1. Introduction and Background

The development of gas resources from the Marcellus Shale has been a success story for the government and people of the United States. It also represents the success of a federal research program that was put into place during a crisis to solve specific problems with energy supplies. Scientific and engineering data collected under this research program ultimately proved to be extremely valuable decades later, when technological advances finally allowed for the economic production of the resource. The large quantities of gas now being produced from shale are simply astounding, even to those who have a history with this resource.

BASIC GEOLOGY

The best place to start this story is with the rock itself. Shale is the name of a class of sedimentary rocks made of tiny grains of quartz, flakes of clay, and carbonate minerals such as calcite—the mineral components of mud. In fact, the generic term for this rock is "mudstone." Mudstones are subdivided into (1) predominantly silt or (2) predominantly clay. Silt-rich rocks are called siltstone.

The mud was deposited as clastic sediment in quiet water and then buried under younger sediments. The weight of these younger sediments compressed and heated the mud, driving out most of the water, cementing the minerals together, and turning the material into a rock through the process of lithification.

Clay is both a size term for very small sediment particles, and a type of mineral called a phyllosilicate, related to mica, that forms tiny sheets or flakes. As the sediment is deposited, the flakes of clay tend to stack together flat, one on top of another like a deck of cards, and as a result, lithified, clay-rich mudstone often has a finely layered structure that allows it to split into paper-thin sheets. This property is called fissility. Under the strict sense of the term, a fine-grained, clastic rock must exhibit fissility to be called shale. Many parts of the Marcellus Shale are non-fissile calcareous or silty mudstone, but the formation name "Marcellus Shale" is applied to the entire unit.

The proportion of the three primary mineral components of mudrocks (clay, quartz, and carbonate) varies in any particular shale, but most are composed of some combination of these end members. Shales also typically contain secondary minerals, such as pyrite and siderite, that precipitated out of the water trapped within the sediment, and diagenetic minerals, such as dolomite, that precipitated from fluids passing through natural fracture systems over geologic time. The sediment making up the bulk of shale is clastic in nature. As such, similar fine-grained but non-clastic carbonate rocks like chalk are classified as limestones. Intermediate rocks composed of both clastic and carbonate minerals are known as shaly limestones or calcareous shales, depending on the proportion of the constituents.

Rocks composed of something as simple as mud may not seem very exotic, but taking a closer look often reveals some interesting features. Shale contains complex and often rather strange-looking grain and pore structures (Schieber, 2010; Goral et al., 2015), and laboratory experiments using flumes have shown that the depositional environments of fine-grained clastic sediment are often complicated.

From an oil and gas production perspective, shale comes in two varieties—dark and light—depending on how much organic material is included with the mineral matter. Organic-rich shales are commonly known as black shale, and organic carbon contents of only a few percent are needed to turn the rock "black" (Hosterman and Whitlow, 1980). Organic-lean shales are lighter-gray, green, or sometimes red in color, but they are referred to generically as "gray" shale. Black shales were deposited under anoxic conditions, which preserved the organic material from decay. Most of the organic material originated from dead plant fragments that accumulated with the sediment. The organic remains were subjected to heat and pressure in the absence of oxygen over geologic time periods during lithification, and this converted the organic material into hydrocarbons, such as petroleum, natural gas, and coal.

The Marcellus Shale was deposited in the Appalachian Basin between ~400 and 385 million years ago during the Middle Devonian Period. (A million years is commonly abbreviated as a mega-annum, or Ma. Age dates and boundary picks are from the *Geological Society of America Geologic Time Scale* compiled by Walker and Geissman, 2009.)

The Marcellus Shale is named for the type section that occurs in an outcrop on State Route 175 near Slate Hill Road less than 1.6 km (1 mile) south of the small village of Marcellus, in Onondaga County, New York (Figure 1). The exposure here along the eastern valley wall of Ninemile Creek was described by Cooper (1930), and the formation was named after the town.

Soeder, D.J., 2017, Introduction and Background, *in* Soeder, D.J., Unconventional: The Development of Natural Gas from the Marcellus Shale: Geological Society of America Special Paper 527, p. 5–16, doi:10.1130/2017.2527(01).

The lower boundary of the Marcellus Shale is sharp, resting on the Onondaga Limestone. In contrast, the upper boundary is gradational, changing over a distance of several meters into the Mahantango Shale, an organic-lean gray shale named by Willard (1935) for exposures in the valley of Mahantango Creek in Snyder County, Pennsylvania. The Marcellus and Mahantango Shales are combined into a larger geologic formation called the Hamilton Group, which may or may not (depending on the author) also include the Tully Limestone above the Mahantango (Stamm, 2015).

The village name of Marcellus honors a famous Roman general and consul, Marcus Claudius Marcellus (268–208 B.C.). A number of other New York towns in the area also bear classical Greek or Roman names (i.e., Ithaca, Utica, Rome, Syracuse, etc.). General Marcellus was known as "The Sword of Rome" and most famously led Roman troops against Hannibal of Carthage. He is credited with preventing the army of Carthage from approaching close to the City of Rome itself by keeping them occupied out in the Italian countryside. Marcellus was eventually ambushed on a scouting mission by Hannibal's cavalry and died a soldier's death on the battlefield at age 60, impaled on a spear. The Roman historian Plutarch recorded his exploits (http://classics.mit.edu/Plutarch/marcellu.html).

Figure 1. Fissile and fractured Marcellus Shale at the type section near Marcellus, New York. Rock hammer (33 cm or 13 in.) is included for scale. Photograph by Daniel J. Soeder, 2010.

