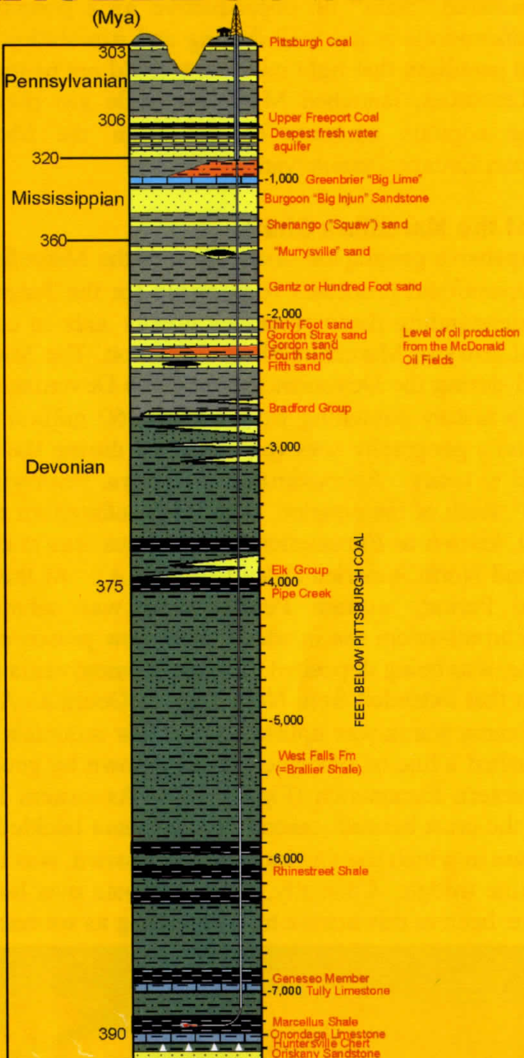
GEOLOGY OF THE MARCELLUS SHALE



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Geology Underlies it All

Introduction

For more than 70 years, gas well drillers in the Appalachian region have recognized a "show" or trace of gas within the fine-grained black shale that overlies the main deep gas reservoir target, the Oriskany Sandstone. This black shale, known by geologists as the Marcellus Shale, has generally been acknowledged as the likely source for much of the gas within the prolifically productive Oriskany Sandstone layers, but itself was considered "tight" or unproductive as a potential gas reservoir. Recent innovations in gas well drilling and stimulation have changed the long-held paradigm that tight rock units could not be productive. In 2003 Range Resources, launched Marcellus shale gas play by drilling and producing copious amounts of gas from the Marcellus Shale in Washington County, Pennsylvania.

Origin of the Marcellus Shale

The expansive geographic distribution of the Marcellus Shale is related to the depositional processes responsible for the formation of this rock unit. Understanding these processes greatly aids in comprehending the whys and hows of Marcellus Shale formation. The Marcellus Shale was deposited during the Devonian Period. The Devonian spans the interval of Earth's history stretching from 415 to 360 million years ago (Mya). The region's geography was very different during the Devonian Period, compared to today. Approximately 410 Mya, Pennsylvania was located about 35° south of the equator, along the southeastern edge of an ancient continent, known as Euramerica. Euramerica was made up of what are Europe and North America today (Figure 1A). At the beginning of the Devonian Period, western Pennsylvania was submerged beneath a shallow current-swept sea in which sand, now preserved as the Oriskany Sandstone, was being deposited. Eastern Pennsylvania was part of a long peninsula that extended from New York to Georgia. At about 390 Mya, eastern Pennsylvania was uplifted into a low mountain chain as tectonic forces pushed a line of volcanic islands, known by geologists as Acadia, against eastern Euramerica (Figure 1B). As eastern Pennsylvania was uplifted, the crust beneath central Pennsylvania buckled downward. The shallow sea in which the Oriskany was deposited, was transformed into a deep marine trough. Currently, there is debate over how deep the water may have been in this marine trough. Along its western margin, in Ohio

