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Introduction

The U.S. Energy Information Administration (EIA) is adding and updating geologic information and maps of the major tight oil and shale gas plays for the continental United States. This document outlines updated information and maps for the Marcellus play of the Appalachian basin. The geologic features characterized and updated since the 2011 Marcellus shale play map include contoured elevation of the top of formation (structure), contoured thickness (isopach), paleogeography elements, and tectonic structures (regional faults and folds etc.), as well as play boundaries, well location, and initial wellhead yields (oil-to gas-ratios) of wells producing from January 2000 through December 2016.

These geologic elements are documented and integrated into a series of maps. The Marcellus play map consists of layers of geologic and production information that users can view either as separate thematic maps (such as Figure 1) or as interactive layers of the U.S. Energy Mapping System. Data sources include DrillingInfo Inc. (DI, a commercial oil and gas well database), the United States Geological Survey (USGS), New York State Geological Survey, Ohio State Geological Survey, Pennsylvania Bureau of Topographic & Geologic Survey, West Virginia Geological & Economic Survey, EIA reports, peer-reviewed research papers, and academic theses.

Currently, EIA's access to well-level data is limited, and EIA is working to expand its well-level data to include well-log representation. Additional map layers will be added as additional geologic data (such as petrophysical and thermodynamic formation properties) become available.

The Marcellus formation extent in the Appalachian basin and Play boundaries

The Marcellus Middle Devonian-age organic-rich formation, also known as Marcellus Shale, extends in the subsurface from New York State in the north to northeastern Kentucky and Tennessee in the south and is the most prolific natural gas-producing formation in the Appalachian basin. The formation footprint covers about 95,000 square miles with a prospective area about 72,000 square miles. The Marcellus formation includes the Upper Marcellus and Lower Marcellus intervals. The Lower Marcellus has a significantly higher organic matter concentration compared with the Upper Marcellus. Recorded high spectral gamma-ray log values of the Lower Marcellus are indicative of the abundant Total Organic Carbon (TOC).

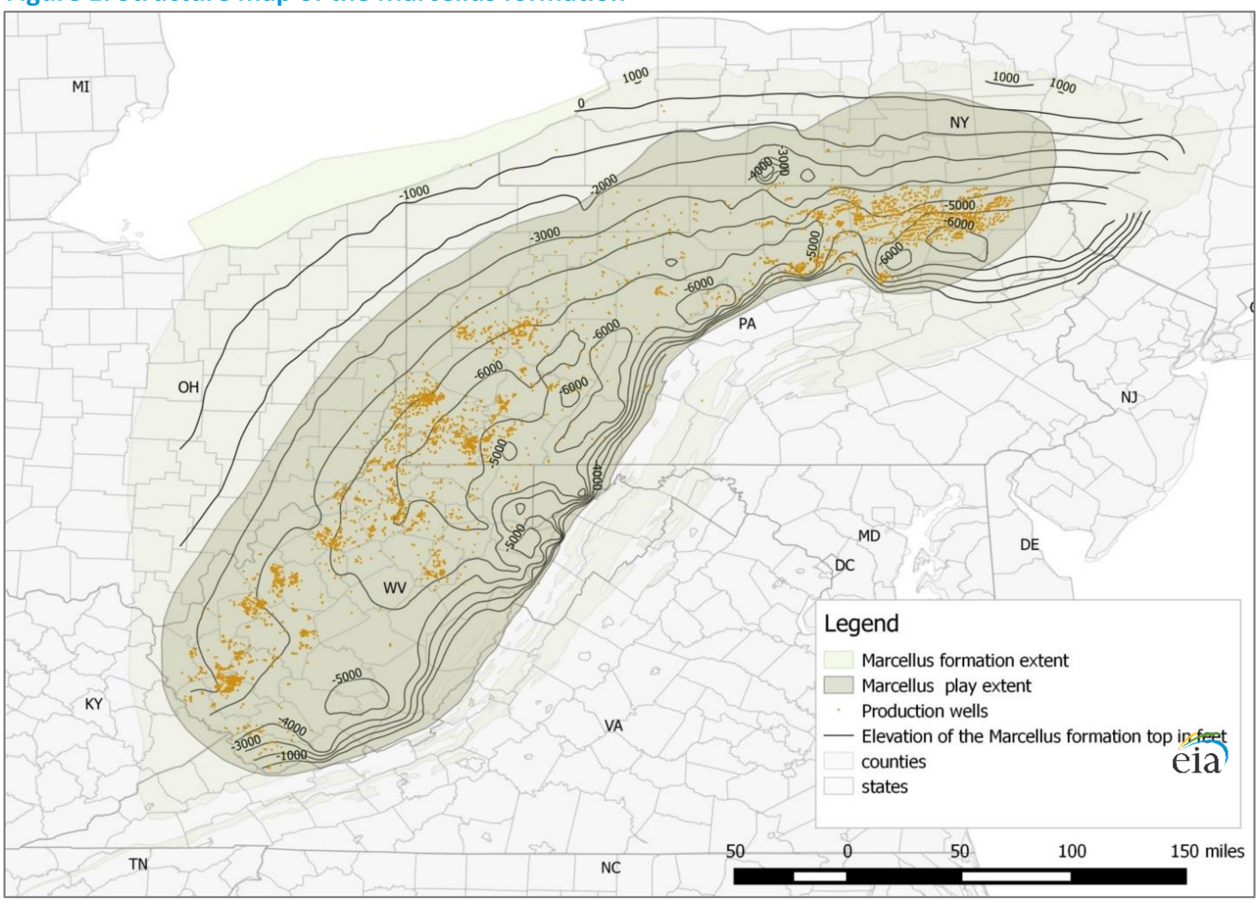
Overall Marcellus structure and thickness are influenced by the basement tectonics patterns. EIA estimates proven reserves in the Marcellus Play of 77.2 trillion cubic feet (Tcf) at year end 2015 which makes it one of the largest natural gas plays in the U.S. The Marcellus has oil reserves of 143 million barrels (MMbbls). The Marcellus play footprint extends across five states: New York, Pennsylvania, Ohio, West Virginia, and Kentucky. Like with other continuous plays, key geologic and technical criteria that control play boundaries include thermal maturity, total organic carbon (TOC), formation thickness, porosity, depth, pressure, and the ability to be fractured.

