Unconventional natural gas resources in Pennsylvania: The backstory of the modern Marcellus Shale play

Kristin M. Carter, John A. Harper, Katherine W. Schmid, and Jaime Kostelnik

ABSTRACT

Pennsylvania is not only the birthplace of the modern petroleum industry but also the focus of the modern Marcellus Shale gas play. For more than 150 yr, Pennsylvania has experienced a rich history of oil and gas exploration and production, witnessed the advent of modern petroleum regulations, and now sits deep in the heart of the largest domestic shale gas play the United States has ever seen. Although a known source rock for decades, the Marcellus Shale was not considered a viable gas reservoir until Range Resources Corporation (Range) discovered the play with its completion of the Renz No. 1 well in Washington County in October 2004. Using horizontal drilling and hydraulic fracturing techniques used by operators working the Barnett Shale gas play, Range has gone on to complete hundreds of horizontal shale gas wells in Washington County alone. Other operators have followed suit in counties from one corner of the state to the other, and as of June 2011, the Commonwealth has issued nearly 6500 Marcellus Shale gas well permits. Based on publicly reported well completion and production data, an average Marcellus Shale gas well requires 2.9 million gal of water during the hydraulic fracturing process and produces 1.3 mmcf gas/day. Furthermore, the U.S. Energy Information Administration has estimated that as of mid-2011, daily Marcellus Shale gas production in Pennsylvania exceeds 2.8 bcf. Because of the level of drilling activity and production associated with the Marcellus play, Pennsylvania has become the nexus of shale gas production and water management issues.

INTRODUCTION AND PURPOSE

Like any notable subject, Pennsylvania's modern Marcellus Shale gas play has an interesting and complex backstory. The birthplace of the modern petroleum industry, Pennsylvania has experienced

DOI:10.1306/eg.09281111008

AUTHORS

Kristin M. Carter ~ *Pennsylvania Geological Survey, 400 Waterfront Drive, Pittsburgh, Pennsylvania 15222; krcarter@pa.gov*

Kristin Carter has been a geologist with the Pennsylvania Geological Survey since 2001 and currently serves as chief of the Petroleum and Subsurface Geology Section in Pittsburgh, Pennsylvania. Kristin researches oil, gas, and subsurface geology for the Commonwealth and also enjoys petroleum history. Before her employment with the Survey, Kristin worked for nearly a decade in the environmental consulting field, where she investigated matters of groundwater flow and quality, contaminant fate and transport, and mine reclamation. Kristin received her M.S. degree in geological sciences from Lehigh University in 1993 and her B.S. degree in geology and environmental science (double major) from Allegheny College in 1991.

John A. Harper ~ *Pennsylvania Geological Survey, 400 Waterfront Drive, Pittsburgh, Pennsylvania 15222; jharper@pa.gov*

John Harper has been a geologist with the Pennsylvania Geological Survey for more than 34 yr and currently serves as chief of the Geologic Resources Division. His duties include overseeing the work of the Survey's Mineral Resource Analysis and the Petroleum and Subsurface Geology sections, which have been studying various geologic resources in Pennsylvania, including petroleum geology and engineering, coal resources, industrial minerals, and both organic and inorganic geochemistry. During his tenure with the Survey, John has worked on numerous projects dealing with the Commonwealth's oil, gas, and subsurface geology, including Department of Energy–sponsored studies such as the Eastern Gas Shales Project, the atlas of major Appalachian gas plays, A Geologic Playbook for Trenton–Black River Basin Exploration, and the Midwest Regional Carbon Sequestration Partnership. He holds a 1968 B.A. degree in geography and earth science from Indiana University of Pennsylvania, a 1972 M.S. degree in geology from the University of Florida, and a 1977 Ph.D. in paleontology and paleoecology from the University of Pittsburgh.

Katherine W. Schmid ~ *Pennsylvania Geological Survey, 400 Waterfront Drive, Pittsburgh, Pennsylvania 15222; kschmid@pa.gov*

Katherine Schmid joined the Pennsylvania Geological Survey's Petroleum and Subsurface

Geology Section in 2010 as a geologic scientist and conducts oil, gas, and subsurface geology research for the Commonwealth. Before coming to the Survey, Katherine was employed in the oil and gas industry for 5 yr, where her work focused on both organic-rich shale and siliciclastic reservoirs across the state. Katherine received her M.S. degree in geological sciences from the University of Pittsburgh in 2005 and her B.S. degree in geology from the Ohio State University in 1999.

Jaime Kostelnik ~ *Weatherford Laboratories, 16161 Table Mountain Parkway, Golden, Colorado 80403; jaime.kostelnik@weatherfordlabs.com*

Jaime Kostelnik joined the Pennsylvania Geological Survey in 2002 and, until July 2011, served as a senior geologist for the Survey's Petroleum and Subsurface Geology Section. During her tenure with the Commonwealth, her research activities included Appalachian Basin petrology and petrography, sedimentary geology, and organic geochemistry. Jaime recently accepted a position with Weatherford Laboratories in Golden, Colorado, as a senior geologist. She holds an M.S. degree in geology from Wright State University (2001) and a B.S. degree in geology from Juniata College (1999).

ACKNOWLEDGEMENTS

We thank each of our technical reviewers, whose experience and insightful reviews greatly improved the content of this article. In addition, we extend our gratitude to John E. Egers, Jr., who provided critical input to the legal issues discussed herein; to Stuart O. Reese, who contributed valuable information, statistics, and maps regarding private water supplies in Pennsylvania; and to Austin Mitchell, Ph.D. candidate at Carnegie Mellon University's Department of Engineering & Public Policy, who assisted greatly with our analysis of reported hydraulic fracturing water usage for completed Marcellus wells. Last but not the least, we thank the Pennsylvania Department of Conservation and Natural Resources executive staff, including our state geologist, George E. W. Love, for supporting our research endeavors in the field of petroleum geology.

EDITOR'S NOTE

This manuscript was reviewed by six reviewers and accepted for publication by James A. Drahovzal.

a long history of oil and gas exploration and production, much of which predates modern regulation. To be sure, Pennsylvania has been the place of many firsts and important industry developments with respect to both oil and gas. For the purpose of this article, however, we have chosen to focus on discoveries and advancements because they mainly relate to gas drilling and primary production, with the intent of demystifying the Marcellus Shale gas play.

The backstory of the modern Marcellus Shale gas play intertwines science and perception, law and regulation, and begs to be told. Accordingly, this article highlights critical issues regarding the history, geology, water issues, and regulation of Pennsylvania's oil and gas industry, in general, and the Marcellus Shale play, in particular. The intent of this approach is to give readers a better appreciation for improvements in technology, evolution of geologic understanding, and changes in regulatory oversight—all with a view toward how these are being applied today to shale gas resources in the Commonwealth.

HISTORY OF PETROLEUM DRILLING IN PENNSYLVANIA

Pennsylvania is no stranger to oil and gas. Centuries ago, Seneca Indians gathered oil emanating from seeps along Oil Creek in Venango County by installing crude dams along the stream bank using blankets, bark, or cloths to skim oil from the top of the water column (Carll, 1887; Giddens, 1947; Carter and Flaherty, 2011). The early settlers of northwestern Pennsylvania saw how the Seneca made good use of the oil—as a medicine, an illuminant, and more—and found value in this resource as well. It was not until 1768, however, that the first written account of petroleum in Pennsylvania was prepared by David Zeisberger, a Moravian missionary, who observed oil at the confluence of Tionesta Creek and the Allegheny River in Forest County (Giddens, 1947; Carter and Sager, 2010). In fact, it was the oil seeps found throughout the Oil Creek Valley that attracted many investors to investigate this potential resource.

