Stratigraphy and Petrophysics of the Middle Devonian Black Shale Interval in West Virginia and Southwest Pennsylvania

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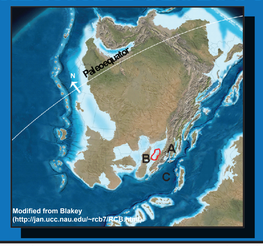
ABSTRACT

In the Central Appalachian basin, the Middle Devonian organic-rich shale interval, including the Marcellus Shale, has become a major target for natural gas exploration and production. This unconventional gas reservoir is widespread across the basin and has significant potential to produce large volumes of gas. Although the Middle Devonian organic-rich shale interval is a large resource, with high economic potential, the stratigraphic distribution, depositional patterns, and petrophysical characteristics are not adequately characterized in the subsurface. Using an extensive log and core database, the lithostratigraphic boundaries of the Marcellus and associated units were established, and correlated throughout West Virginia and southwestern Pennsylvania. Within individual units log characteristics, tied to core information were used to map the lithology, fluid content, distribution and thickness of organic-rich facies across the region. Using previous studies on organic shale, relationships between the natural radioactivity (as measured by the spectral gamma-ray log) were incorporated with techniques to identify potential gas-rich intervals. The comparison between the Uranium content and the measured bulk density and modified saturation equations, identified intervals in the Middle Devonian with high gas saturations. In the study area, the depositional dynamics among thickness, lithology and organic content define fairways of thick gas prone intervals within different Middle Devonian black shale units. However, within a small local area, micro-anoxic environments result in significant variations in black shale deposition and presence of thin limestone intervals from well-to-well. Deposition and spatial distribution of organic-rich facies in the Marcellus, as well as its overlying and underlying units (e.g., Harrell Shale), is a complex process that must account for sediment input and development of micro-anoxic environments. Within a regional subsurface stratigraphic framework of the Middle Devonian in the Appalachian basin, an improved understanding of depositional dynamics can provide a better focus on exploration targets.

STUDY AREA

The study area encompasses the state of West Virginia (green) and southwest Pennsylvania (pink). It is located in the geological province of the central Appalachian basin and covers an area of approximately 23,500 mi^2 (60,865 km^2).

REGIONAL GEOLOGY



The study area is outlined in red on the paleogeographic interpretation of the Middle Devonian (385 Ma). The paleogeographic features surrounding the study area are the Acadian Mountains (A) to the east, the Cincinnati Arch (B) to the west and 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.

LITHOSTRATIGRAPHY

Age	Formation	Member
Upper Devonian	Alexander	
	Huron	
	Rhinestreet Shale	
	Harrell Shale	
Middle Devonian	Tully Limestone	
	Mahantango Shale	
	Marcellus Shale	Purcell Limestone
	Onondaga Limestone	
	Huntersville Chert	
	Needmore Shale	
	Oriskany Sandstone	

Onondaga Limestone- fine-grained limestone that is distributed widely in the subsurface across the study area. 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.

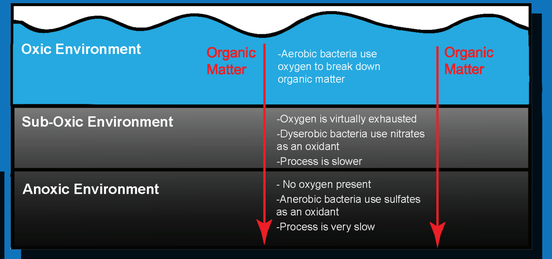
Marcellus Shale- in core and outcrop it is predominantly gray-black to black thinly laminated non-calcareous fissile pyritic organic-rich shale. The Marcellus does have a formal limestone member, which is the Purcell Limestone. It is a fine-grained limestone that outcrops to the east of the study area.

Mahantango Shale- the Mahantango outcrops in eastern West Virginia and central Pennsylvania. It is also referred to as the Hamilton Shale because the time equivalent unit in New York is part of the Hamilton Group, however in the study area it is formally called to the Mahantango Shale. 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. Some of these units can be have high to low angle crossbeds, conglomerates, bioturbation, and multiple other types of sedimentary structures. Its log signature in the subsurface has a gradational contact with the underlying Marcellus and the overlying Tully Limestone.

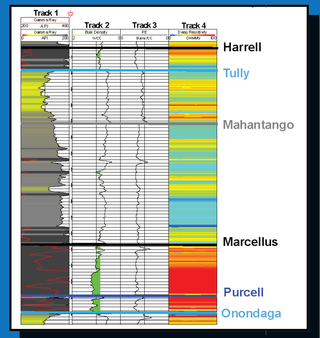
Tully Limestone- in the study area, the Tully is a fine-grained limestone and has been intensely studied in outcrop near its type section in New York where it increases significantly in depositional complexity.

Harrell Shale- the Harrell is a black organic, fissile shale that is similar to the Marcellus in lithology and possibly it's depositional environment. It is also referred to as the Burket Shale; however in the study area the proper name is the Harrell Shale.