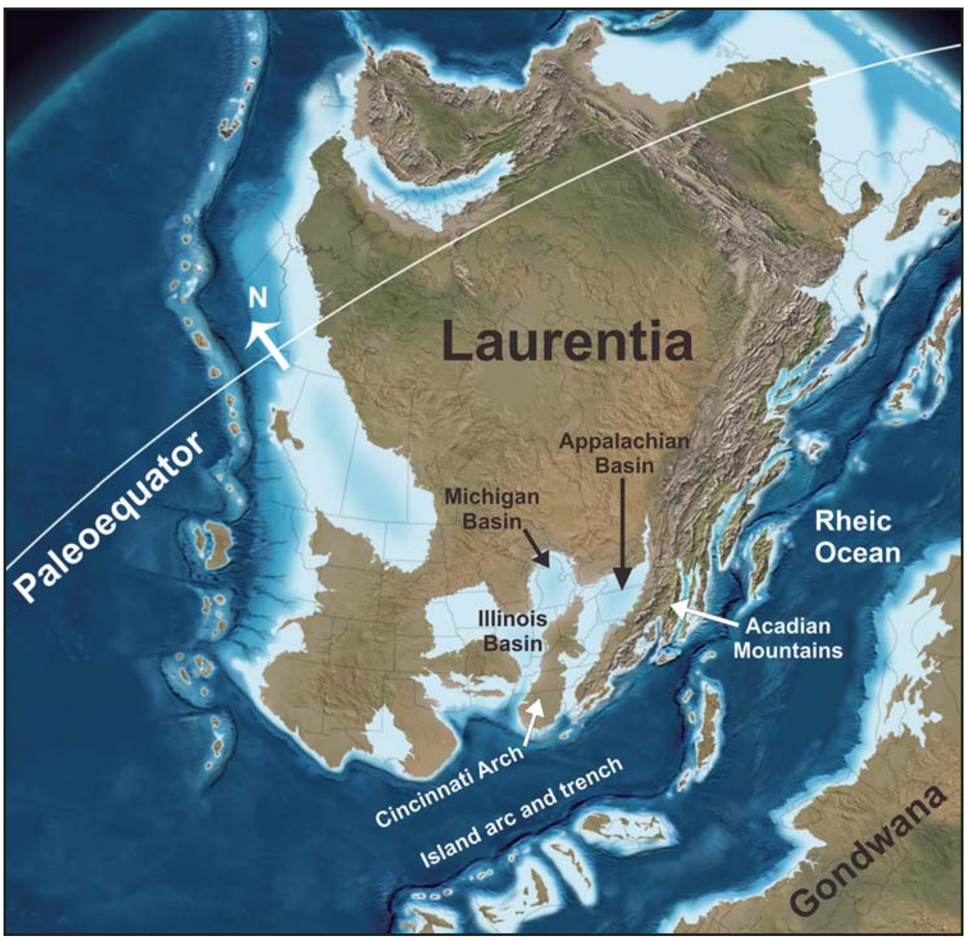

Figure 2. Reconstruction of ocean and land geography on the ancient continent of Laurentia (containing ancestral North America) during Marcellus Shale deposition in the Appalachian Basin 385 m.y. ago. The ancient continent of Gondwana, containing ancestral Africa and Europe, can be seen looming in the corner at lower right. The Rheic Ocean is closing along a subduction zone marked by the island arc and trench as Gondwana heads toward Laurentia, eventually forming the supercontinent of Pangea and creating the Appalachian Mountains in the process. Figure is drawn on a base map from Blakey (2011).

Geologic Framework

The Appalachian Basin is a large depression in Earth's crust on the eastern margin of North America, filled with sedimentary rocks. It is deeper in the east and shallower to the west, forming and filling from ca. 520 Ma to ca. 250 Ma, and experiencing several episodes of mountain building along its eastern edge. Because of continental drift, the ancestral North American continent known as Laurentia, which contained the Appalachian Basin, was located largely south of the equator during the Devonian (416–359 Ma), Mississippian (359–318 Ma), and Pennsylvanian (318–299 Ma) geological periods.

An inland sea flooded the Appalachian Basin from New York to Georgia (Figure 2). Such inland water bodies on continental platforms are known as epeiric or epicontinental seas. Modern analogs include the Baltic Sea and Hudson Bay, although the Appalachian Sea was much warmer than either. The Marcellus Shale was deposited in this inland sea on top of some Early to Middle Devonian limestones and sandstones. A great river delta was built out into the sea on top of the Marcellus Shale during the Upper Devonian Period (374–359 Ma). The Catskill Mountains of New York are the remains of this delta (Schwietering, 1979). The delta system was actually quite complex, with as many as five major river systems contributing sediment to the basin along some 160 km (100 miles) of coastal plain shoreline (Boswell and Donaldson, 1988). Eventually, as much as 4 km (12,000 vertical ft) of sediment in the Catskill Delta accumulated on top of the Marcellus Shale (Milici and Swezey, 2006). The deep burial of the Marcellus Shale exposed it to fairly high pressures and temperatures (Rowan, 2006), which broke down nearly all of the complex hydrocarbons in this rock to methane (CH_4), the simplest and most common form of natural gas.

Additional black shales were deposited into the Appalachian Basin throughout the Upper Devonian (374–360 Ma) and Lower Mississippian Periods (360–352 Ma), including the Geneseo, Middlesex, Rhinestreet, Dunkirk, Huron, Cleveland, and Sunbury Shales. All are organic rich, and many contain gas (Potter et al., 1980). Gray, organic-lean shales and siltstones were deposited between the black shale units, as basin anoxia decreased or sediment influx became greater. A representative cross section of these rocks is shown in Figure 3.

A thin, older, Lower Devonian formation called the Mandata Shale occurs beneath the Marcellus Shale (Baez et al., 2004), but it is separated from the main Devonian shale sequence by the Onondaga Limestone, the Oriskany Sandstone, and Helderberg Group limestone units. The Marcellus Shale is generally