Early Oil

Perhaps the most noteworthy investment in the Oil Creek Valley during the 1850s was made by the Seneca Rock Oil Company, a group of Connecticut-based investors that included Dr. Francis H. Brewer, George H. Bissell, Benjamin Silliman, Jr., and James M. Townsend. The company leased land called the Hibbard farm in Titusville and subsequently retained "Colonel" Edwin Laurentine Drake to visit the site in April 1858 (Carter, 2009; Harper, 2009). No doubt Drake observed the natural oil seeps along Oil Creek and saw the shallow pits dug by Indians to gather the product, but his particular charge, as conceived by Bissell, was to drill a well to extract oil from the ground (Carll, 1887; Giddens, 1947; Brice, 2009). In subsequent months, Drake investigated the drilling techniques of salt-well drillers

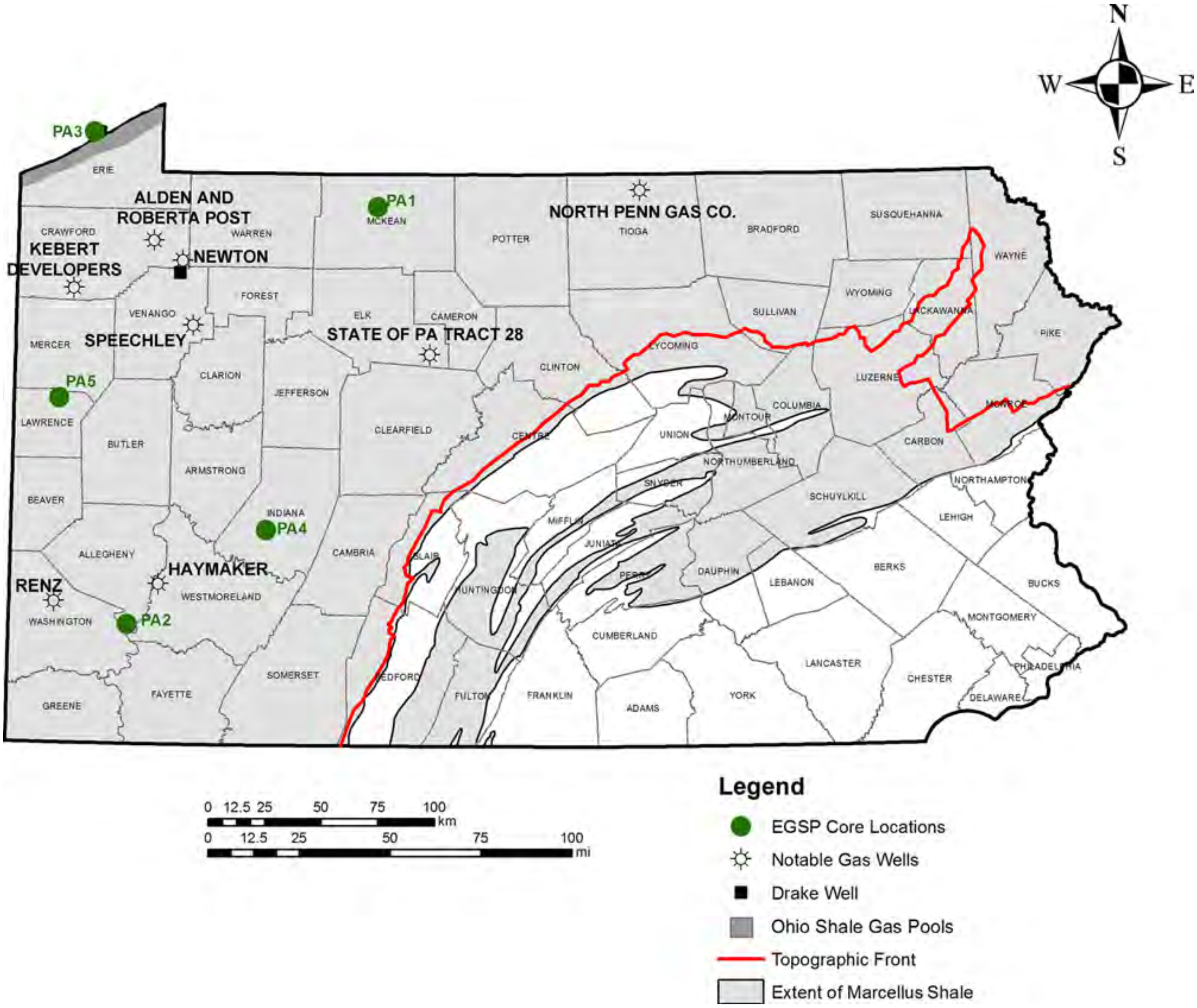


Figure 1. Map of Pennsylvania illustrating the location of notable wells and other relevant features discussed in this article. EGSP = Eastern Gas Shales Project.

operating in the Tarentum area north of Pittsburgh; procured a steam engine and other necessary equipment; and after many efforts to identify a competent, dependable driller, eventually retained William A. "Uncle Billy" Smith. Drilling commenced in June 1859 but encountered several obstacles along the way, such as slow drilling rates, shallow groundwater, and poor borehole integrity. Eventually, Drake struck oil in Titusville (Figure 1) on August 27, 1859, at a depth of 69.5 ft (21.2 m) (Giddens, 1947). Drake's well produced about 40 bbl oil/day initially, but by October 1865, the well was producing only 5 bbl oil/day (Boyle, 1898).

And so with some ingenuity, hard work, and luck, Drake inaugurated the modern petroleum industry by successfully demonstrating the application of salt-well drilling techniques to the extraction of oil from subsurface reservoirs. Soon after the completion of Drake's well, an oil boom ensued throughout northwestern Pennsylvania. Several farms were lease for petroleum drilling and many wells, such as the Crossley, McClintock No. 1, Fountain, Woodford, Sherman, and Noble, became famous as they spewed black gold, producing volumes of tens to thousands of barrels of oil per day (Carter, 2009).

Early Gas

Even before Drake's efforts in Titusville, the other form of petroleum, natural gas, was being explored in northeastern United States. Known as the first commercial natural gas well in the world, the well hand dug by William Hart in Fredonia, New York, in 1821 was completed to a depth of 27 ft (8 m) using a pick and a shovel. By 1825, it supplied several users in the area with enough gas for lighting purposes. In 1850, Hart's well was deepened to 50 ft (15 m), at which time it was piped to Fredonia's Main Street to light not only the street lights but also the stores and local hotel (Henry, 1873; Brice, 2009; Harper and Kostelnik, 2010). Of course, after the Drake well, both oil and gas wells were drilled.

The earliest shale gas wells of record in Pennsylvania were drilled in 1860 in Erie County (Figure 1) (Ashley and Robinson, 1922). These wells, drilled near the Lake Erie shoreline, produced only minor amounts of gas from the Upper Devonian Ohio Shale, yet were enough to spawn further drilling. Between 1860 and 1878, three gas pools were identified: Erie, Fairview, and Northeast (Ashley and Robinson, 1922). Although no specific well records could be located for these early wells, White (1881, p. 120) provided some level of detail:

"The gas and oil wells at Erie vary in depth from 450′ to 1200′. Deming's planning mill well got gas at 453′ (i.e., in Portage layers 650± from the top down). The average depth of gas flow is about 600′..."

By all accounts, the first commercial gas well drilled in Pennsylvania was the Newton Well (Figure 1) in Oil Creek Township, Crawford County. This well was completed to a depth of 786 ft (240 m) on May 11, 1872, and produced from the Upper Devonian Venango Group (Third Sand of drillers) (Henry, 1873). From the Pennsylvania Geological Survey (the Survey)'s historical well card file:

"The flow of gas from this well when first struck has been estimated at 5,000,000 ft^3/day. In 1877, an attempt to make an accurate measurement of it was made by means of a geometer prepared for the purpose, but the volume of gas was so great that the effort failed. Shortly after the well was struck, pipes were laid to Titusville, and the gas was introduced into many dwellings and used by refiners and others for heating purposes. It is still used in this manner as far as the well is able to supply them. The flow has gradually decreased from the start and is now (March 1877) comparatively small."

Indeed, the Newton Well made headlines for both its open flow and the fact that it necessitated a 5.5-mi (8.9-km) pipeline to Titusville. Noted by John Carll (1887, p. 600) as "the first natural gas plant of the kind in the country" in his annual report on the oil and gas region of Pennsylvania, the Newton Well and pipeline furnished heat and light to approximately 250 residents and local industry. Subsequent Survey reports also referred to the Newton Well's commercial-scale production, but because no detailed records were kept on Pennsylvania oil and gas production until 1882, the actual productivity of the Newton Well cannot be quantified (Sisler et al., 1933).

The famous Haymaker No. 1 well (Figure 1) was completed on November 3, 1878, on the Remaley farm in Murrysville, Westmoreland County (Johnson, 1925), and was reported by Carll (1887, p. 673) as a flowing gas well that was producing "with unabated volume." The well produced gas at a depth of 1320 ft (402 m) from the Upper Devonian Murrysville Sandstone, discovering the gas field of the same name (Carll, 1887). Based on the success of this well, several others were drilled in the same area, along the Murrysville anticline, and recorded initial open flows of several million cubic feet of gas (Johnson, 1925). The Haymaker well has been credited with the success of electric light utilities (Westinghouse and others) and many glassmaking factories throughout southwestern Pennsylvania.

Another gas producer of comparable notoriety was the Speechley Well (Figure 1) in Pinegrove Township, Venango County. This well was drilled on the Samuel Speechley farm at Coal Hill in 1885 and is identified on historical maps as United Natural Gas Company Well No. 157 (Dickey et al., 1943; Dickey and Matteson, 1945) and in Pennsylvania's current-day Pennsylvania Internet Record Imaging System/Wells Information System (PA*IRIS/WIS) as Permit No. 121-01747. No production records for the Speechley Well are available because the well was never gauged, but Dickey et al. (1943) reported that the well's open flow was very large and that it supplied enough gas for all of Oil City.