The boundaries of the Marcellus formation (Figure 1) are outlined to the north, south, and east by the outcrop belt of the formation and to the west by the pinching out of the Marcellus by the Middle Devonian Unconformity buried in the subsurface. The northwest boundary of the Marcellus Play is roughly defined by the end of the oil window and the beginning of the immature area, and the southeast boundary is defined by the end of the gas window ends and the beginning of the over-mature area, according to a study that used thermal maturity modeling calibrated to published vitrinite reflectance (%R_o) data (East et al., 2012). The limits of the oil window correlate to the subsea depth range of 1,000- 5,000 feet, and the limits of the gas window correlate to the subsea depth range of 3,000- 6,500 feet. The change in depth in relation to maturity reflects the amount of differential subsidence within the Appalachian basin and subsequent uplifeet and erosion with certain basement blocks.

Structure map of the Marcellus formation

Contoured elevation maps or subsea depth to the top of a geologic formation (also called structure maps) are constructed from two types of data: (1) point-measurement depth data referenced to sea level (well observations) for areas where a formation is located in subsurface, (2) and elevation data of formation outcrops that provide the third dimension for characterizing depth or elevation of a reservoir on an otherwise two-dimensional map.

Figure 1. Structure map of the Marcellus formation



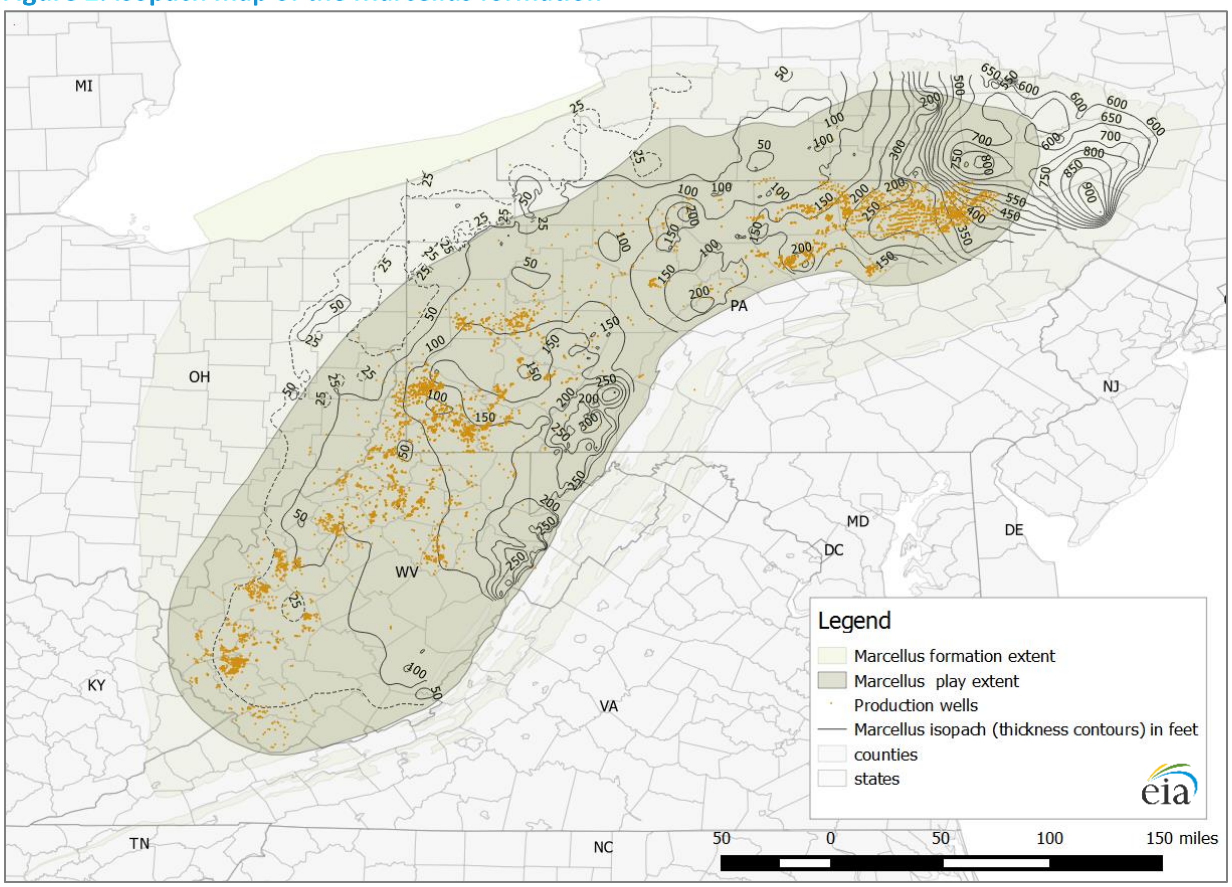
Source: U.S. Energy Information Administration based on DrillingInfo Inc., New York State Geological Survey, Ohio State Geological Survey, Pennsylvania Bureau of Topographic & Geologic Survey, West Virginia Geological & Economic Survey, U.S. Geological Survey.