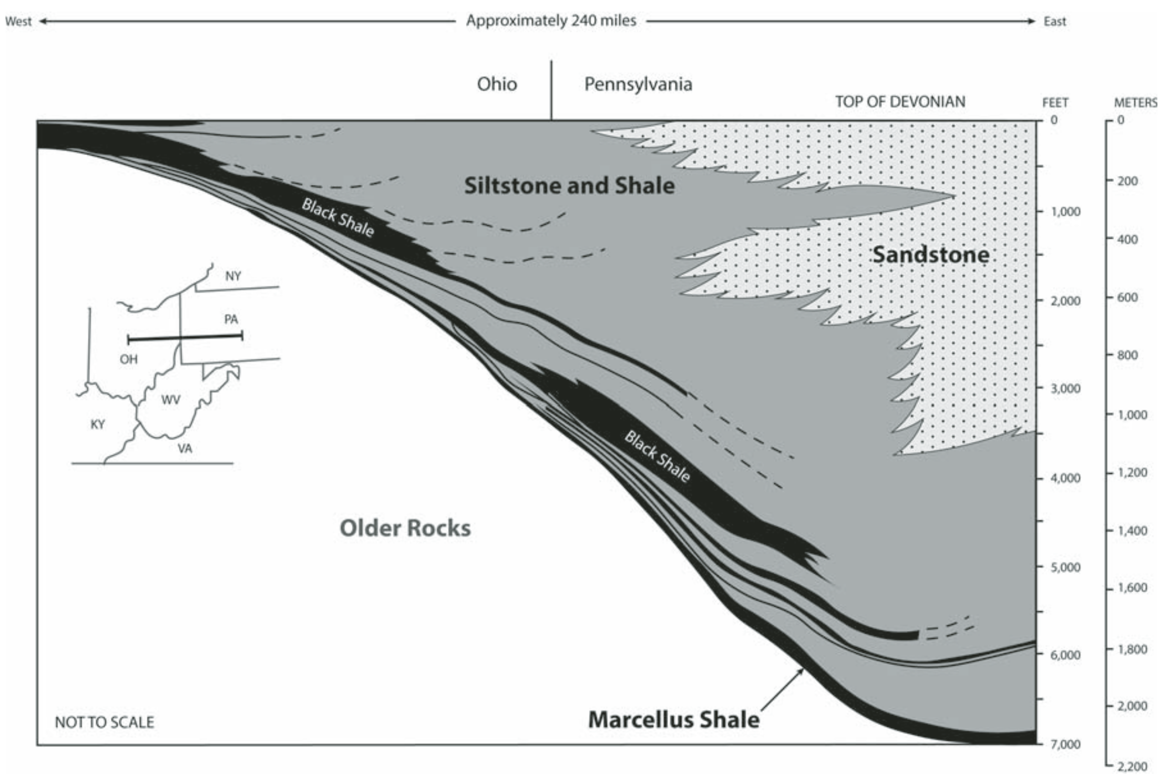

Figure 3. Vertical cross section of the Appalachian Basin from Ohio into Pennsylvania (see inset map for location) showing the layered sequence of Devonian-age black and gray shales (the Marcellus Shale is at the bottom) with coarser sandstones. The drawing is strongly exaggerated in the vertical dimension. Figure is modified from Potter et al. (1980). Abbreviations in inset: KY—Kentucky; NY—New York; OH—Ohio; PA—Pennsylvania; VA—Virginia; WV—West Virginia.

considered to be the basal unit of the main Devonian shale sequence, overlain by more than 2 km of continuous sediment deposition into the Appalachian Basin from Middle Devonian to Lower Mississippian time.

The basin became increasingly shallow in the Upper Devonian and Mississippian Periods (359–318 Ma). Several of the sedimentary deposits were exposed to the atmosphere, resulting in the oxidation of iron minerals that typically color the rocks red. For example, the "red beds" of the Upper Devonian Catskill Formation and the underlying Lock Haven Formation are prominently exposed in Pennsylvania along Route 322 west of State College. Likewise, the red shale and sandstone beds of the Mississippian Mauch Chunk Formation are recognizable at a number of locations in eastern West Virginia, including an outcrop on Route 72 along the Cheat River north of Parsons. The Pennsylvanian-age sediments (318–299 Ma) on top of the Mississippian rocks were deposited in a very shallow basin—many of the Pennsylvanian coals were formed from woody plants growing in fluvial and paludal wetlands.

Geologic Structure

Pulses of clastic sediment deposition into a basin are often influenced by episodes of mountain building along the basin margin followed by erosion. Plate-tectonics theory describes Earth's crust as being divided into a number of large plates that float on the semiliquid mantle. Plates can do one of three things at their boundaries: (1) pull apart, allowing magma to upwell and create new land on mid-ocean ridges such as Iceland; (2) slide past one another, causing earthquakes like the San Andreas fault in California; or (3) collide and force one plate to descend beneath another in what is known as a subduction zone, forming deep ocean trenches like the Japan Trench. As the descending plate melts, the resulting magma will often rise and create an arc of volcanic islands behind the subduction zone, such as the islands of Japan.

On the edges of continents, a mountain-building episode, which is known as an orogeny, can occur when plate-tectonic movements cause land masses to uplift or collide. As a slab of ocean crust descends into a subduction zone, the lighter continental crust on top is rafted along like an empty canoe and may eventually collide with another floating continent. This is not exactly a car wreck—the continents "crash" into each other at the rate of a few centimeters per year, or about the speed at which human fingernails grow. Nevertheless, such a collision is powerful and inexorable, crumpling and folding the continental rocks. The force will thrust the rocks downward into Earth's interior and upward into the sky, forming mountains. The Himalayas are the highest and one of the newest mountain ranges on the planet, currently being thrust upward by a continental collision between India and southern Asia.

The eastern edge of the Appalachian Basin recorded three distinct orogenic events as this part of ancient Laurentia faced the closing Iapetus Ocean and then the closing Rheic Ocean during Paleozoic time (Nance and Linnemann, 2008). The oldest mountain range in the Appalachian Basin dates from the Taconic orogeny, which occurred in the Late Ordovician to Early Silurian Periods (458–439 Ma). This mountain range formed when Laurentia collided with an oceanic island-arc system (Colton, 1970). The collision had closed off the ancient Iapetus Ocean by the Late Silurian Period, and another, more southern ocean, called the Rheic Ocean (refer back to Fig. 2), was formed as the ancient continents moved about (Nance and Linnemann, 2008).

The seam where continents join is known as a suture zone, and the Blue Ridge Mountains that extend from Georgia to Pennsylvania mark the suture zone of the Taconic orogeny (Clark, 2008; Nance and Linnemann, 2008). One of the dominant rock units forming the Blue Ridge is a greenish metamorphic rock called metabasalt. These rocks were originally erupted from a mid-ocean ridge as lava and comprised the seafloor of the ancient ocean. The Catoctin Metabasalt, visible in roadcuts through the Blue Ridge along Interstate 70, west of Frederick, Maryland, and on Interstate 66 east of Front Royal, Virginia, is all that remains of the Iapetus Ocean.

The next mountain range resulted from the Acadian orogeny during the Middle Devonian to Lower Mississippian Periods (387–352 Ma), caused by collisions between Laurentia and a series of minor continental bodies called terranes with the exotic names of Avalonia, Baltica, and Armorica (Hatcher, 1989; Bruner and Smosna, 2011). Terranes are fragments of continental crust broken off from a tectonic plate and accreted onto another tectonic plate. Terranes retain their original geology, which usually differs from their neighbors. The Acadian orogeny created a mountain range in what is now New England, which was the principal source area for sediments that formed the Marcellus Shale, and the rocks of the Catskill Delta above it.

Late in the Pennsylvanian Period (320–286 Ma) and continuing into the Permian (286–245 Ma), the ancient continents of Laurentia and Gondwana collided head-on to fully close the Rheic Ocean and assemble the supercontinent of Pangea (see Hatcher, 1989). The episode of mountain building that resulted from this collision was the Allegheny orogeny, which formed the Appalachian Mountain range (Clark, 2008). The suture zone from the closure of the Rheic Ocean is deep beneath the Atlantic Coastal Plain, and it is not visible at the surface (Nance and Linnemann, 2008).

During a continental collision, rock layers arch upward into anticlines, or warp downward into synclines, similar to the crumpling hood of a car hitting a brick wall. Cross sections of some of these folds in the Appalachians show steep angles of the rocks on the flanks of parallel ridges, and a reconstruction of where they would have met overhead suggests that the original peaks easily rose 5 km (16,000 ft) or higher above sea level (Hatcher, 1989). While not as lofty as the Himalayas, because the collision was slower and spread out across a wider contact area, these were still very substantial mountains when first formed.