The notable wells discussed above are only a few of the many thousands of gas wells that have produced from the Upper Devonian during the past 100 yr. Pennsylvania has produced more than 12 tcf of gas during the last century, most of which (~10 tcf) was produced from these shallow reservoirs (Pennsylvania Internet Record Imaging System/Wells Information System, 2011).

Twentieth Century and Beyond

The extent and scope of Pennsylvania's petroleum exploration continued to grow in the 20th century. At the height of the Great Depression in the 1930s, operators were drilling deep wells in north-central Pennsylvania to extract gas (likely sourced by the Marcellus Shale) from the Lower Devonian Oriskany Sandstone. The first Oriskany gas well, the North Penn Gas Company No. 1143 (Figure 1), was completed on September 11, 1930, discovering the Tioga gas field in Tioga County (Kostelnik and Carter, 2009). This activity continued and expanded throughout western and north-central Pennsylvania at large for several decades. By 1980, the Oriskany reservoir was found to produce in different physiographic settings and under multiple trapping mechanisms and also served as a very effective gas storage reservoir (Pennsylvania Department of Conservation and Natural Resources, 2009). Of the approximately 1700 Oriskany gas wells drilled in Pennsylvania to date, more than 1000 are still active as gas producers, gas storage wells, or observation wells (Kostelnik and Carter, 2009).

Another frequently drilled siliciclastic gas-producing reservoir is the Lower Silurian Medina Group of northwestern Pennsylvania and its equivalent Tuscarora Sandstone in central Pennsylvania. Although surrounding states and Canada discovered and were producing this particular reservoir since the late 1800s (McCormac et al., 1996) and Pennsylvania operators first discovered gas in the Medina in 1947, operators did not produce the Medina extensively until the mid-1970s (Laughrey, 1984). Many of the Medina wells completed in the late 1970s and early 1980s in Pennsylvania and surrounding states were related to the Federal Energy Regulatory Commission's designation of the Medina Group play as a "tight" sand in these areas. This enabled producers to receive tax credits for wells producing from Medina reservoirs (McCormac et al., 1996). The reservoir characteristics of two particular Medina-producing fields in Pennsylvania, the Athens and Geneva fields of Crawford County, were evaluated in detail by Laughrey (1984). The discovery well for the Athens field, the Alden and Roberta Post No. 1 (Figure 1), was completed by Columbia Gas Transmission Company on September 20, 1974. The Greenwood pool of Geneva field was discovered by the Kebert Developers No. 1 (Figure 1) and completed by N-Ren Corporation on November 7, 1975 (Laughrey, 1984). Although not as prolific as it once was, the Medina Group is still drilled for gas in Pennsylvania today.

Fast forward to the 21st century, Pennsylvania found itself in the middle of another prospective deep gas play. Although recognized as a viable gas play along the perimeter of the Appalachian Basin since the mid-1880s (Wickstrom, 1996), Ordovician carbonate rocks of the Trenton and Black River formations were not explored seriously in Pennsylvania until the early 2000s. Historical Trenton-Black River production occurred along the Lima-Indiana trend of Ohio and Indiana (westward of the basin) between mid-1885 and the 1930s (Wickstrom, 1996). The more recent Trenton-Black River play resulted in the organization of a consortium of universities, operators, producing companies, and geologic surveys that prepared a comprehensive basin-wide geologic play book for the fractured and sometimes hydrothermally altered reservoir. In Pennsylvania, Trenton-Black River rocks have been structurally and hydrothermally altered to varying degrees, depending on location (Patchen et al., 2006). To date, less than a dozen gas wells have reported production from the Trenton-Black River reservoir in Pennsylvania.

The modern Marcellus Shale gas play was established with the completion of the vertically drilled Renz No. 1 (Figure 2) in Mount Pleasant Township, Washington County, Pennsylvania, by Range Resources Corporation (Range) in 2004 (Pennsylvania Internet Record Imaging System/Wells Information System, 2011). Originally drilled in 2003 with deeper Devonian and Silurian targets in mind, Range revisited this well in October 2004 to hydraulically fracture (or "frac") the organic-rich parts of the Hamilton Group, which reported very large gas shows during drilling operations the year before. Range began producing shale gas at the Renz No. 1 in 2005 and subsequently used drilling and hydraulic fracturing techniques used by Texas operators in the Barnett Shale gas play to drill hundreds of horizontal shale gas wells in Washington County alone (Harper and Kostelnik, 2010; Pennsylvania Internet Record Imaging System/Wells Information System, 2011). The Marcellus play truly represents an unconventional gas play in that (1) the organic materials that generated the natural gas have remained in the shale, (2) the reservoir and seal characteristics are markedly different from those in a conventional petroleum system, and (3) reservoir porosity and permeability are very low. The terms "Marcellus Shale" and "Marcellus play," as referred to in this article, represent all organic-rich shales in the Middle Devonian Hamilton Group and not strictly to the Marcellus Formation alone.

This section has provided only a brief overview of the many oil- and gas-producing reservoirs within Pennsylvania's borders. Note that although the research community, industry, and media may periodically focus on one play or another, the industry continues to develop these many resources throughout Pennsylvania to the current day.

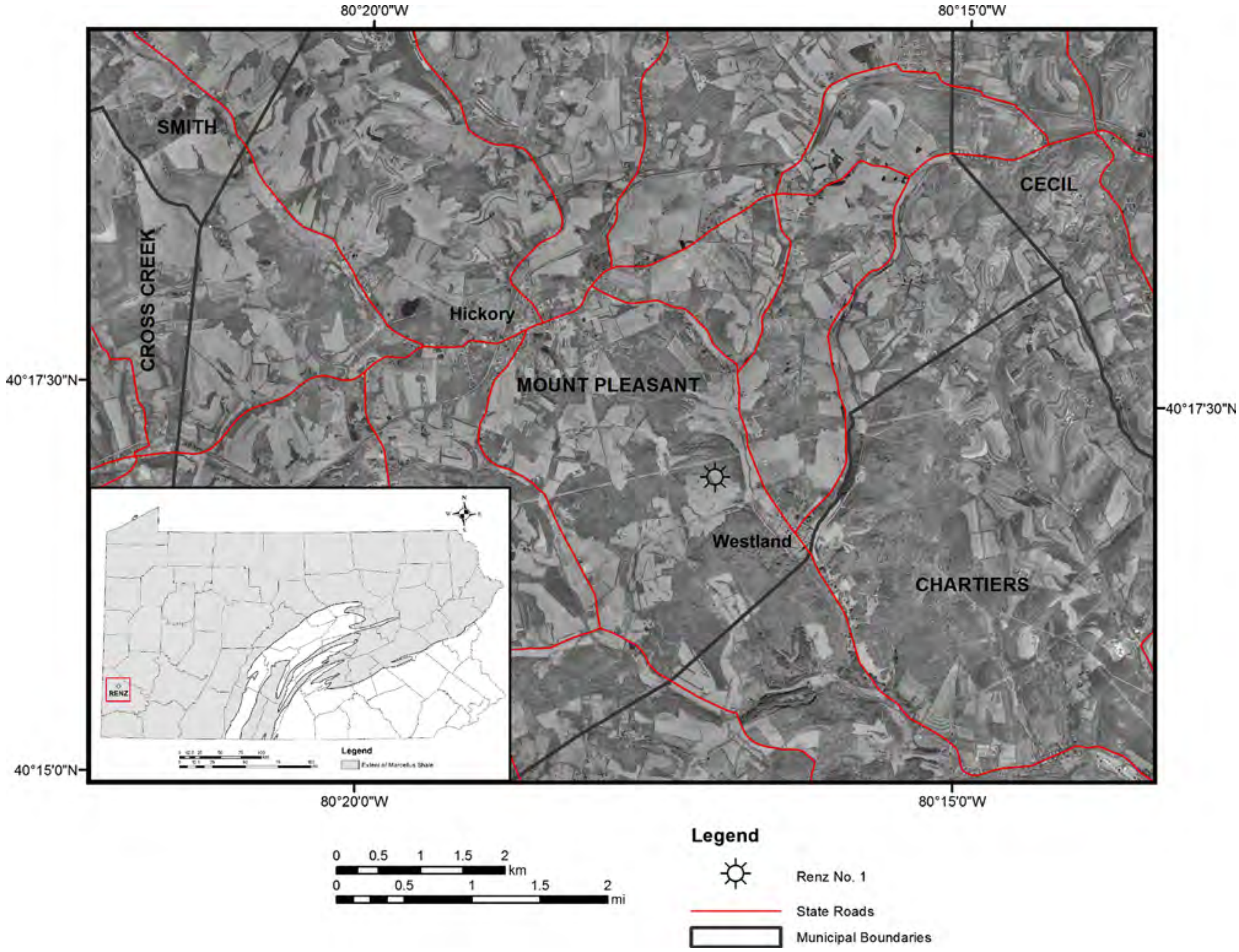


Figure 2. Location of the Renz No. 1 well (Mount Pleasant Township, Washington County), the discovery well for the modern Marcellus Shale gas play.