To generate the structure map (Figure 1), EIA used stratigraphic correlations provided by state geological survey agencies based on well log interpretation from 2,416 wells. The top of the Marcellus formation ranges in elevation from 1,000 feet to -8,000 feet subsea depth (measured depth from 100 to 9,900 feet) and primarily produces gas in northeast Pennsylvania, but becomes more *liquids-rich* in less thermally mature areas of southwestern Pennsylvania, West Virginia, and southeastern Ohio. As the structure map shows, the Appalachian basin is an asymmetric depression. The depth of the Marcellus formation increases gradually from northwest to southeast, with an abrupt uplift along the Appalachian Mountains structural front where it forms an outcrop belt. The deepest portion of the Marcellus shale is related to the synclines adjacent to the structural front. Most of the producing wells are located in areas where the subsea depth of the formation is in the -2,000 to -6,000 foot interval. The Marcellus currently produces in four states: Pennsylvania, West Virginia, Ohio, and New York. Because of the recent ban on hydraulic fracturing in New York, natural gas production in New York State is from wells drilled prior to the ban in 2010.

Thickness (isopach) map of the Marcellus formation

Thickness maps (isopachs) show spatial distribution of formation thickness across the formation

Figure 2. Isopach map of the Marcellus formation



Source: U.S. Energy Information Administration based on DrillingInfo Inc., New York State Geological Survey, Ohio State Geological Survey, Pennsylvania Bureau of Topographic & Geologic Survey, West Virginia Geological & Economic Survey, U.S. Geological Survey.

footprint. Thickness values are used, in combination with reservoir petrophysical properties such as porosity and thermodynamic parameters (reservoir temperature and pressure), to calculate resource volumes, such as oil-in place and gas-in-place estimates.

The isopach map for the Marcellus formation (Figure 2) is constructed from subsurface point measurements from individual wells that include both depth to the top and to the base of the Marcellus formation. These stratigraphic picks are provided by state geological survey agencies based on well log interpretation from 2,416 wells.

The Marcellus thickness ranges from 0 to 950 feet across the Appalachian basin. This formation generally shows a decrease in thickness westward from the central part of the basin and pinches out in the subsurface along its eastern limit. As the isopach map demonstrates, the formation can be as thick as 900 feet in south-central New York and decreases to the south and east, varying from 200 feet to 600 feet in adjacent northeastern Pennsylvania. The thick, potentially gas-rich interval extends southwest in an arc through the synclines of New York, Pennsylvania, and West Virginia and parallels the Appalachian structural front. Most of the current production is located in areas where formation thickness is more than 50 feet.