The intrusive igneous rocks and high-grade metamorphic bedrock in the present-day Piedmont area east of the Blue Ridge are part of the deep continental basement crust called the craton. In the Piedmont, these basement rocks were uplifted by the Allegheny orogeny and exposed at the surface by subsequent erosion. The high degree of metamorphism suggests that they were once covered by a great deal of overlying rock. The weathered granite, gneiss, and schist remain as evidence that the ancient core of the mountains once stood here.

No one crossing the Appalachians today would mistake them for serious mountains like the Rockies or Alps. Even the highest existing peaks, such as Clingmans Dome in Tennessee (2025 m or 6643 ft), or Mount Mitchell in North Carolina (2037 m or 6684 ft), would be considered little more than foothills in places like Colorado. The difference is age. The steep slopes of the ancestral Appalachians subjected the highest peaks to the most intense erosion, and after hundreds of millions of years of ice, snow, sleet, rain, and wind, only the nubs remain. Much of the sediment making up the Atlantic Coastal Plain, Eastern Continental Shelf, Mississippi Embayment, and the Gulf Coast washed down from the ancestral Appalachian Mountains. The present-day Appalachians consist mostly of low ridges of erosion-resistant sedimentary rock strata that will also disappear someday.

The supercontinent of Pangea began to split apart in the Triassic Period (245–200 Ma), creating a number of small rift basins up and down the present-day East Coast of the United States (many of these rift basins contain organic-rich black shales, some of which are being assessed for gas; see Milici et al., 2012). As Earth's crust began to pull apart, volcanic activity resumed, sending magma into fractures that cooled into linear dikes that occur from New Jersey to Georgia. The newly separated continents became modern North America on the western landmass, and modern Europe and Africa on the east. The ocean that formed between them is the Atlantic, which continues to slowly widen. Every year, the distance of a flight from New York to London increases by a few centimeters (see Withjack et al., 1998).

The Allegheny orogeny created tight folds and high peaks on the eastern margin of the basin in an area known as the Valley and Ridge Province. These folds have, in fact, brought the Marcellus Shale to the surface, where it outcrops in many places (Soeder et al., 2014a). To the west of these tightly folded rocks, the forces building the Appalachian Mountains thrust up a series of broader, flatter folds along a linear feature called the Allegheny structural front (Price, 1931).

The mountains along the Allegheny Front were less steep and are therefore eroded more slowly than the original, lofty Valley and Ridge peaks, and the even higher mountains of the Blue Ridge and Piedmont. The Allegheny Front now has some of the highest mountains remaining in the Appalachians. These include: Spruce Knob, the highest point in West Virginia; Backbone Mountain, the highest point in Maryland; and Mount Davis, the highest point in Pennsylvania.

The gentle folds of Laurel Mountain and Chestnut Ridge mark the western edge of the Allegheny Mountains. Westward from the base of these ridges, into northwest Pennsylvania, central Ohio, West Virginia, and eastern Kentucky, the flat-lying rocks of the Appalachian Basin have been vertically uplifted to form the Appalachian Plateau. This plateau is analogous to the Tibetan Plateau formed at the distant edge of the folds and thrusts making up the Himalaya Mountains, although it is much lower. The bulk of the Marcellus Shale and other sedimentary rocks in this central and western part of the Appalachian Basin were relatively undisturbed by the Appalachian mountain building to the east.

Formation of Black Shale

A common interpretation of the origin of black shales is that organic-rich muds were deposited in anoxic, deep water below a permanent pycnocline or density boundary (Boyce and Carr, 2010). Although anoxia is important to preserve organic matter in the sediment, deep water is not the only way to create low-oxygen bottom conditions.

An assessment of modern depositional environments for black muds suggests that two factors are critical for the preservation of organic matter: (1) high productivity of algae in the water column (Wrightstone, 2011), which is mainly controlled by nutrient input, and (2) deposition of organic material in a water body that has a low rate of sediment input, thereby minimizing the "dilution" of organic carbon with inorganic mineral sediment (Smith and Leone, 2010). These processes together create organic-rich muds. Animals and aerobic microbes feeding on the high-organic-content mud quickly deplete the limited dissolved oxygen in the bottom water, creating anoxic conditions that prohibit further consumption of organics, thus preserving the mud to later form a black shale.

In what has become the classical view, often referred to as the "Black Sea" model, black shales are thought to have formed in a deep, restricted, foreland basin somewhat like the modern-day Black Sea (Ettensohn, 2008). The alternating sequence of black shale units and intervening coarser clastic wedges in the northern Appalachian Basin (refer back to Fig. 3) has been interpreted by Ettensohn (2012) as evidence of the cyclic nature of Acadian mountain building, which sent pulses of sediment into the basin that can be used to approximate water depths during black-shale deposition.

The deposition of each black shale unit was explained by Ettensohn (2012) as the result of an episode of rapid subsidence in a foreland basin below the pycnocline, followed by the infilling of the basin with shales and coarser clastics. Ettensohn (2012) measured the thickness of the clastic wedges above each black shale to estimate, within an order-of-magnitude, the absolute basin depth. His assumption that sea level is represented by the top of the clastic wedge is affected by the one-time nature of each subsidence event, the possible underfilling of the basin, and the varying effects of compaction. Nevertheless, water depths in the northern Appalachian Basin estimated by this approach range from 80 m to 310 m (250–1000 ft) during deposition of Early Devonian through early Mississippian black, organic-rich muds. The estimates also show a general deepening with time, which may reflect the cumulative effects of tectonic loading, plus rising Devonian sea levels.

The water depths proposed for such a model are unusually deep compared to modern epeiric seas, which tend to have depths of less than 100 m, leading other researchers to suggest that a different model is needed (see Arthur and Sageman, 2005). Several papers have postulated that Appalachian black shales were deposited in quiet, shallow water with little sediment influx on the distal margin of the basin (i.e., Schieber, 1994; Mosher, 2010; Smith and Leone, 2010). Evidence from petrographic studies of both the Utica and Marcellus Shales by Smith and Leone (2010) includes fossil skeletal material found in black shales, described as "calci-silt." The fossil material is composed of fragments from echinoderms, bryozoans, brachiopods, and other animals that typically lived on the sea bottom, not floating in the water column. The presence of these benthic animals suggests that the upper layers of sediment were not permanently anoxic, but possibly just seasonally disoxyic.

These ideas align with a shallow seasonal model for anoxia proposed by Tyson and Pearson (1991). They postulated an early/midspring algal bloom in the water column fed by nutrients released during winter storms. By late spring, the algae had created organic matter that descended to the seafloor as "marine snow." The "snow" consisted of organic matter surrounded by minerals, such as clay, suspended in the water. Such "organomineralic" aggregates helped to protect the organic matter from being eaten as it descended to the seafloor. Shallow water also reduced the descent time, further improving the chances of organics not being consumed on the way down. The water column stratified over the summer, and a redox boundary formed at the sediment-water interface as decay bacteria consumed oxygen. The anoxic conditions halted decay and preserved the organic matter in the sediment. Late fall and winter storms then remixed the water column and brought nutrients back to the surface water.