EVOLUTION OF WELL STIMULATION TECHNOLOGIES

Before the wide-scale deployment of hydraulic fracturing, Pennsylvania's shallow oil and gas wells were typically stimulated or "torpedoed" by shooting with nitroglycerin or black powder to break up rock exposed in the open part of the borehole, thereby creating fractures that enhanced the flow of hydrocarbons (Fettke, 1951, 1952a, 1953, 1954; Lytle, 1965). Because shooting was dangerous and commonly unpredictable, the introduction of hydraulic fracturing was a welcome change, and the practice of shooting dropped off precipitously by the late 1950s except in certain areas of eastern Kentucky and southern West Virginia (Moore, 1959).

The practice of hydraulic fracturing to enhance oil and gas well production dates back to 1949, when Stanolind Oil and Halliburton conducted commercial-scale hydraulic fracturing at wells in Oklahoma and Texas (Range Resources LLC, 2010; Petroleum Transfer Technology Council, 2011). In fact, Halliburton was the first to patent the so-called "hydrafrac" process, which gave exclusive rights at the time to pump relatively large volumes of fluid and sand (proppant) under high pressure into oil and gas wells to stimulate production. Pumping rates during these hydraulic fracturing jobs increased from a couple barrels of fluid per minute in the 1950s to 20 bbl/min by the 1960s (Petroleum Transfer Technology Council, 2011). The most commonly used frac fluids between 1949 and 1954 were crude oil, kerosene, and acid either in their natural state or as a gel, but by the late 1950s, more than 20% of the hydraulic fracturing jobs in the Appalachian Basin were using water as the frac fluid (Moore, 1959). Changes in the size of frac jobs occurred as well, as the petroleum industry observed how the use of larger volumes injected at higher pressures

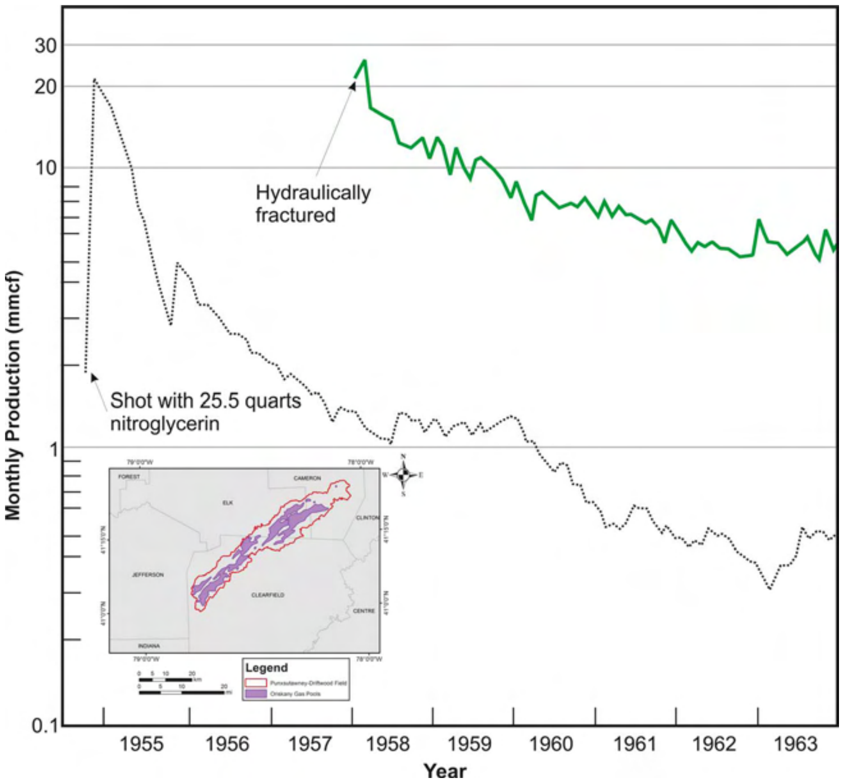


Figure 3. A tale of two wells in Punxsutawney-Driftwood field, Clearfield County (see inset map). Cumulative production as measured in 1963 was as follows: the hydraulically fractured well produced 625 mmcf (6-yr period), whereas the shot well produced 242 mmcf (9-yr period). (Modified from Lytle, 1965, and reprinted with permission of the Interstate Oil and Gas Compact Commission).

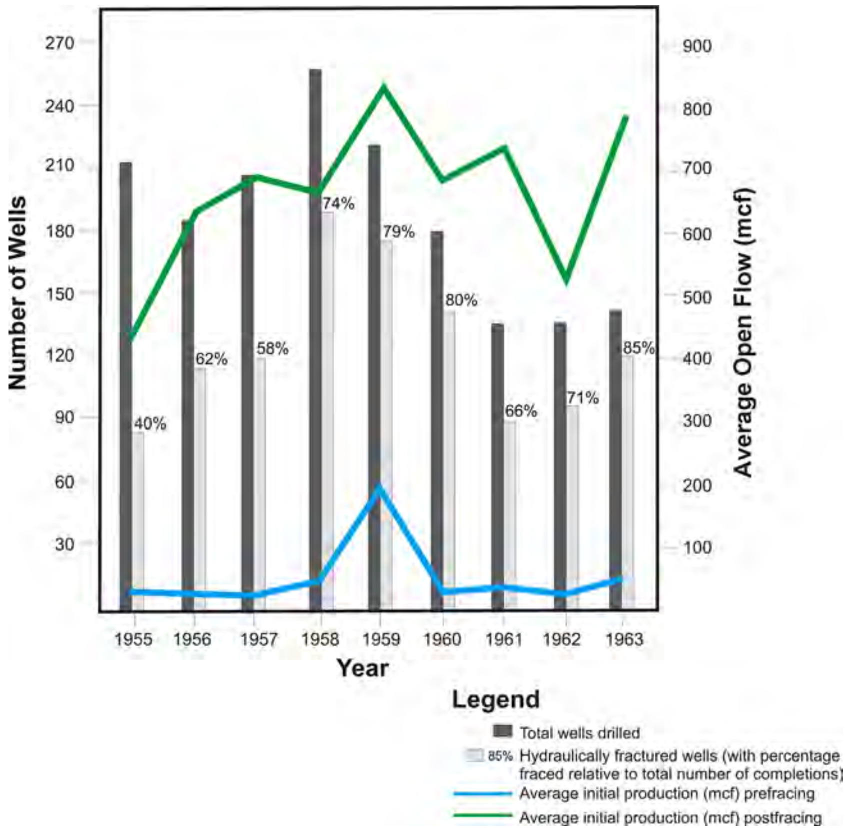
resulted in better oil and/or gas production from the reservoirs. As a comparison, data gathered at the end of 1954 showed that the average volume of fluid used during the hydraulic fracturing process was 2000 to 4500 gal (7571–17,034 L). In just 5 yr, these volumes had increased an order of magnitude from 12,000 up to 20,000 gal (45,425–75,708 L) in the deep gas-producing areas of Pennsylvania (Moore, 1959).

The first application of hydraulic fracturing to deep gas wells in Pennsylvania was performed in December 1953 at the State of Pennsylvania Tract 28 No. 3 well, situated in Punxsutawney-Driftwood field, Elk County (Figure 1). The well produced 1.1 mmcf after fracing (Fettke, 1954). By the middle of 1954, hydraulic fracturing was becoming more popular and successful in Pennsylvania (Moore, 1959; Lytle, 1965). Hydraulic fracturing of deep gas reservoirs focused mainly on the Oriskany Sandstone and Middle Devonian Huntersville Chert and used large volumes of water, up to 20,000 gal (75,708 L) of water containing as much as 20,000 lb (9072 kg) of variously sized sand grains (Moore, 1959). An example of improvements in production created by hydraulic fracturing is shown in Figure 3 using data from two Oriskany wells in Punxsutawney-Driftwood field, Clearfield County. Even several years after treatment, the fraced well's monthly production was approximately 11 times greater than the shot well. By 1963, more than 70% of the deep gas wells drilled in Pennsylvania were stimulated using hydraulic fracturing techniques (Lytle, 1964).