Summary of the Marcellus Play geology

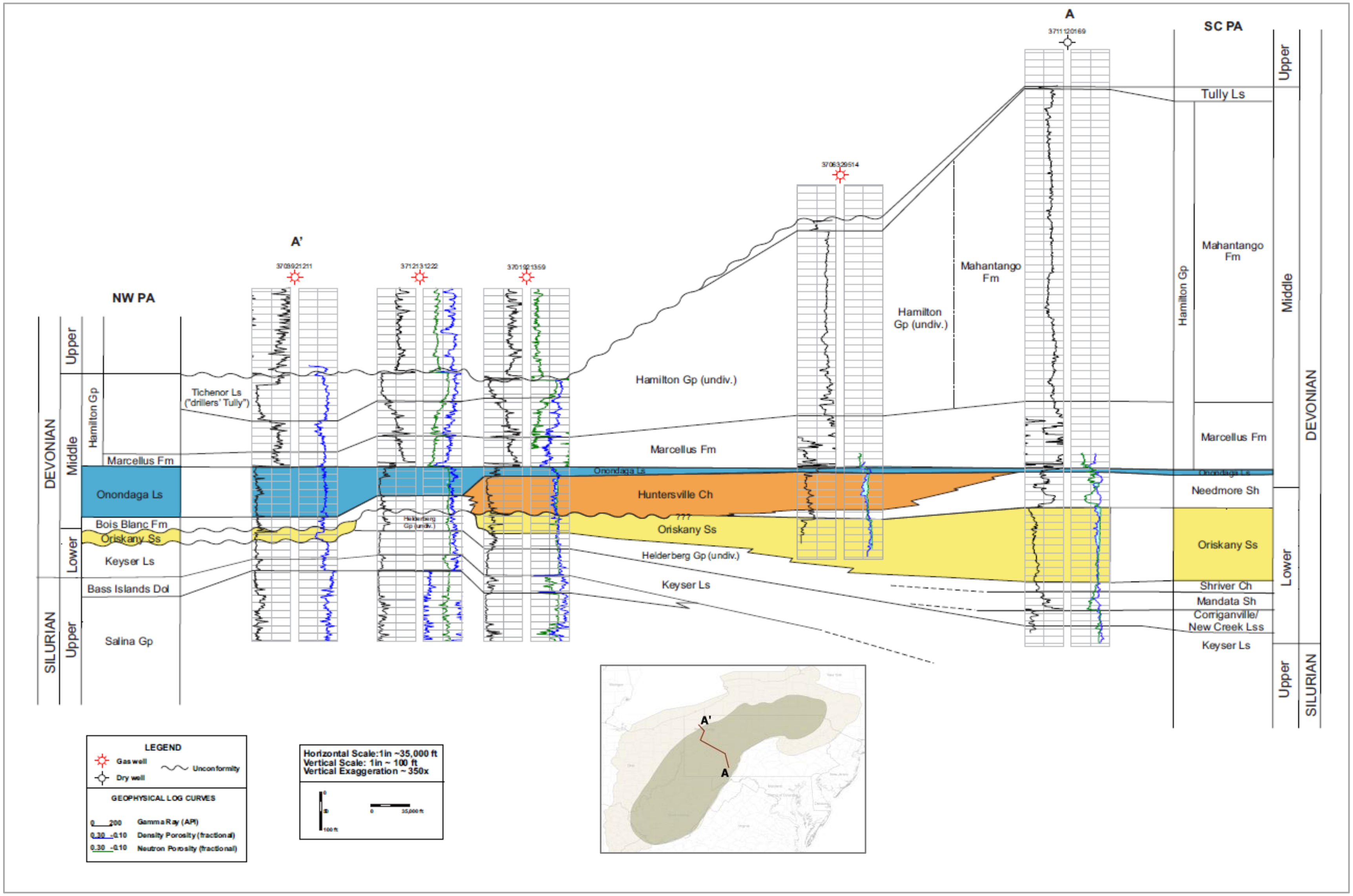
Regional stratigraphy and lithology

The Marcellus formation is a part of the ancient sedimentary system known as the Appalachian basin. The organic-rich black shale of the Marcellus formation was deposited in a foreland basin roughly paralleling the structural front of the present-day Appalachian Mountains during the Middle Devonian time about 390 million years ago (Harper, 1999). The Marcellus Shale is described as carbonaceous silty black shale that encloses scattered pyrite, carbonate concretions, and scarce fossils. Several beds of calcareous shale and black limestone and one or more zones of concretions that vary in composition, abundance, and character have also been recognized (Ettensohn and Baron, 1981; Harper, 1999; Roen and Walker, 1996). The Marcellus lithology varies significantly across the Appalachian basin. This lithological heterogeneity is controlled by depositional and diagenetic processes.

Typically, the Marcellus shale is laminated (fissile) and lacks bioturbation. According to previous studies the chief minerals are 9% - 35% mixed-layer clays (more abundant in upper member); 10% - 60% quartz, 0% - 10% feldspar, 5% - 13% pyrite (more common toward the base of the formation), 3% - 48% calcite, 0% - 10% dolomite (carbonate minerals much more abundant in the lower Marcellus member), and 0% - 6% gypsum (Avary and Lewis, 2008; Boyce and Carr, 2009; Roen, 1984; Wrightstone, 2008; Zielinski and McIver, 1982).

