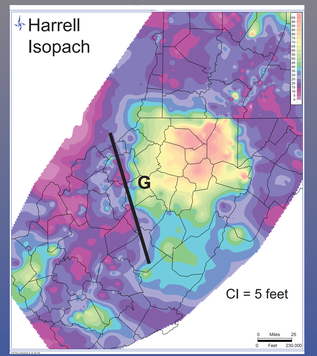
Isopach of the Purcell Limestone Member of the Marcellus Shale. This map is representative of limestone units within the Marcellus Shale. The map has a northeast to southwest trend and the limestone unit generally does not occur in the west or central regions of the study area. The one geographic exception is the thin west to east trend in the northern region of the study area (C). The Purcell is encompassed by the Marcellus Shale. The Purcell would have been deposited in a oxic environment and the Marcellus Shale would have been deposited in an anoxic environment. According to the black sea 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 localized anoxic environments that are influenced by factors such as sediment supply, paleo-topography and water chemistry.



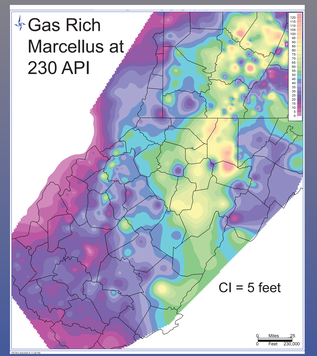
Isopach of the Mahantango Shale where the warm colors represent the thicker values and the cooler colors are thiner. The Mahantango can be as thick as 800ft (244m) to the northeast and decreases to the south and to the west in thickness. The Mahantango outcrops to the northwest in central Pennsylvania and eastern West Virginia. In northwest Pennsylvania the Mahantango contains a variety of beds including limestone, conglomerates, sands and shale units that have a wide range of sedimentary structures. Moving south in the outcrop belt to eastern West Virginia, the Mahantango lacks the a variety of lithologies and beds and is primarily a calcareous shale with occasional limestone beds. As mentioned earlier, the northwest-southeast trend that influenced the deposition of the Marcellus appears to be affecting the Mahantango (D).



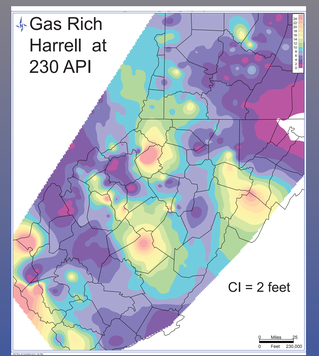
Isopach of the Tully Limestone. The warm colors represent the thick values and the cooler colors are thin. The Tully decreases in thickness to the south and east. It is thickest to the north which coincides with the underlying Mahantango thin and the Tully is absent where the Mahantango is thick (E). The Mahantango and Tully could be related, because the Mahantango does have a calcareous component in outcrop. If the sediment supply for the Mahantango is shut off the Tully Limestone can build up and prograde to the south. The southern extents of the Tully Limestone are marked by a northwest to southeast trend (F). This is the same geographic area in which the underlying Marcellus and Mahantango show rapid changes in depositional thickness.



Isopach of the Harrell Shale. The warm colors represent the thick values and the cooler colors are thin. The Harrell has a unique distribution in thickness. The previous patterns observed in the underlying units appear to affect Harrell deposition, but not as much as the underlying units(G). The thickest values for the Harrell are located in north-central West Virginia.



Map of the Marcellus Shale gamma ray values greater than 230 API.The warm colors represent the thick values and the cooler colors are thin. Based on analysis of wells with spectral gamma ray logs, Uranium (U) concentration can identify zones with high probability for gas, and is a major component of the standard gamma ray (SGR). Using the SGR values greater than 230 API can indicate areas with a higher potential for gas content.



Map of the Harrell Shale gamma ray values greater than 230 API. The warm colors represent the thick values and the cooler colors are thin. Based on analysis of wells with spectral gamma ray logs, Uranium (U) concentration can identify zones with high probability for gas, and is a major component of the standard gamma ray (SGR). Using the SGR values greater than 230 API can indicate areas with a higher potential for gas content.

CONCLUSIONS

- Marcellus Shale is defined in the subsurface by exceeding 200 API and a bulk density of less than 2.55 g/cc.
- Spatial changes in thickness in the Marcellus can be explained by micro anoxic environments, rather than synchronous anoxic bottom waters.
- For a shale, the Marcellus has a reactively high volume of quartz.
- Pyrite and gas influence the lithologic analysis of the Marcellus.
- Free and bound gas can be correlated to higher Uranium values.
- Free and bound gas potential exists in the Marcellus, Mahantango, and Harrell Shale that can be identified in a log when the Uranium exceeds the bulk density.
- A modified Archie and Simandoux equation using Uranium content predicts a more accurate value for water and gas saturations.
- The Rome Trough appears to have influenced the deposition of the Marcellus Shale in western West Virginia.
- A northwest to southeast trend in central West Virginia appears to have influenced the depositional thickness of the entire interval.
- Potential for gas rich areas in the Marcellus and Harrell can be identified by mapping where the gamma ray exceeds 230 API's.

ACKNOWLEDGEMENTS

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