Since the mid-1950s, hydraulic fracturing became more frequently applied not just to newly drilled deep gas wells, but also to new shallow oil and gas wells, producing and service wells associated with secondary oil recovery, and even gas storage wells (Moore, 1959; Lytle, 1965). Shallow oil and gas wells were typically fraced with crude oil or kerosene gel because crude was readily available from other locally producing wells (Moore, 1959). In 1955, fracing was applied to 40% of the shallow gas wells completed in Pennsylvania and was responsible for a 15-fold increase in average open flow (Fettke and Lytle, 1956). In 1956, 62% of Pennsylvania's shallow gas wells were hydraulically fractured, which increased their average open flow by 23 times (Lytle, 1957). By 1963, 85% of newly drilled shallow gas wells were fraced, and their corresponding open flows increased as much as 27 times (Lytle, 1964, 1965) (Figure 4).

The hydraulic fracturing of shallow oil sands, in contrast, was not used until 1963. The Cemetery Lot Well No. 6, completed in Pleasant Township, Warren County, produced oil from the Upper Devonian Bradford Group (Glade sand of drillers) and was the first oil well in primary production to be successfully stimulated via hydraulic fracturing in Pennsylvania (Rough and Eckard,

Figure 4. Summary of hydraulic fracturing activity (bar graph) and corresponding production volumes (linear plot) in Pennsylvania's shallow gas wells during the period of 1955 to 1963 (modified from Lytle, 1965, and reprinted with permission of the Interstate Oil and Gas Compact Commission).



1963; Lytle, 1964). The well produced 50 bbl oil/day after fracing and, after several months, had produced more than 1600 bbl, giving Warren County a great boost in oil production in 1963 (Lytle, 1965). Data presented by Rough and Eckard (1963) for these Glade sand-producing wells indicated that newly completed wells had higher production rates postfracing than older wells stimulated using the same technique and that newly drilled oil wells in this area of Warren County produced 12 times more than those completed using more traditional shooting techniques.

ADVENT OF MODERN OIL AND GAS REGULATIONS

Introduction

The statutory and regulatory history of the oil and gas industry in Pennsylvania is not as extensive as its legacy of drilling and production. The state's regulatory agency, the Pennsylvania Department of Environmental Protection (DEP), has estimated that since the completion of the Drake well in 1859, more than 350,000 oil and gas wells have been drilled in the Commonwealth (Department of Environmental Protection, 2009a), of which the state has some form of record for approximately 180,000 (Pennsylvania Internet Record Imaging System/Wells Information System, 2011). Countless statutes and regulations have been enacted during this time frame, but only a small number pertain to the exploration and development of petroleum resources. This section offers a historical synopsis of oil and gas laws and regulations from the late 1800s through the current day, noting those that have particular relevance to the development of Marcellus Shale gas resources. It is by no means intended to provide a comprehensive discussion of the legal or regulatory issues associated with the exploration and development of oil and gas resources in Pennsylvania.

As a preface to this discussion, the following definition of terms is warranted. The body of documentation used to regulate the oil and gas industry in Pennsylvania is composed of both statutes and regulations. "Statutes" are laws enacted by the Pennsylvania legislature. In contrast, "regulations" are certain rules written by those working with the state executive branch, sometimes in conjunction and collaboration with industry and the public, and are adopted into the Pennsylvania Code to enforce statutes in more detail. Ultimately, all statutes and regulations are consistent with the Pennsylvania State Constitution.

The Industry's First Century in Pennsylvania

The earliest oversight of Pennsylvania's petroleum industry came in May 1891, at which time the state legislature passed two statutes; one relating to the plugging of abandoned wells and the other granting right of action to those who provided labor and/or materials for oil and gas well installation or production (Burcat, 2008; U.S. Department of Energy, 2009). These statutes were followed by four more in 1921, which related to well owner rights, well-plugging methods, and penalties for mismanagement of oil and gas wells (Burcat, 2008). Although these particular laws are roughly a century old, they are still in effect in Pennsylvania.

Originally enacted in June 1937, Pennsylvania Act 394, the Clean Streams Law, is another important statute that relates to petroleum development. The Clean Streams Law has been amended several times, as recently as October 2006, and has as its goal not only to protect but also enhance the quantity and quality of water available to Pennsylvanians (Department of Environmental Protection, 2011d).

The next interjection of Commonwealth statutes occurred during the mid-20th century. On November 30, 1955, the Pennsylvania legislature passed Act 225, the Gas Operations, Well-Drilling, Petroleum and Coal Mining Act. The specific purpose of this statute was to address standards for drilling oil and gas wells in areas where coal mining was occurring (Department of Environmental Protection, 2001). Nearly 6 yr later, in July 1961, Pennsylvania Act 359, known as the Oil and Gas Conservation Law, was passed. The intent of this statute was to encourage efficient means of petroleum exploration and development while protecting the rights of both producers and subsurface rights owners (Burcat, 2008; Department of Environmental Protection, 2011c). In particular, Act 359 applies only to those oil or gas wells that have penetrated to the top of the Middle Devonian Onondaga Limestone (or its stratigraphic equivalent) and have been drilled to depths in excess of 3800 ft (1158 m). The act established permitting, well spacing, and unitization requirements for such wells (Department of Environmental Protection, 2011c).

Modern and Current Regulation

In December 1984, two additional statutes were passed by the Pennsylvania legislature, the Coal and Gas Resource Coordination Act and the Oil and Gas Act. The first of these, the Coal and Gas Resource Coordination Act (Pennsylvania Act 214), is very specific in scope; it applies only to those instances where gas wells may be drilled in areas where workable coal is present and intends to minimize legal disagreements between the subsurface rights owners where both resources will be extracted (Burcat, 2008; Department of Environmental Protection, 2011a). This act was amended in May 2011 to address shale gas drilling techniques that have been increasingly used in Pennsylvania in recent years and is now referred to as Act 2 of 2011. As an example, the current act addresses the shale gas industry's use of centrally located well pads to complete multiple horizontal wells, otherwise defined as "well clusters" (E. Draper, 2011, personal communication).

The second statute enacted in 1984 was the Oil and Gas Act (Pennsylvania Act 223). It repealed Act 225 of 1955 altogether and, for nearly 30 yr, has served as the Commonwealth's primary legislation for regulating the petroleum industry and protecting the environment. The Oil and Gas Act not only provided the state with a more comprehensive approach to regulating the industry but also required operators to report drilling and production details, necessitated bonding requirements, and provided safeguards for water and wetlands (Burcat, 2008; Department of Environmental Protection, 2011b).

Based on the authority of these and other Pennsylvania statutes, the executive branch adopted further provisions and rules related to oil and gas exploration and development. Specifically, chapter 78 of the Pennsylvania Code was adopted in August 1987 and is based on the authority provided, in part or in whole, by the Oil and Gas Act of 1984 and the Coal and Gas Resource Coordination Act of 1984. Chapter 79 of the Pennsylvania Code addresses the issue of oil and gas conservation, under the authority of the Oil and Gas Conservation Law of 1961, and was adopted in August 1971.

Federal Oversight

By the late 1980s, work was being done at the federal level to evaluate whether waste derived from the oil and gas industry should be exempted under the 1976 Resource Conservation and Recovery Act (RCRA) Subtitle C or its 1980 amendments (U.S. Department of Energy, 2009). In July 1988, the U.S. Environmental Protection Agency (EPA) issued a determination that such wastes should not be regulated under RCRA Subtitle C and that the EPA would support state efforts to enhance their respective regulatory programs (U.S.

Department of Energy, 2009). In 1989, the Interstate Oil Compact Commission (predecessor to today's Interstate Oil and Gas Compact Commission) formed the Council on Regulatory Needs and worked with the EPA, the states, industry, and various stakeholders to evaluate state oil and gas regulatory programs across the country. This study, which addressed state regulation of petroleum exploration and production wastes, was published in 1990 and is more commonly referred to as the "1990 Guidelines" (U.S. Department of Energy, 2009; State Review of Oil and Natural Gas Environmental Regulations, 2010). As part of their continuing work, the Council revised and updated these guidelines in 1994. This multidisciplinary committee of regulators, industry, and stakeholders eventually became a nonprofit oversight group in 1999, now named State Review of Oil and Natural Gas Environmental Regulations, Inc. (STRONGER) (U.S. Department of Energy, 2009; State Review of Oil and Natural Gas Environmental Regulations, 2010). Since then, STRONGER has revised the guidelines for review of state oil and gas regulatory programs twice and, in 2009, formed a hydraulic fracturing workgroup to evaluate fracing issues and put forth guidelines to address them (State Review of Oil and Natural Gas Environmental Regulations, 2010). To this end, the DEP worked with STRONGER in 2010 to formally evaluate Commonwealth's hydraulic fracturing program (State Review of Oil and Natural Gas Environmental Regulations, 2010).