Figure 3 shows the regional stratigraphy of the Devonian interval, including the Marcellus Formation. The Middle Devonian Marcellus Formation is the basal member of the Hamilton Group and typically overlies the limestone of the Onondaga Formation. Previous studies identified regional basal unconformity, so the Marcellus could be underlain by the Lower Devonian Huntersville Chert or an older

Figure 3. Geological cross-section through the Appalachian basin with the regional stratigraphic schema of the Devonian interval

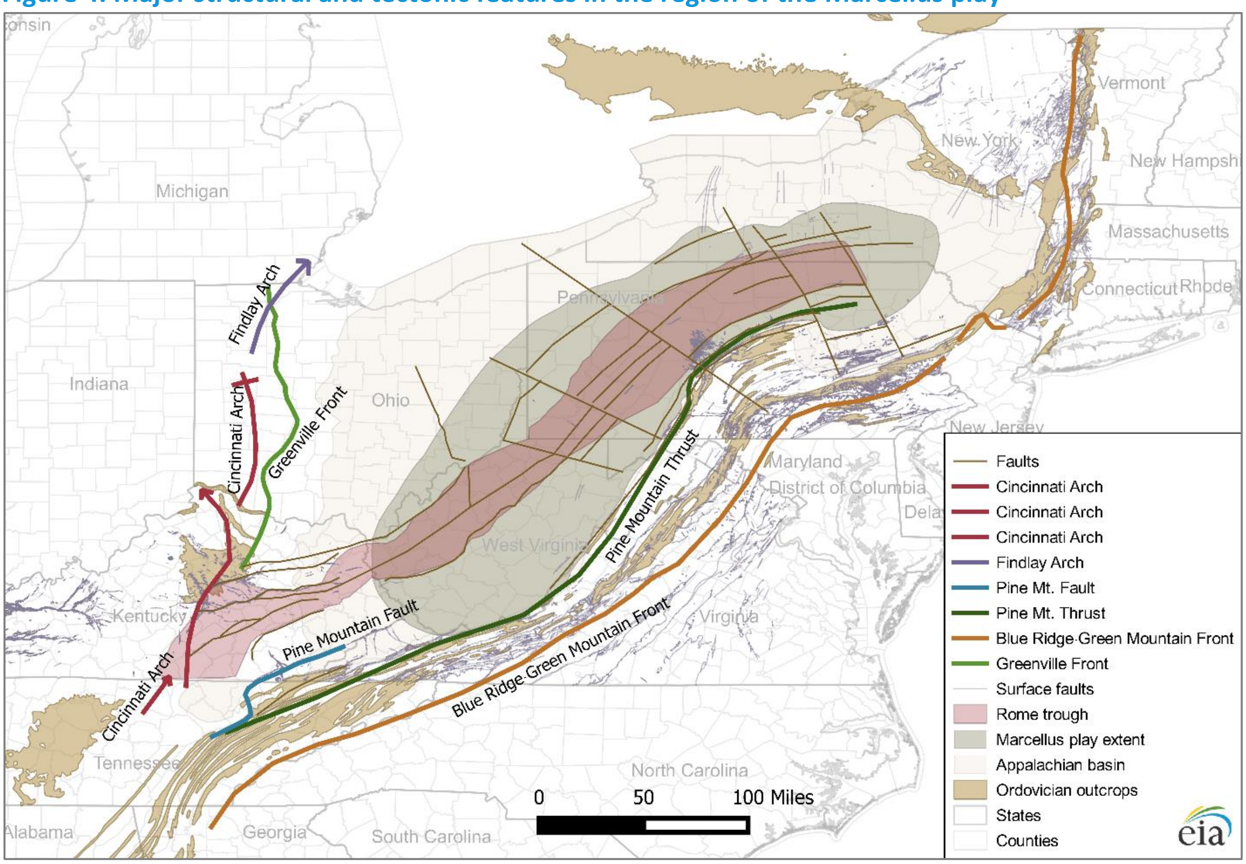


Source: Pennsylvania Bureau of Topographic & Geologic Survey; Popova et al., 2014 formation (Anderson and others, 1985). The Marcellus formation is covered above by the Middle Devonian Mahantango Formation. The Marcellus interval is divided into two members: the lower Marcellus/Union Springs Shale and the upper Marcellus/Oatka Creek Shale. The Marcellus exhibits several different pressure regimes across the Appalachian basin. Generally, the Marcellus is underpressured to the southwest and normal-pressured to potentially overpressured to the northeast, with a transitional area in between. Likely, the highest ultimate recoveries will be from the normal to over-pressured areas. The presence of these distinct pressure regimes and variations in lithology requires different approaches to well stimulation and completion (Zagorski et al., 2012).