Smith and Leone (2010) noted that many black shale units in the Appalachian Basin and elsewhere rest on erosional unconformities at the top of the underlying limestones. In addition to the Marcellus Shale, the Rhinestreet Shale, Barnett Shale, Haynesville Shale, Woodford Shale, Pierre Shale, and Bakken Shale all onlap unconformities, suggesting that many black shales formed as part of a distal basin margin transgression onto a surface that may have been eroded during a previous sea-level lowstand.

As the Appalachian Basin filled with sediment and the lithospheric load to the east decreased with erosion of the Acadian highlands, the geographic depositional center for the Upper Devonian black shales moved progressively westward. The Huron and Cleveland Shales were deposited on the flank of the Cincinnati Arch, a structural feature located roughly along the Ohio-Indiana State line, which approximates the western boundary of the Appalachian Basin (Ryder et al., 2012). The Cincinnati Arch was probably not a deep-water environment. The black Antrim Shale in the Michigan Basin has been shown by fossil content (Matthews, 1983) to be the same age as the Huron Shale and identical in character, suggesting that this black shale may have been draped across the Cincinnati Arch during the Late Devonian (374–360 Ma) Period.

The change in sedimentary facies across a basin has been understood in geology for quite some time. Details of such facies were described by Caster (1934) across the Appalachian Basin in northern Pennsylvania. Using fossils as biomarkers, he was able to trace various key beds in the Upper Devonian that changed character significantly from east to west. The sediments grade laterally from nearshore coarse sandy material to offshore finer siltstones and gray shales, and eventually to distal marine black shales and limestones as one moves from the Catskill source area out into the basin. This is illustrated schematically in the cross section shown previously in Figure 3.

Facies can also change vertically with changes in water depth over time, probably driven by sea-level variations. Walker-Milani (2011) identified six different lithofacies in the Marcellus Shale in West Virginia that are related to water energy, depth, oxygen levels, and other factors. The presence of these complex lithofacies would not be expected in the uniform bottom waters of a deep ocean.

The Upper Devonian–age Brallier Formation overlies the Hamilton Group in the central part of the Appalachian Basin and is stratigraphically equivalent to shales to the west. It is composed of quiet-water shales interbedded with turbidity current deposits, known as "turbidites" (Hasson and Dennison, 1978). These are unstable silty and sandy sediments deposited on a slope close to shore that collapsed into an underwater avalanche or landslide. The moving sediments formed a dense, bottom-hugging suspension called a turbidity current, which continued to flow downhill and carried coarse material very long distances (Bouma, 1962). Some of the other coarse Upper Devonian sediments in the eastern part of the basin, such as the Greenland Gap or Hampshire Formations, are shallow-water shelf or storm deposits.

Marcellus Boundaries

The Onondaga Limestone is present beneath most of the Marcellus Shale. It is named for exposures along Onondaga Lake and other locations in Onondaga County, New York (Hall, 1839). The contact of the Marcellus Shale against the Onondaga Limestone is sharp, indicating an abrupt change in depositional environment between the two units across an unconformity. The Onondaga Limestone extends southward from New York at least to northern West Virginia. In assessments done under the Eastern Gas Shales Project (EGSP) for the U.S. Department of Energy (DOE) to determine the gas potential of organic-rich shales in the Appalachian, Michigan, and Illinois Basins, the Onondaga Limestone was recognized below the Marcellus Shale at a depth of 2286 m (7500 ft) in the EGSP WV-6 core drilled at Morgantown in 1978, and at a depth of 2019 m (6625 ft) in the EGSP WV-7 core, drilled in 1978 near New Martinsville, close to the Ohio River (Chen et al., 2015). Toward the eastern margin of the basin, the Onondaga Limestone grades into the time-equivalent Needmore Shale (Willard, 1939), which is named for exposures near the town of Needmore in Fulton County, Pennsylvania.

Several volcaniclastic units known as the Tioga ash beds (see Roen and Hosterman, 1982) occur near the top of the Onondaga Limestone and Needmore Shale and into the base of the Marcellus Shale. Because a volcanic eruption is virtually "instantaneous" as far as geologic time is concerned, ash beds provide excellent markers for the location of the seafloor at a given time. Dennison and Textoris (1988) identified the Kawkawlin Bentonite in the Michigan Basin as a Tioga equivalent, and used the ash as a time-stratigraphic unit to reconstruct the tectonic and depositional environments in the eastern United States at the beginning of Marcellus Shale deposition.

The volcanic eruptions left behind at least eight distinct layers of Tioga ash (Dennison, 1961). Dennison and Textoris (1970, p. 293) indicated that granodiorite plutons "found in Fluvanna County, Virginia are of the correct general age and composition to represent the Tioga magma." A few years later, armed with improved sedimentary thickness and paleowind direction data, Dennison and Textoris (1988) moved the location of the possible source volcano farther northeast, near the present-day city of Fredericksburg, Virginia, and hidden beneath the Blue Ridge overthrust. Plate-tectonics theory suggests that the volcanic eruptions were probably caused by the melting of a descending tectonic plate under the Laurentian continent at the onset of the Acadian orogeny as Gondwana slowly approached across the closing Rheic Ocean (refer back to Fig. 2).

The third type of rock unit, along with the Needmore Shale and Onondaga Limestone, that underlies the Marcellus Shale is the Huntersville Chert, named after the small hamlet of Huntersville along the Greenbrier River in Pocahontas County, West Virginia (Woodward, 1943). The Huntersville Chert is a chemostratigraphic unit formed by the silicification of the Needmore Shale and Marcellus Shale by postdepositional hydrothermal or diagenetic alteration. Some researchers have suggested that the Tioga ash bed might be the source of the silica, because both it and the Huntersville Chert become thicker to the southeast (Woodward, 1943). Although this is the general direction of the assumed Tioga source volcano in what is now the Virginia Piedmont, the idea is hotly debated. Another interpretation is that the silica was provided by windblown dust (Cecil, 2004).

Rowan (2006) created thermal history profiles using wells in the Appalachian Plateau that indicated the existing rocks were once buried as much as 3.8 km (12,500 ft) deeper than their present position. Despite the fact that a great deal of the original surface has been eroded away, the Appalachian Plateau still stands more than 300 m (1000 ft) on average above sea level and is an impressive topographic feature. From central Ohio westward, the sedimentary rocks of the Appalachian Basin thin and pinch out against the Cincinnati Arch.