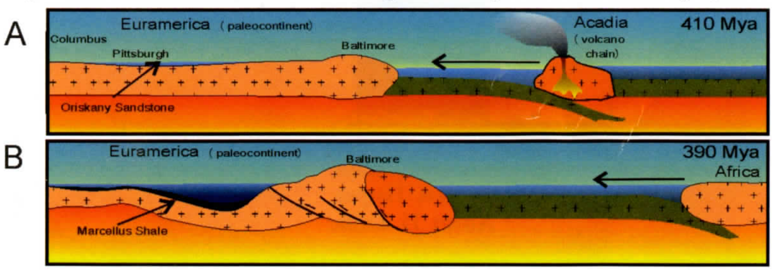

Figure 1. Devonian plate tectonic cross-sections. As the Acadia island volcano chain approached Euramerica (A), the Oriskany Sandstone was deposited in a shallow inland seaway. Acadia collides with Euramerica, (B) uplifting the Acadian mountain chain along the eastern edge of Euramerica and depressing a marine trough in the interior.

and western Pennsylvania, water depths may have been relatively shallow. However, from eastern West Virginia though east-central Pennsylvania, the hundreds of feet of accumulated Marcellus indicate that the trough subsided very rapidly, and water depths may have been in the thousands of feet (Figure 2B). Although the shallow surface waters within this trough were warm, sunlit, current-swept, and full of marine plankton, waters somewhat deeper were stagnant and devoid of any oxygen or life. This is because there were few currents present in this inland seaway. Without currents to stir up and oxygenate the waters, a dense layer of cold and salty water settled into the deepest parts of the marine basin. Such sharp density gradient are called pycnoclines (pronounced *pick-no-cline*). Plankton that flourished in the shallows or near the surface would die and sink into the stagnant depths below the pycnocline. Over millions of years their remains accumulated on the sea floor as hundreds of feet of black, putrid muds (Figure 2B).

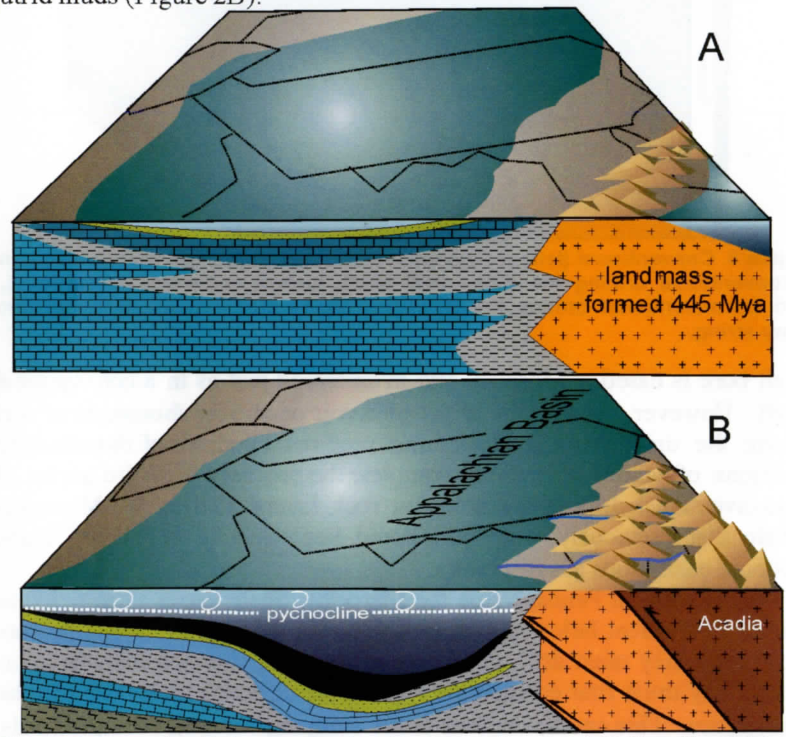

Figure 2. Devonian Paleogeography. A. Approximately 410 Mya, the Oriskany Sandstone is deposited in a shallow inland sea. B. 390 Mya, collision of the Acadia island change and eastern Euramerica uplifts a mountain range and depresses the continental interior, forming a deep trough.

As the mountain chain in eastern Pennsylvania was uplifted, weathering and erosion of the highlands outpaced the subsidence of the marine trough to the west. Rivers flowing from the mountains carried sand, silt, and clays to the sea to the west. These sediments were deposited along a broad deltaic shoreline that built itself westward. Finer sediments were swept into the deeper parts of the trough. The organic muds accumulating on the sea floor were mixed with and ultimately buried by an accumulation of fine sand, silt, and clay thousands of feet thick. Burial of the Marcellus organic-rich muds beneath this thick pile of sediments compressed and compacted the muds into shale, but it also began to heat and change organic matter.