Structural and tectonic features

The Appalachian foreland basin encloses a platform-margin sedimentary succession that is dominated by siliciclastic and carbonate sequences of the Early Cambrian age through Early Permian age. The Appalachian basin is an asymmetrical, northeast-trending trough bounded by the Blue Ridge Green Mountains front to the southeast and the Cincinnati arch to the northwest (Figure 4) and was formed in response to the Alleghanian orogenic event (Quinlan and Beaumont, 1984; Gao et. al., 2000). Major causes of subsidence during Paleozoic were related to tectonic flexure of the lithosphere and sediment

Figure 4. Major structural and tectonic features in the region of the Marcellus play



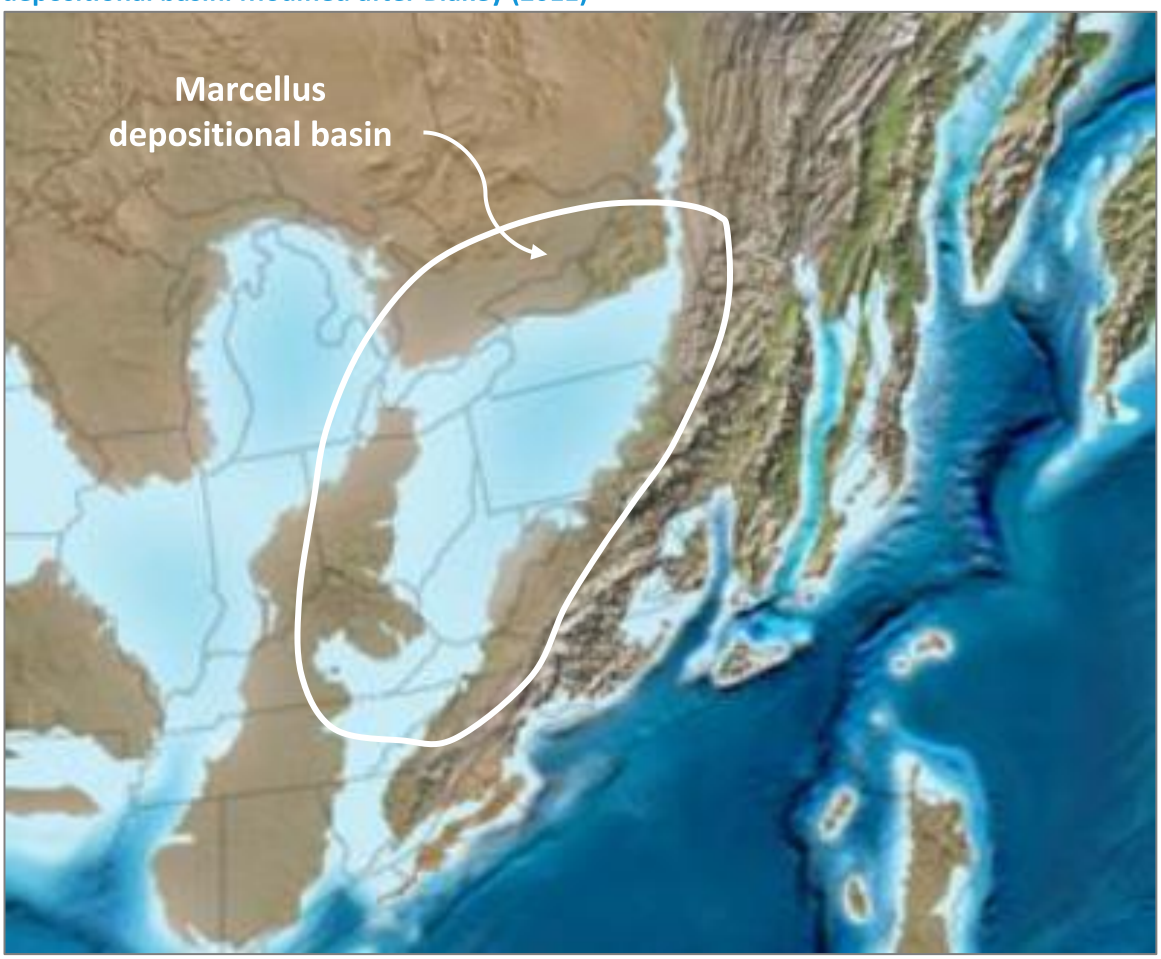
Source: U.S. Energy Information Administration based on DrillingInfo Inc., New York State Geological Survey, Ohio State Geological Survey, Pennsylvania Bureau of Topographic & Geologic Survey, West Virginia Geological & Economic Survey, U.S. Geological Survey.

loading associated with the rejuvenation of the Appalachian foreland basin (Castle, 2001).

The basin dips from a zero-edge in the northeast to the southwest, reaching a depth of more than 5 kilometers at the thrust and fold belt of the Appalachian Mountains. The well-studied middle Devonian Marcellus formation of the Appalachian Basin is an eastward and southeastward thickening wedge of shallow marine claystone and limestone and is exposed in northeast-trending folds in the Valley and Ridge province of the central Appalachians (Filer, 2003; Harper, 1999).

The basement structure of the Appalachian basin, along with major interpreted faults and the projected position of the Rome trough, serve as tectonic features controlling depositional and burial history of the sedimentary formations in the region, including the Marcellus shale. The mapped basement faults fall into two catrgories: (1) faults that strike parallel to the basin and are associated to the Rome trough, and (2) transform faults that are developed perpendicular to the strike of the basin and are interpreted

Figure 5. Middle Devonian paleogeographic reconstruction (385 Ma) exhibiting the Marcellus Shale depositional basin. Modified after Blakey (2011)



as cross-strike structural discontinuities (Harper and Laughrey, 1987). These basement faults represent zones of weakness assumed to have been reactivated several times during the Paleozoic period and have continued well into Quaternary (Negus-De Wyss, 1979; Shumaker, 1993).