The gas-producing part of the Marcellus Shale lies primarily beneath the Appalachian Plateau (Zagorski et al., 2012). The rocks here are flat-lying and relatively undisturbed. The shale is still buried quite deeply throughout most of the basin—generally 2–3 km (6000–8000 ft) or more below the land surface. The Marcellus becomes thinner toward the west, eventually disappearing as a feather edge deep underground in Ontario, central Ohio, western West Virginia, and eastern Kentucky (Figure 4). To the south, the Devonian shale section is compressed, and the Marcellus becomes a component of another black shale known as the Millboro Shale, which extends into southwestern Virginia (Butts, 1940).

The only places to view exposed outcrops of the Marcellus Shale at the surface are along the northern and eastern edges of the Appalachian Basin. The northern edge of the Marcellus Shale is exposed in New York State near the Finger Lakes. The rocks here are horizontal and well preserved. The Marcellus Shale sits on top of the Onondaga Limestone, which in turn lies above the Oriskany Sandstone (Figure 5). The Onondaga Limestone and

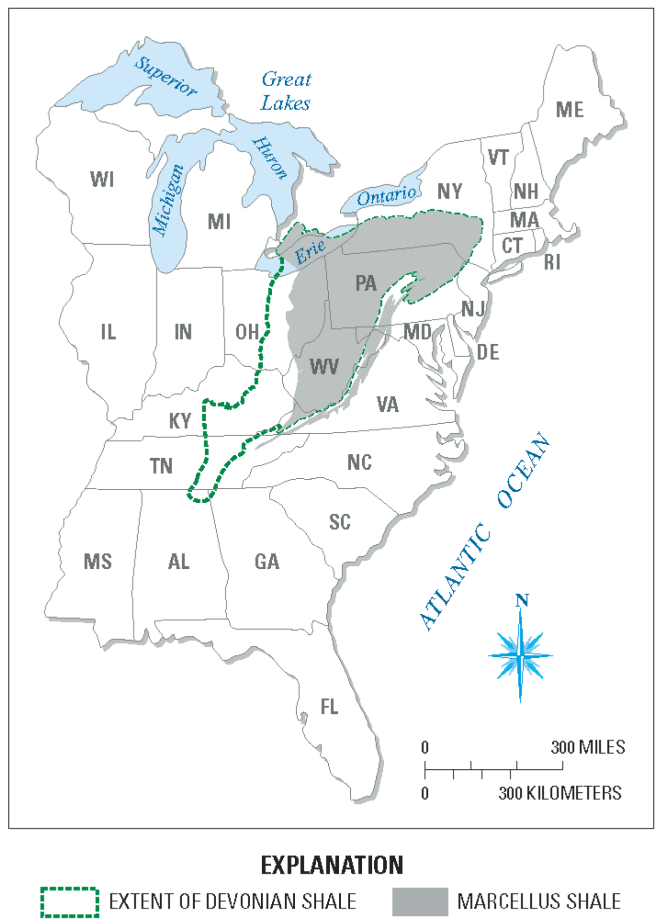

Figure 4. Map showing the lateral extent of the Marcellus Shale in the Appalachian Basin. Map is modified from Soeder and Kappel (2009). WI—Wisconsin; IL—Illinois; IN—Indiana; MI—Michigan; OH—Ohio; KY—Kentucky; TN—Tennessee; MS—Mississippi; AL—Alabama; GA—Georgia; FL—Florida; SC—South Carolina; NC—North Carolina; VA—Virginia; WV—West Virginia; PA—Pennsylvania; MD—Maryland; DE—Delaware; NJ—New Jersey; NY—New York; CT—Connecticut; RI—Rhode Island; MA—Massachusetts; NH—New Hampshire; VT—Vermont; and ME—Maine.

Figure 5. Hanson quarry at Oriskany Falls, New York. Marcellus Shale is at the top left, near the white truck. The base of the Marcellus is the top of the Onondaga Limestone at the upper bench. The Oriskany Sandstone is identified in the quarry wall a short distance below the second bench as a yellowish layer below a small slope break. The rock below the Oriskany is Helderberg Limestone, which is the main production from this quarry. Photograph by Daniel J. Soeder.

the Helderberg Limestone beneath it are quarried at a number of locations in New York. Quarry operators often allow geological sampling of the Marcellus Shale.

In central Pennsylvania and eastern West Virginia, the Marcellus Shale was brought to the surface by folding during the Allegheny orogeny and exposed by erosion (Soeder et al., 2014a). The folds have tilted the originally horizontal shale beds to very steep dips, sometimes nearly vertical (Figure 6). It is occasionally overturned as well. The Oriskany Sandstone is one of the erosion-resistant rocks that form ridges in the Appalachian Valley and Ridge Province. Because many shales look alike, one of the best ways to locate the Marcellus Shale in the Appalachian Mountains is to find an Oriskany Sandstone ridge and then proceed up section to the Marcellus Shale.

Shale is a soft rock, and it was often deformed in these folds as it was squeezed and smeared between harder rocks above and below. This disruption makes folded shale a challenge to map and sample. There may be internal small folds within the shale or faults that cause the section to repeat itself several times in an outcrop (Walker-Milani, 2011). Some Marcellus-Millboro Shale

Figure 6. Steeply dipping beds of Marcellus Shale in a quarry roadcut across the Warm Springs anticline near Berkeley Springs, West Virginia. The originally horizontal beds dip from upper left of photo toward the people in the road at lower right. The grayish rock on the left side of the photo is the Needmore Shale, age-equivalent to the Onondaga Limestone, and below the darker Marcellus Shale. Photograph by Daniel J. Soeder.

locations in Virginia near fold axes contain flatter-lying outcrops that are less deformed (Soeder et al., 2014a).

Outcrop samples have limited value for geological and geochemical analysis due to long-term exposure to weathering, which affects the mineral and organic composition of the rock, as well as the microscopic structure. Also, by definition, these rocks are from the perimeter of the basin, not the central parts where gas is being produced, and it is unclear how closely outcrop samples may correspond to the lithology of the shale being drilled. Many operators have been happy to provide drill cuttings of the shale, but these consist of sand-size particles of limited usefulness. It is difficult and expensive to obtain fresh drill core samples of the Marcellus Shale from deep within the basin, but it is necessary in order to determine certain rock and reservoir properties.

The Marcellus Shale is composed of three primary subunits or members (Figure 7). The basal subunit is the Union Springs Member, named for a town in New York on the eastern shore of Cayuga Lake (Cooper, 1930). It consists of organic-rich, black silty mudstone, siltstone, and limestone. The Union Springs is the most organic and gas-productive part of the Marcellus Shale. It does not contain very much clay, so it lacks significant fissility, typically splitting along bedding planes into slabs or flagstones that are a centimeter to a few centimeters thick (a half inch to a few inches). The high silica content gives these a tendency to shatter like crockery when struck with a hammer. The brittleness of the rock causes it to break easily during hydraulic fracturing.