Metamorphism of the Organic Matter

The deposition and preservation of the remains of millions of generations of plankton was only the beginning of the journey that the Marcellus Shale would follow to make it a suitable hydrocarbon source bed and gas producer. The accumulated plankton remains were degraded, in the sediment, into an amorphous mass of organic molecules known as kerogen. Following the deposition of the Marcellus, 385 Mya, the shale was buried by thousands of feet of sediment that filled the trough. This burial, and the creation of the Appalachian Mountains, about 240 Mya, heated the organic matter contained within the Marcellus Shale. As the paleo-temperature of the shale was elevated, the organic matter within the Marcellus began to change. This low temperature metamorphism of organic matter is called catagenesis. The kerogen contains some hydrogen and carbon molecules which possess bonds that are relatively easily broken when heated. As the temperature of the kerogen was raised, the bonds between some of the hydrogen atoms were weakened or broken. This breaking of the hydrogen molecular bonds is known as "cracking." Cracking produces shorter hydrocarbon molecules. Initially, cracking can lead to the production of liquid hydrocarbon molecules (Figure 3). If the heating of the kerogen ended at this point, primarily petroleum or "oil" would be preserved. However, increased and prolonged heating continues to break the hydrogen bonds into shorter and shorter molecules. Application of enough heat and pressure results in the breaking of nearly all the hydrogen bonds, producing molecules that are gas. Methane, the shortest hydrocarbon molecule, is the principal component of natural gas. The organic residue left behind when all the shorter hydrocarbon molecules are broken and driven off is called asphalt.

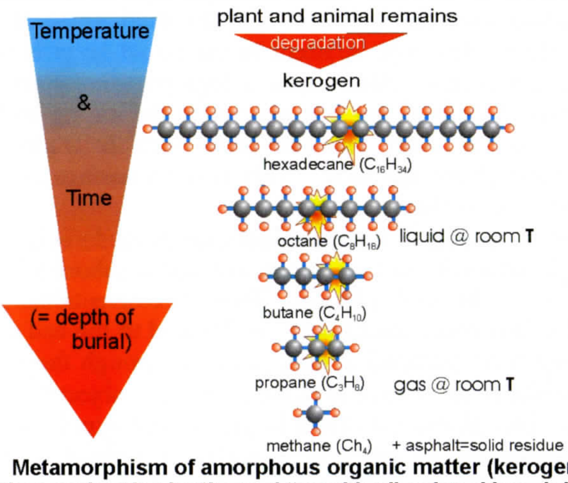

Figure 3. Metamorphism of amorphous organic matter (kerogen) into shorter hydrocarbon molecules by thermal "cracking" or breaking. Initial long molecules are progressively reduce to molecules of shorter length as heat and pressure are applied.

As the kerogen is metamorphosed, and the liquid or gaseous hydrocarbons are released, these relatively small molecules move through pores or fractures in the rock to nearby accumulation sites, known as reservoirs. For most of the Appalachian region the nearest suitable reservoir is the Oriskany Sandstone. However, much of the hydrocarbon remains in the source bed, and, in the case of the Marcellus, it has remained there sealed within this nonporous, tight, rock unit.

Drilling the Marcellus Shale

The impermeable Marcellus Shale serves as an excellent seal, or cap, above the relatively porous Oriskany Sandstone reservoir. Because of limitations in conventional well-drilling technologies and the nonporous and impermeable character of the shale, the Marcellus was not itself exploited for gas production. However, recent innovations in well drilling and improvements in well stimulation have now changed that paradigm. Thus, the Marcellus Shale, which continuously underlies up to 95,000 square miles of the Appalachian Basin, can itself be considered a vast gas reservoir (Figures 2B, 4).