A paleogeographic reconstruction of the Middle Devonian (385 Ma[1]) shows present-day West Virginia; Pennsylvania; and parts of New York, Virginia, Maryland; and Ohio as a nearly enclosed epicontinental sea (Woodrow, 1985; Blakey, 2011). The model developed by Ettensohn (1985; 1992; 2008) suggests that major orogenic highlands (Acadian Highlands) were located to the east of the Marcellus depositional basin from which clastic sediments were derived. These highlands also contributed to deformational loading, providing the accommodation space for accumulating sediments within the subsiding basin. The paleogeographic reconstruction shows that the organic-rich deposition occurred in a large, nearly enclosed, three-sided embayment. In other words, this geometry created restricted marine circulation within the Appalachian Basin during Middle Devonian time.

Thermal maturity and initial yields (oil-to-gas ratios of wells producing from the Marcellus formation)

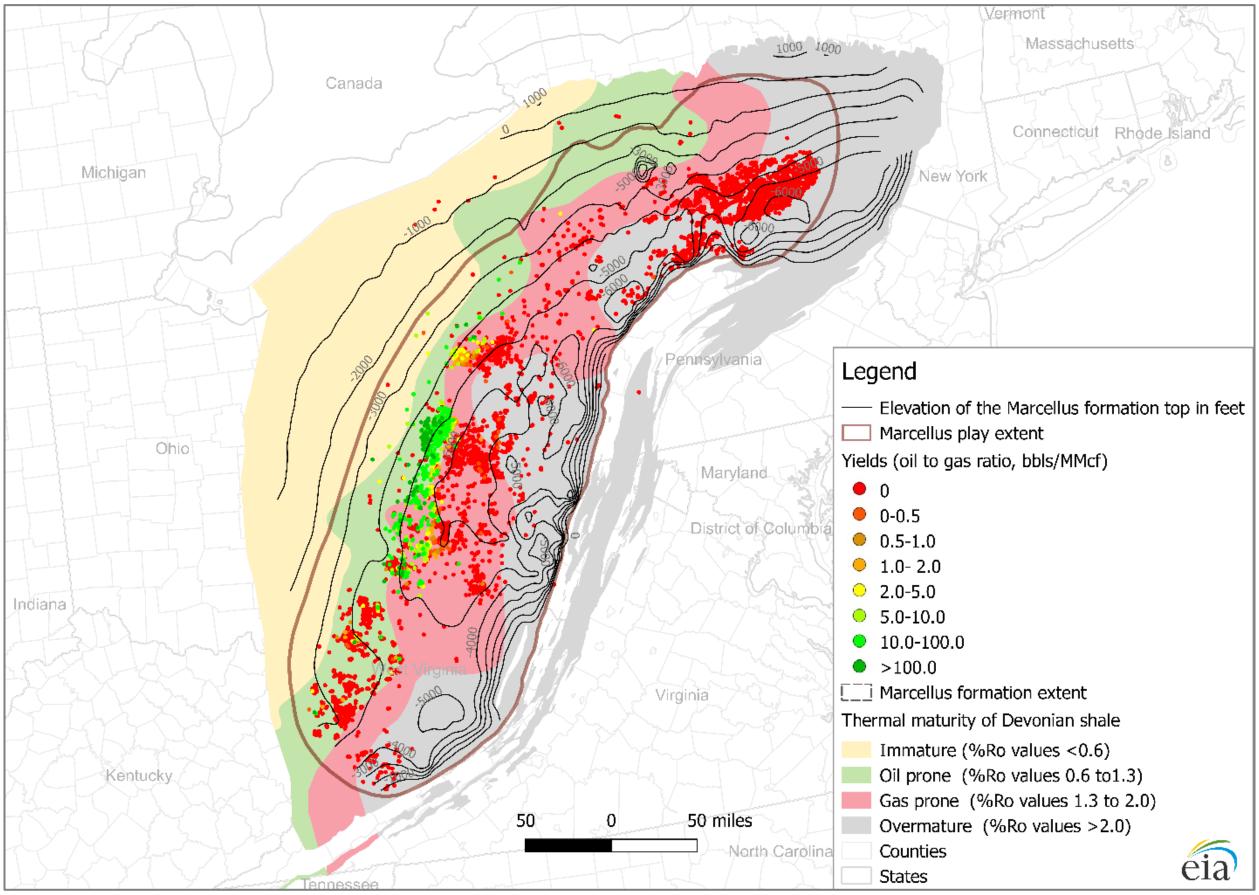
Crude oil and natural gas are produced by the heating the organic materials (i.e., kerogen) found in some rocks. When organic-rich rocks, usually shales, are buried over long periods of time, they are exposed to increasing temperatures and pressures. Heat causes the organic matter to change into the waxy material known as kerogen, then into oil, and finally into natural gas as the temperature further increases. Thermal maturity is the level of thermal alteration of rock that reflects the degree of organic matter transformation (e.g., conversion of sedimentary organic matter to petroleum or cracking of oil to natural gas).