Recent Regulatory Changes in Pennsylvania

For the last couple of years, the DEP has been working on changes to chapter 78 of the Pennsylvania Code to address certain issues related to Marcellus Shale exploration and development. Issues of particular concern include incidents of well control and stray gas migration, new ways of drilling and completing unconventional gas wells (specifically, horizontal drilling and massive frac jobs), disclosure requirements for additives used in frac fluids, and the production reporting mandated by Pennsylvania Act 15 of 2010 (English, 2011). On February 5, 2011, the new rulemaking went into effect and is reflected in significant revisions to subchapter D of chapter 78, as well as certain changes to subchapters A, C, and E. The most noteworthy changes to subchapter D involve well control, well construction standards (in particular, casing and cementing work), existing well integrity, response to stray gas issues, and matters of well reporting (English, 2011).

As of June 2011, the DEP continues to evaluate further revisions to chapter 78 of the Pennsylvania Code, intending to revise regulations involving well plugging, environmental protection performance standards, and other necessary improvements, as needed (English, 2011).

THE EASTERN GAS SHALES PROJECT

In the 1950s, the United States had a seemingly unlimited supply of oil and natural gas. By 1968, however, that supply began to diminish as demand exceeded the reserves being added by exploratory drilling (Roen, 1993). In October 1973, members of the Organization of Arab Petroleum Exporting Countries began an oil embargo in response to the U.S. decision to resupply the Israeli military during the Yom Kippur war earlier that month. This was the beginning of an "energy crisis" that lasted throughout the 1970s. As a result, the U.S. began to recognize the necessity of expanding research and development into alternative forms of energy. To facilitate this, the Energy Research and Development Administration (ERDA) was created in 1975 to combine the federal government's activities into a single agency. The following year, ERDA initiated the Enhanced Gas Recovery (EGR) Program to focus research efforts on unconventional natural gas resources such as "tight" gas sands, ultradeep reservoirs, and organic-rich shales. As the energy crisis extended into the late 1970s, all of the federal energy agencies were reorganized into the U.S. Department of Energy (DOE). The DOE's primary goal was to provide incentive to overcome the inertia associated with commercial development of the nation's energy resources, including unconventional resources (Smith, 1977).

One of the EGR programs within DOE's purview, the Eastern Gas Shales Project (EGSP), was initiated to evaluate the gas potential of, and to enhance gas production from, the extensive Devonian and Mississippian organic-rich black shales within the Appalachian, Illinois, and Michigan basins in the eastern United States. The EGSP program had two purposes: (1) determine the extent, thickness, structural complexity, and stratigraphic equivalence of all Devonian organic-rich shales throughout the three basins and (2) develop and implement new drilling, stimulation, and recovery technologies to increase production potential (Harper, 2008). Teams of geologists from the U.S. Geological Survey, various state geological surveys, and universities

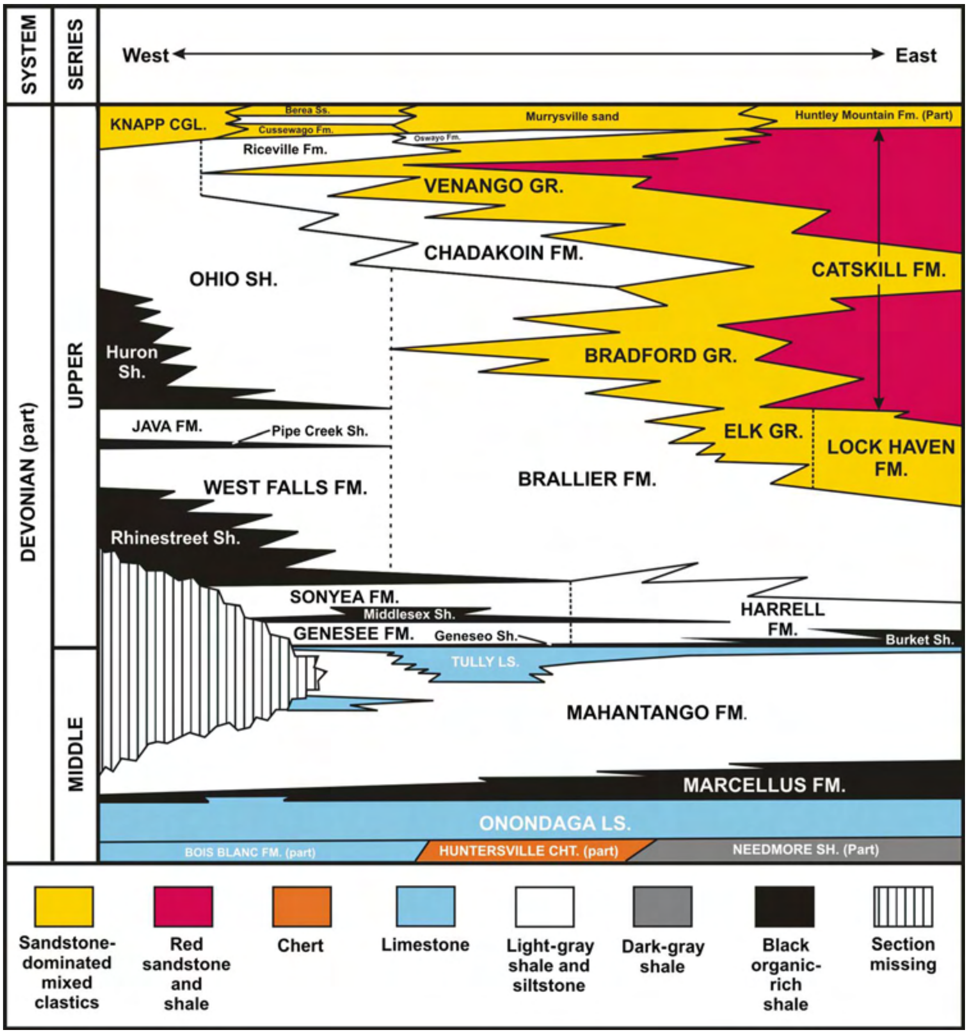


Figure 5. Correlation diagram of Middle and Upper Devonian formations in western and north-central Pennsylvania (modified from Carter, 2007) FM. = Formation; SH. = Shale; GR. = Group; LS. = Limestone; CHT. = Chert.

correlated and mapped the stratigraphy and structural geology. For example, the Survey team spent several years correlating wireline logs and performing basic mapping of the Upper Devonian Ohio, Java, West Falls, Sonyea, and Genesee formations and of the Middle Devonian Hamilton Group, which includes the Marcellus Shale at its base (Figure 5). Geophysicists developed new technologies to locate fracture systems in the shales that could be potential reservoirs. Teams of geochemists investigated ways to modify the shale matrix to increase gas flow. Engineers derived and tested both mathematical and practical models of various fracturing techniques and directional drilling procedures. And while all of these were occurring, industry drilled and cored numerous test wells in each of the states involved in EGSP. Five wells were drilled in Pennsylvania (Figure 1; Table 1), and cores of the Devonian shales collected from each provided a wealth of data regarding bedding, mineralogy, fracture systems, and so forth.

Gamma-Ray Log Interpretation

Eastern Gas Shales Project researchers used gamma-ray logs as the primary source of data for correlating strata and determining net thickness, as outlined by Piotrowski and Harper (1979) and Schmoker (1981). Almost all of the natural gamma radiation emitted from rocks is caused by the radioactive potassium isotope (K-40) found in feldspars, micas, and other common silicate minerals. Shale, composed primarily of clay minerals, has a significantly higher K-40 content than sandstones or carbonates, so that it is relatively easy to distinguish most of these rock types on wireline logs. In addition, elements of the uranium and thorium series can be found in minor amounts in many sedimentary rocks. Marine organic-rich black shales, in particular, have higher than normal radioactivity responses. Although thorium is insoluble in water and remains stable during diagenesis, uranium forms highly soluble uranyl compounds in oxidizing

Table 1. List of EGSP Wells in Pennsylvania*

EGSP** Well No.	Permit No.	County	Well Name	Date Logged
PA1	083-37291	McKean	Minard Run Exploration No.1	February 1979
PA2	003-20980	Allegheny	Combustion Engineering No. 1	March 1979
PA3	049-20846	Erie	Presque Isle State Park No. 1	October 1979
PA4	063-25073	Indiana	Glen McCall No. 5	November 1979
PA5	073-20022	Lawrence	Sokevitz No. 1	December 1979

*See Figure 1 for locations.
**EGSP = Eastern Gas Shales Project.