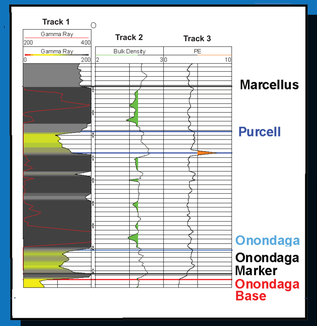
DEPOSITIONAL ENVIRONMENTS: STRATIFIED WATER COLOUMN



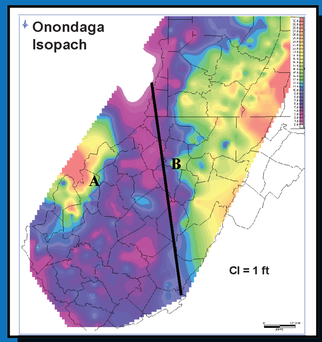
TYPE LOGS



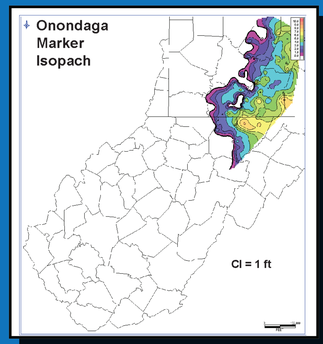
Defining Characteristics			
Stratigraphic Unit	Gamma Ray	PE Value	Bulk Density
Onondaga Limestone	Clean (30–110 API)	Approx. 5	2.71
Marcellus Shale	> 200 API	N/A	< 2.55
Purcell Limestone	< 200 API	Approx. 5	2.71
Mahantango Shale	< 200 API	N/A	> 2.55
Tully Limestone	Clean (30–110 API)	Approx. 5	2.71
Harrell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



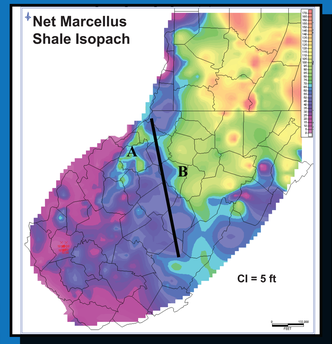
The log to the left best represents the overall sequence of the units in question. Note the contact of the Marcellus- Mahantango as well as the Mahantango-Tully is gradational in the log. The log above gives a better representation of the Purcell, Onondaga, and Onondaga Marker. The Onondaga Limestone has a basal black shale marker, designated Onondaga Marker, existing in the core and the log. In the log, it is easily identified by the high gamma ray signature. To the left, is a table that summarizes the characteristics used to identify these units in the sub-surface.



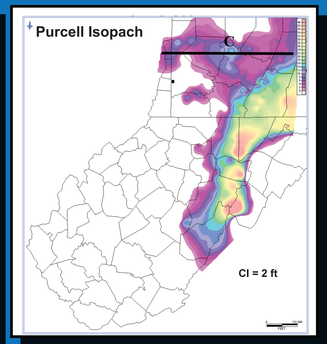
The anomalous thick to the southwest (A) is located at the west bound limb of the Rome Trough. The Onondaga is thick on the up-thrown side of the fault because the slight change in water depth allows for more limestone deposition. There is a rapid change in the overall thickness of the Onondaga trending northwest to southeast (B). This rapid change is the result of an underlying paleo-structure that influences the Onondaga and the overlying units.



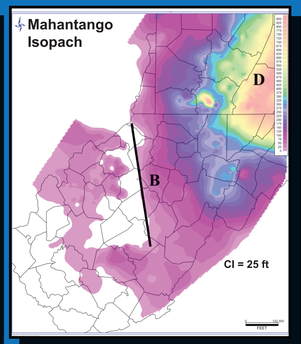
The marker is only present to the northwest and reaches an approximate maximum thickness of 10 feet. Also, the marker is only present in the Onondaga formation and the thickest deposits are in the subsurface to the northeast. The presence of this black shale marker has implications when analyzing the depositional environments because of the spatial location of the black shale marker in relation to thick limestone deposits.



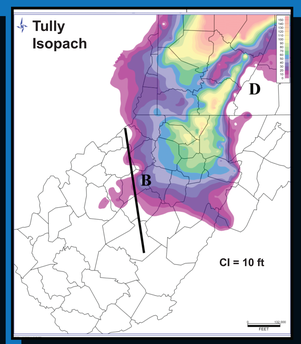
The anomalous thick (A) that trends southwest to northeast is located at the west-bounding limb of the Rome Trough structure. This thick suggests the Rome Trough structure was active during the deposition of the Marcellus Shale. Also, there is a significant change in thickness where the Marcellus sharply decreases from 100ft (30.4m) to 60ft (18.3m) or less (B). The change in thickness is trending from northwest to southeast and is possibly influenced by some kind of paleo structure.



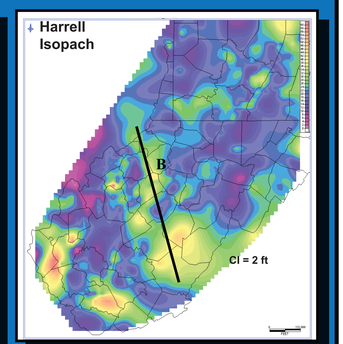
This map is representative of limestone units within the Marcellus Shale. The map has a northeast to southwest trend and the limestone unit generally does not occur in the west or central regions of the study area. The one geographic exception is the thin, west to east trend in the northern region of the study area (C). This trend is more than likely a result of a paleo-high that allowed for limestone deposition.



The Mahantango can be as thick as 800ft (244m) (D) to the northeast and decreases in thickness to the south and to the west. The paleo-feature, B, that influenced the deposition of the Marcellus, also influenced the Mahantango.



The Tully is thick to the north coinciding with the underlying Mahantango thin and the Tully is absent where the Mahantango is thick (D). Given the gradational contact between the Tully and Mahantango, the two units must be depositionally related. The southern extents of the Tully Limestone are marked by a northwest to southeast trend (B).



The Harrell has a sporadic distribution in thickness; however, the same paleo structure (B) that influenced the deposition of the Onondaga, Marcellus, Mahantango, and Tully units affected Harrell deposition. The Harrell is significantly thicker in this area (B) trending northwest to southeast.