Thermal maturity values (based on vitrinite reflectance, R_o measurements of core samples) in the Marcellus Shale generally increase in a southeastern direction, as shown in Figure 6, ranging from 0.5% R_o to more than 3.5% across the Appalachian basin. Recent Marcellus Shale drilling activity and results suggest that the most substantial hydrocarbon production takes place roughly southeastward of the 0.6% R_o maturity contour in the western parts of West Virginia, eastern Ohio, Pennsylvania, and southern New York.

At thermal maturity values of greater than 3.5% R_o, the hydrocarbon production potential from the Marcellus Shale may become problematic based on the limited drilling results released to date. Figure 6 also shows the distribution of production across the play in terms of initial yields. Yields represent the ratio of oil to natural gas produced from a well, expressed in barrels per million cubic feet (bbls/MMcf). The distribution of oil and natural gas in a formation is mainly controlled by the thermal maturity of a rock, which is an indication of potential hydrocarbon generation. Thermal maturity is mostly defined by burial depth.

[1] Ma is abbreviated from Latin mega-annum, a million years

Figure 6. Initial Yields (oil-to-gas ratios, barrels per million cubic feet (bbls/MMcf)) of Marcellus wells as of December 2016



Source: U.S. Energy Information Administration based on DrillingInfo Inc., and U.S. Geological Survey.

In the Initial Yields map, dry natural gas wells in the Marcellus play are mostly located in the eastern portion of the play, and liquids-rich wells are typically located in the western portion. Figure 6 shows that the two sweet spots in the Marcellus play exhibit different thermal maturity characteristics. In southwestern Pennsylvania and northern West Virginia, the established production to date from the Marcellus occurs in a vitrinite reflectance range of 1.0% to 2.8% R_o, with commercial natural gas discoveries occurring both in the dry gas window to the east (within subsea formation depth in a range of -5,000 feet to -6,500 feet), as well as in the gas- condensate portion of the play to the west. British thermal unit (Btu) contents in the Marcellus Shale for this area range from approximately 1000 in the east to 1,400 mmBtu/mcf in the western areas near the 1.3% R_o contour and correlate to the subsea formation depth range of -3,500 feet to -5,000 feet. The established productive areas of the Marcellus in the northeastern part of the play have a higher thermal maturity profile, with the most natural gas production occurring between R_o values of 2.0% to more than 3.0%. The limits of the gas window in this area correspond to subsea depth between -3,000 feet and -6,500 feet. The Btu values here are in the range of 1,000 to 1,080 MMBtu/mcf (Repetski et. al., 2008).

Total Organic Carbon Content

Analytical results from multiple well core samples indicate that Total Organic Carbon (TOC) content in the Marcellus formation ranges from less than 1% to 20% (Zielinski and Mciver, 1982; Nyahay et al., 2007; Reed and Dunbar, 2008). Known good source rocks typically contain 2.0% TOC or higher. As such, the Marcellus Shale has some of the highest TOC content of continuous plays in the United States.

One of the best proxy measurements of TOC content in the Marcellus formation is its gamma-ray count. A strong correlation exists between the organic content of Appalachian shales and gamma-ray log intensity (Schmoker, 1981). As such, TOC content (5%) can be detected with gamma-ray counts of 200 API[2] units or greater. Gamma-ray counts in the Lower member of the Marcellus formation often exceed 400 API units, which generally indicates higher TOC contents in the basal part of Marcellus.

In some areas, particularly in southwestern Pennsylvania and northern West Virginia, measurements in excess of 300 to 400 API units are not uncommon and reflect the generally higher TOC contents in the southwestern Marcellus play area when compared with the northeastern parts of the play. Within the Marcellus Shale play, TOC content can be directly related to porosity development resulting from the conversion of kerogen to hydrocarbons (Zagorski, et al., 2012)

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[2] In the United States gamma ray logs are scaled in American Petroleum Institute (API) units. To provide a common scale, API built a calibration facility at the University of Houston. It consists of a concrete-filled pit, 4 feet in diameter, with three 8-foot beds penetrated by a 5 1/2-inch hole cased with 17-lbm casing. The top and bottom beds are composed of extremely-low-radioactivity concrete. The middle bed was made approximately twice as radioactive as a typical midcontinent U.S. shale, resulting in the zone containing 13 parts per million (ppm) uranium, 24 ppm thorium, and 4% potassium. The gamma ray API unit is defined as 1/200 of the difference between the count rate recorded by a logging tool in the middle of the radioactive bed and that recorded in the middle of the nonradioactive bed.

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