environments that reduce to tetravalent uranium ions by organic matter in reducing environments such as organic-rich muds (Adams and Weaver, 1958; Leckie et al., 1990). This uranium is then concentrated in the sediments by being fixed in organic complexes, adsorbed on organic material, or adsorbed on clay minerals. In addition, Veeh (1967; also Veeh et al., 1974) found that some sedimentary rocks absorb uranium from seawater. Marine black shales typically have uranium concentrations between 4 and 25 ppm and may approach 100 ppm, although values between 25 and 55 ppm are considered anomalous and values greater than 55 ppm are considered to be ore concentrations (Kochenov and Baturin, 2002). Thus, relatively high gamma-ray log responses typically define organic-rich shales (Figure 6). In those areas where shale-gas production had been

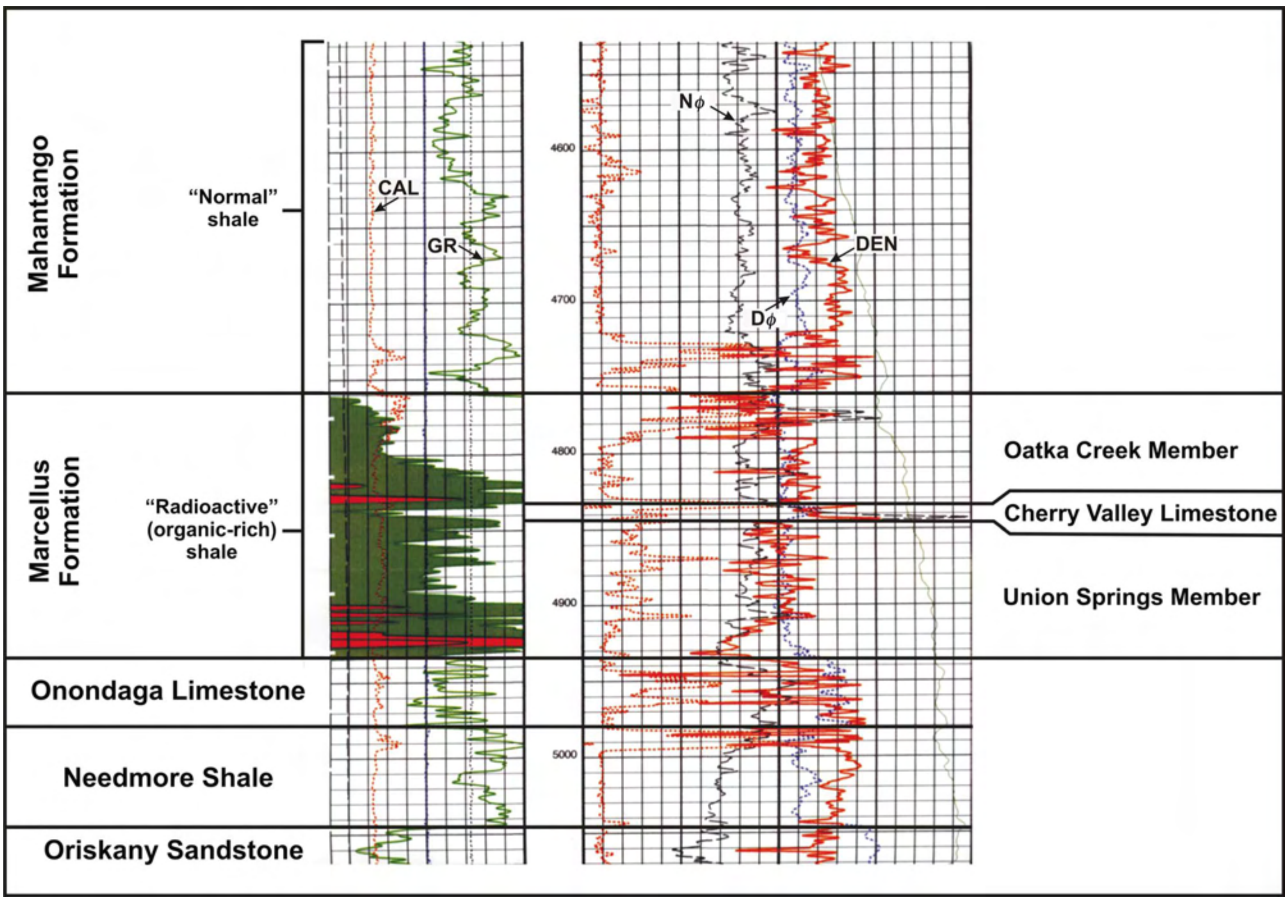


Figure 6. Diagram of parts of a typical wireline log showing the standard stratigraphic nomenclature of the Marcellus Formation in the subsurface of Pennsylvania. Indicated log signatures include CAL = caliper; GR = gamma ray; Nϕ = neutron porosity; Dϕ = density porosity; DEN = bulk density.

developed and studied historically (e.g., the Big Sandy field in eastern Kentucky), researchers found that an empirical relationship exists between high gamma-ray response and gas production from organic-rich shales (Bagnall and Ryan, 1976; Martin and Nuckols, 1976; Majchszak, 1978; Smith, 1978). In addition, Schmoker (1978, 1979, 1980; also Meyer and Nederlof, 1984) has shown that gamma-ray, formation density, and other wireline log signatures can be used to calculate the organic richness or total organic carbon (TOC) of a source rock.

Findings and Deliverables

The EGSP products included numerous cross sections, maps, and technical reports (e.g., Piotrowski and Harper, 1979) showing structure, total formation thicknesses, net feet of black shale, and net feet of sandstone throughout the entire Middle and Upper Devonian sequence in western and north-central Pennsylvania. At the time, it was determined that the Devonian organic-rich shales could be important gas reservoirs, at least in northwestern Pennsylvania where they were both thick (especially the Huron Member of the Ohio Shale and the Rhinestreet Member of the West Falls Formation; see Figure 5) and close to the surface. Homeowners, small businesses, and even a few large manufacturing plants willing to drill a few hundred to 1000 ft (305 m) within a few miles of the shore of Lake Erie found a cheap domestic source of natural gas. This had been occurring since the 1860s (White, 1881). By 1890, more than 200 wells were known to have been drilled in the vicinity of Erie, Pennsylvania (Harper, 1980), and interest spurred by EGSP resulted in numerous shallow wells being drilled in Erie County during the 1980s and 1990s. The wells did not provide a lot of volume—flows generally were, at best, only a few tens of cubic feet per day and at a few ounces to a few pounds of pressure—but, aside from the coldest months of the year, they typically provided the owner with a steady and adequate supply of natural gas for cooking and heating.

The EGSP produced much optimism about Devonian shale. All of the shale formations were thought to have excellent potential, especially with the expected development of better technology for inducing and enhancing fracture systems. This was particularly true of the shallower formations such as the thick Huron and Rhinestreet shales. The deeper shales, especially the Marcellus Formation, were considered to be much less attractive targets. Development of natural gas from these rocks would essentially be in limbo until gas prices increased and technology advanced enough to make drilling and completion competitive with more conventional targets.

The Eastern Gas Shales Project Legacy

Although the DOE continued its research and testing of Devonian shales through 1992, the furor experienced during the heyday of EGSP faded during the early 1980s because of low gas prices and lack of sufficiently useful technologies for extracting the gas. The numerous reports that resulted from EGSP, as well as other independently sponsored studies, added a wealth of new information to an already overwhelming volume of literature on Devonian and Mississippian organic-rich shales. In addition, it significantly enhanced our understanding of these complex rocks and their potential for gas production. The complete EGSP library has remained relatively obscure until recent years because of a general lack of interest. It is quite extensive and includes a variety of physical, chemical, geologic, and engineering information. Published in 2007, the National Energy Technology Laboratory's compendium of natural gas archives (National Energy Technology Laboratory, 2007) contains a significant part of this library. In addition, some excellent summaries, such as those by Roen and Kepferle (1993), have been published that provide very useful information on shales, in general, and EGSP, in particular.

GEOLOGIC INTERPRETATIONS THROUGH TIME

Since the late 1980s, our understanding of the geologic history, depositional environment, and lithology of Devonian organic-rich shales has continued to evolve. This section provides the Survey's current evaluation of Marcellus lithostratigraphy followed by our assessment of sequence-stratigraphic concepts as applied to Devonian rocks including the Marcellus Formation.