Hundreds of thousands of conventional gas wells, both shallow and deep, have been drilled in the Appalachian Basin. In conventional wells, the well bore is drilled vertically from the drilling rig, or platform, to a target reservoir rock layer below ground by connecting a continuous string of drilling pipe. At the end of the drill string, at the bottom of the hole, a drill bit grinds away at the rock. The motor at the drilling rig turns the entire string of drill pipe as the bit penetrates deeper and deeper. Drilling mud forced down the center of the drill string cools and lubricates the bit and carries ground-up rock to the surface. As the well is deepened, segments of pipe are added at the drilling platform. Government regulations dictate that at various levels, the well bore is to be lined with steel pipe, called casing, and cemented to protect groundwater, coal beds, and the like from being invaded by fluids rising from deeper levels of the well. Once the target layer is reached the drill string is removed from the well bore and the final string of casing is cemented in place. The pipe adjacent to the target layer is perforated using directed explosives. Afterwards, a high-pressure slurry of water and sand is forced through the perforations in the casing and into the cracks in the reservoir layer. The sand props open the cracks, allowing gas to flow freely from the rock. This final procedure is known as hydraulic fracturing, or “hydrofracing.”

In unconventional well drilling, conventional procedures are followed until the driller achieves the rock layers just above (about 500 feet) the target unit (e.g., the Marcellus Shale). Then the conventional drill bit is removed and a “downhole mud motor” is attached to the end of the drill string. Drilling mud, pumped at high pressure through the drill string, acts as a hydraulic fluid. The mud motor is the only object that rotates in the well bore. This allows the driller to gently, and over long distances, change the orientation of the drill string from vertical to horizontal (Figure 4). As a result, the driller can bore laterally for thousands of feet within the target layer. Once completed, the horizontal segment of the

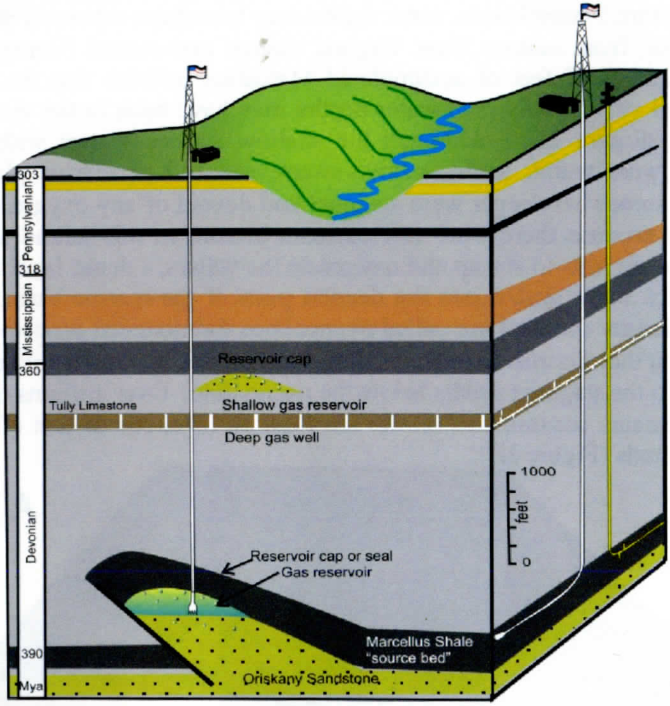

Figure 4. Conventional (left) versus unconventional (right) gas well drilling. In conventional drilling the entire drill shaft, known as the drill string, turns. In unconventional drilling, the downhole mud motor is attached to a stationary string.

well bore is cased, perforated, and hydrofraced just as in a conventional well. However, because the target reservoir occurs for thousands of feet along the drill string, hydrofracing requires hundreds of thousands to millions of gallons of water to complete the process. With the advent of unconventional drilling technologies, rock layers such as the Marcellus Shale that previously were considered unproductive or "tight" units, become continuous gas reservoirs.

Within western Pennsylvania the Marcellus Shale varies from 6,000 to about 10,000 feet below the surface. Because geologists cannot be sure how deep they must drill, at any given location, to reach the Marcellus level, they must first conduct surveys of the different rock layers in the subsurface. This can be done by either studying old well boring records, or conducting seismic surveys. In a seismic survey, a string of sensors is stretched across an area. Then small explosive charges are set off. The waves produced by the explosion penetrate the rock layers below, and are reflected back to the surface. The precise timing of the arrival of the different waves along the sensor string tells the geologist how deep the different rock layers lie beneath the surface. The generalized stratigraphic column on the cover illustrates the rock layers present beneath Carnegie Museum.

Carla Kertis Brezinski made valuable suggestions improving this pamphlet.