The sediment-water interface in a stagnant environment with restricted circulation is said to be "euxinic," which is another term often used by geologists to describe black shales. Euxinic is sometimes used erroneously to mean anoxic. Euxinic waters are commonly anoxic, but not always. Likewise, not all anoxic water has the restricted circulation that defines euxinic water. When euxinic waters are sulfur-rich, reduced sulfur minerals like pyrite (iron sulfide) are commonly deposited in the sediment. The Union Springs Member contains abundant pyrite in laminations and small clustered balls called framboids, named for their raspberry-like appearance.

Above the Union Springs Member, there is a dark, organic-rich carbonate member called the Cherry Valley Limestone, named by Cooper (1930) for a location in east-central New York. It is notable for having many open voids or vugs that contain clear calcite and beige-colored dolomite crystals. The Cherry Valley Limestone is not continuous throughout the entire extent of the Marcellus Shale. It was once thought to disappear to the south in central Pennsylvania, although de Witt et al. (1993) established that it extends into northwestern West Virginia based on drill-core data.

Another limestone, called the Purcell Limestone (Cate, 1963), occurs within the Marcellus Shale in southern Pennsylvania and West Virginia. Geologists disagree about whether the Purcell Limestone is present at the exact same place in the stratigraphy that the Cherry Valley Limestone occupies up north, and is thus a southern equivalent, or if it is a totally separate unit that was deposited at a different time than the Cherry Valley Limestone (Lash and Engelder, 2011; Repetski et al., 2012; Chen et al., 2015). The "type section" of the Purcell Limestone occurs deep in a well on the Purcell gas field in Pennsylvania, and when

Figure 7. Marcellus Shale exposure in the Hanson Aggregates quarry in Oriskany Falls, New York. The flat area in the foreground where several people are standing is the top of Onondaga Limestone. The organic-rich Union Springs Member of the Marcellus Shale is above this, overlain by the blocky, meter-thick Cherry Valley Limestone and the Oatka Creek Member. The cobble and gravel material at the top of the exposure is Pleistocene glacial till. Photograph by Daniel J. Soeder.

it was first described by Cate (1963), he suggested that the name be used informally.

The upper subunit of the Marcellus Shale is called the Oatka Creek Member, named for exposures in the bed of the creek that runs through the town of LeRoy, New York (Cooper, 1930). It makes up the bulk of the outcrop at the Marcellus type section (refer back to Fig. 1), and it is less organic and more clay-rich than the Union Springs Member. In the quarry wall photograph shown in Figure 7, most of the Oatka Creek Member is missing due to erosion, and the upper part of the wall consists of much younger Pleistocene glacial gravels and till from the last ice age.

The Oatka Creek is fissile on many outcrops, including the Marcellus type section, because it is rich in clay. Parts of it also contain abundant ball- or lens-shaped concretions, which range in diameter from a few centimeters to a meter or more, and which are usually composed of siderite, an iron carbonate mineral. The Oatka Creek Member grades upward into the overlying Mahantango Shale, gradually becoming less organic-rich and lighter in color.

The upper formation boundary of the Marcellus Shale is hard to locate in drill cores or on outcrops. Most people select it from wireline well-log data. It is formally defined using paleontology by the change in conodonts and other fossils from the Marcellus Shale to the Mahantango Shale (Harris et al., 1994), although this is not something most people can easily recognize in core or on an outcrop. Many operators consider the lower Mahantango Shale to be part of the same gas-productive zone as the Marcellus Shale and count on it for gas from an interval extending several tens of meters above the Onondaga Limestone and across the formation boundary between the two shales.

The microstratigraphy of the Marcellus Shale is much more complex than explained here, because a number of minor members occur in the thicker parts of the formation in NE Pennsylvania and southern New York (Nyahay et al., 2007; Harper, 2008). See the references cited in this section for more details.

PETROLEUM AND NATURAL GAS FORMATION

A brief explanation of some petroleum geology concepts is presented here to help readers understand how gas was emplaced in the Marcellus Shale. For many, many years, the bulk of commercial oil and gas was produced from “conventional” resources. The hydrocarbons in a conventional oil and gas reservoir were usually created elsewhere, and they migrated into the porous, permeable reservoir rock, commonly a sandstone or limestone, where they were trapped. Conventional reservoirs can typically be produced at economic rates with standard vertical well-drilling technologies.

The Marcellus Shale, gas-bearing coal seams, tight gas sandstones, and methane hydrates are known as “unconventional” resources. These hydrocarbons were typically created in place or very closeby from organic material deposited with the sediment. The reservoirs often consist of low-permeability to very low-permeability materials, and require special engineering techniques, such as horizontal drilling and high-volume hydraulic fracturing (HVHF) to produce economic quantities of oil and gas. These resources tend to be less concentrated, but total quantities are often very large, sometimes extending throughout almost the entire volume of the formation.

Conventional Resources

Hydrocarbon resources in conventional reservoirs tend to be high-grade and concentrated. Classical petroleum geology describes a complex process for filling a conventional reservoir with oil and natural gas (Selley, 2014). A number of conditions and events must occur in a specific order and with the proper timing. If anything goes wrong, the end result is no hydrocarbons. This is the reason why exploration for conventional oil and gas requires a deep knowledge of geology, lots of data, and no small amount of luck. Each step in the process is described in more detail next.

Source Rock

Petroleum and natural gas are formed from decayed plant matter trapped in sediment. Initially, there must be an input and preservation of this organic matter when the sediments are deposited. Two common sources of organic material are algae or other water plants, and woody land plants. Some animals may have contributed as well, but most fossil fuel is derived from preserved plant material, not dead dinosaurs. Oxygen is required by the small animals and aerobic bacteria that carry out the decay process, so if the dead plants settle to the bottom in water that contains low levels of dissolved oxygen, the organic matter is often preserved from decay and buried under more sediment. As such, source rocks consist of fine-grained sediments deposited in quiet water, such as black shale.

Once lithified, the organic plant material becomes kerogen, classified into three major types. Type 1 kerogen is waxy and was derived from freshwater algae; type 2 is oily and comes from marine algae that contained oily or fatty organic compounds known as lipids; and type 3 is coaly and was sourced from woody land plants with high cellulose contents. Kerogen derived from algae tends to form petroleum, while woody land plant kerogen forms coal. All three types of kerogen produce methane, the main component of natural gas.

Thermal Maturity

In addition to containing a few percent of preserved organic matter, the source rock sediment had to be buried deeply and subjected to heat and pressure within Earth over geologic time periods in the absence of oxygen. This process is called thermal maturation, and it breaks down the organic carbohydrates into fossil fuel hydrocarbons. Low levels of thermal maturity produce brown “lignite” coal, “wet” gas, and heavy crude oil. High levels of thermal maturity produce high-grade anthracite coal and dry gas, with no surviving liquid petroleum.

Temperatures within Earth increase with depth along geothermal gradients. These vary somewhat with location, but in most places, the temperature increases by ~25 °C with every kilometer of depth (Blackwell and Richards, 2004), or about 20 °F per thousand feet. Deeper burial of a rock means exposure to higher temperatures.

Rocks often retain evidence of their temperature history. One indicator is a black, glassy, organic material called vitrinite that is a component of type 3 kerogen. The material becomes more reflective to light with higher and longer exposure to elevated temperatures. Assessment of vitrinite reflectance, often abbreviated R_o, is a common tool for determining thermal maturity of source rocks.

In rocks where vitrinite is not present, such as those predating the appearance of land plants, or from sediment deposited in an open-marine environment far from land, other thermal indicators can be applied. One is a small, tooth-like fossil called a conodont element. These record the temperature history of the rock by a color change on a scale known as the conodont alteration index, or CAI (Repetski et al., 2008), wherein the fossil becomes a darker-brown color in response to temperature. Another indicator uses a type of tarry organic material called bitumen to assess thermal maturity by reflectance, followed by an empirical conversion to a R_o value. It is less precise than a direct R_o measurement or a CAI determination, but sometimes it is the only indicator available. Bitumen is commonly used on the Utica Shale, which was deposited during the Ordovician Period before there were any land plants in existence.

The burial history of the Marcellus Shale has defined the thermal maturity. In a burial-history analysis for Devonian formations in western New York, Lash (2008) determined that the Marcellus Shale was initially buried quite rapidly during the Upper Devonian and Mississippian Periods beneath the Catskill Delta, which may have been as thick as 4 km (12,000 ft). During the Pennsylvanian Period and into the Permian, the Marcellus was uplifted by the mountain building of the Allegheny orogeny, and some of the delta sediments above it were eroded. Once the higher mountains to the east started eroding more rapidly, the shale was quickly buried again in the Late Permian and Triassic Periods beneath more sediment. This was followed by steady uplift and erosion to the present time.

An assessment of Appalachian Basin erosion by Rowan (2006) concluded that 2–3 km (7000–10,000 ft) of sedimentary rocks have been removed from above the present-day land surface. When added to the current burial depth of the Marcellus Shale, which is still some 1500–2500 m (5000–8000 ft) deep throughout much of the basin, significant parts of the formation must have been buried as deeply as 3500–5500 m (11,000–18,000 ft). The deeper rocks would have been exposed to temperatures above 175 °C (350 °F) for millions of years.

Most measurements of thermal maturity on the Marcellus Shale place it quite high, well beyond the liquid petroleum range. In fact, nearly the only hydrocarbon present in this shale is dry methane gas, with a small percentage of ethane in the shallower, western parts of the formation.

Reservoir Rock

Rocks that produce conventional oil and gas usually consist of coarse-grained sandstones or limestones with high porosity and permeability. The coarse grain size results in larger pore sizes (imagine comparing the void spaces between a stack of BBs and a stack of bowling balls). Larger pores typically have wide pore openings or apertures, known as pore “throats.” Wide pore throats allow hydrocarbons trapped within the pores to flow freely into a well.

There is a catch, of course. In clastic sediments, the larger grains that make up these rocks were deposited by the high-energy water needed to entrain and transport coarse material. High-energy water is not favorable for the deposition of fine-grained sediment and particles of organic matter; these materials were carried off to be deposited elsewhere in a low-energy, quiet-water environment. Even if any organics were by chance trapped with the coarser material, it was likely that they were consumed by microbes and scavengers combing through the aerobic sediment. Good reservoir rocks usually make poor source rocks, and vice versa.

Carbonate rock or limestone reservoirs often increase in porosity after the dissolution of component grains or matrix. This commonly occurs over geologic time when solutions of hydrothermal groundwater pass through the rock and either dissolve out components or cause the carbonate minerals to recrystallize. Both of these processes typically increase porosity.

Trap and Seal

To contain the gas and oil in a conventional reservoir, there must be some kind of a trap, such as a fold or a fault, to displace the rock layers and create an underground structure that acts as a container to hold the hydrocarbons in the reservoir rock. To be effective, the trap must also include a seal made from an impermeable cap rock, such as shale, gypsum, or salt beds. A body of reservoir rock without a trap and seal will not retain any hydrocarbons.

Migration Pathway

Because the source rocks and reservoir rocks are usually completely different formations, once the oil and gas have formed in the source rock, a migration path is needed for these to get from the source rock to a reservoir rock. This can be a through-going fracture, such as a fault that allows movement through the intervening rocks, or just tilted beds that will let hydrocarbons slowly seep updip.

Timing is everything: If the migration pathway is in place before a reservoir rock is available, the oil and gas will be lost. Likewise, if the reservoir rock is present, but no migration path ever develops, the reservoir stays empty.

In summary, an operator will end up with a nonproductive well in a conventional oil or gas reservoir if any one of the five items described above is missing or occurs out of sequence. It is a tribute to the talents of the petroleum geologists and petroleum engineers that virtually all of the oil and gas produced throughout history, until the first decade of the twenty-first century, has been found in conventional reservoirs.

Unconventional Resources

The Marcellus Shale and other gas shales are in a class of hydrocarbon reserves known as unconventional resources. Although "unconventional" is on the way to becoming "conventional" in the minds of some people, the term does have a specific definition. It means that the target formation must be engineered with some type of reservoir stimulation (such as hydraulic fracturing) to produce economical amounts of hydrocarbons.

Gas in the Marcellus Shale was generated in place from thermally mature organic material that had been deposited with the shale. The Marcellus Shale is a classic source rock (Curiale and Curtis, 2016), and in fact it has contributed significant amounts of gas to overlying conventional reservoirs. However, much gas has also remained within this black shale and can be produced directly from it. Gas shales like the Marcellus represent a new concept in petroleum geology: the source rock is also the reservoir rock.

The U.S. Geological Survey refers to gas shales as "continuous resources," to distinguish them from hydrocarbons in traditional traps and seals (Charpentier and Cook, 2011). One can drill and stimulate a well almost anywhere in a continuous resource with the proper production technology and expect to recover economical amounts of hydrocarbons. The amount of recoverable gas in U.S. shale formations vastly exceeds the remaining amount of recoverable gas in conventional reservoirs.

For many years, limits on engineering technology restricted commercial shale gas to places like the Big Sandy field in Kentucky near the West Virginia border, which has been producing gas since the 1920s from vertical wells in the Ohio Shale thanks to a unique set of natural fractures (Hunter and Young, 1953). Expanding this production to other locations and other shales like the Marcellus required the development of new technology, which worked better than anyone had anticipated and made shale gas wells profitable. This has changed the thinking about potential gas resources in the United States.

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