Introduction: The Hamilton Group

The Marcellus Formation is the lowest stratigraphic unit within the Middle Devonian Hamilton Group in the central Appalachian Basin (Figure 7). Dennison and Hasson (1976) described the Hamilton Group as a classic example of intricate facies changes that have resulted in a complexity of stratigraphic nomenclature

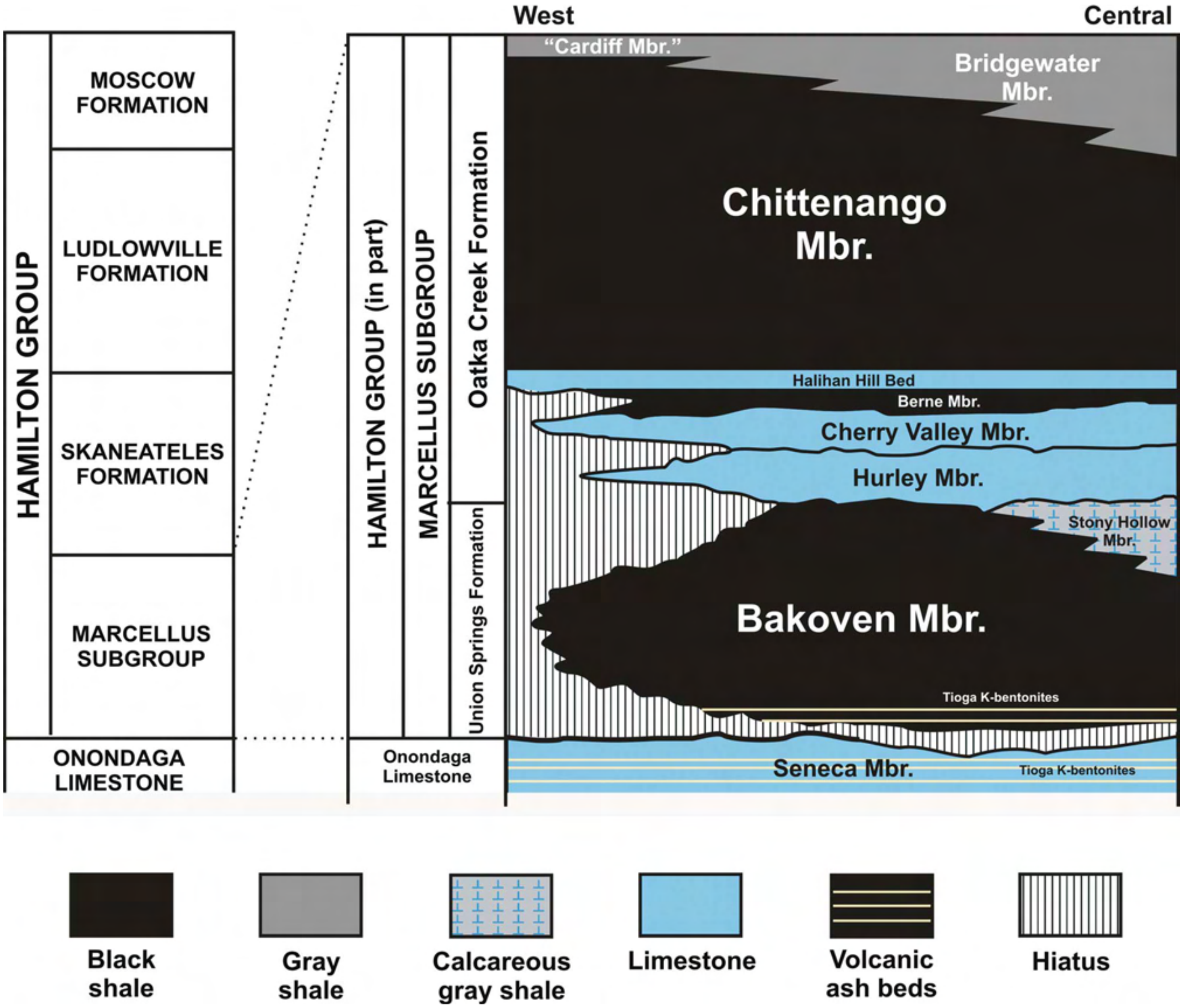


Figure 7. Standard terminology of Marcellus strata in western and central New York. Mbr. = Member.

over its extent. In New York, the standard section includes the Marcellus (currently considered a subgroup), Skaneateles, Ludlowville, and Moscow formations. In Pennsylvania, in those areas where the Skaneateles, Ludlowville, and Moscow cannot be separated or contain coarse clastics, correlative strata above the Marcellus are called Mahantango Formation (Willard, 1935, 1939; Faill et al., 1978).

In much of New York and Pennsylvania, the Hamilton Group, consisting primarily of terrigenous clastic rocks with some limestones and calcareous mudstones, extends from the top of the Onondaga Limestone to the base of the Tully Limestone (Figure 8). In most of the Appalachian Plateau and Valley and Ridge province of Pennsylvania, where the Tully is present and mappable (Heckel, 1969), recognition of the upper Hamilton boundary presents no problems. The Tully is absent in northwestern Pennsylvania and western New York, however, and darker colored Upper Devonian mudrocks and carbonates disconformably overlie the Hamilton Group. In parts of south-central Pennsylvania, where the Tully is represented, if at all, by a concretion zone, the upper boundary of the Hamilton Group is placed at the first appearance of black mudrocks of the basal Upper Devonian (Burket Member of the Harrell Formation). In fact, Faill et al. (1978) considered the Tully to be a member of the Mahantango Formation in the Valley and Ridge province of central Pennsylvania. In Virginia and adjacent parts of West Virginia, the entire Hamilton Group and the overlying Burket shales are considered parts of the Millboro Shale (Butts, 1940; Dennison and Hasson, 1976; De Witt and Roen, 1985;

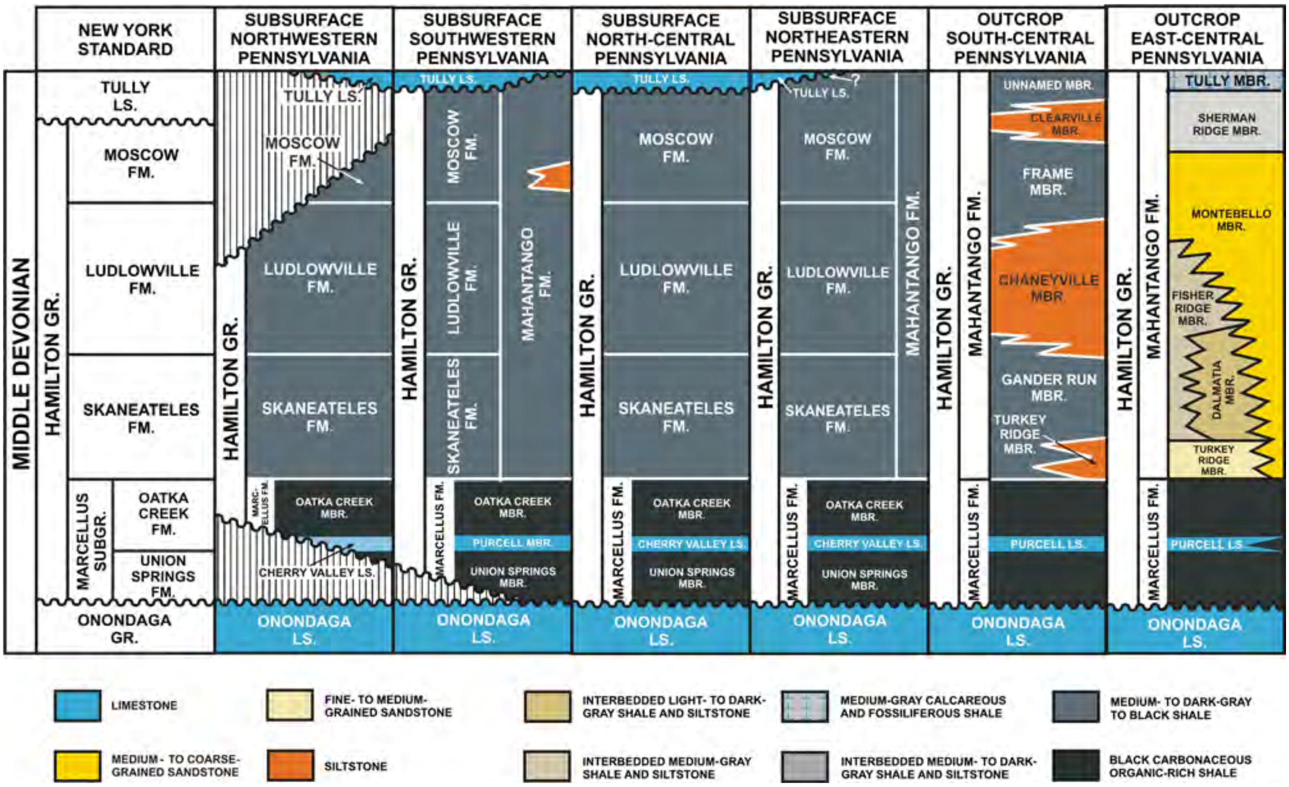


Figure 8. Correlation of Middle Devonian rocks in Pennsylvania, with comparison with the New York standard. Nomenclature for most of Pennsylvania is based on wireline log correlations. Nomenclature for northeastern, south-central, and east-central Pennsylvania, respectively, is based on Sevon et al. (1989), Cate (1963), and Faill et al. (1978). FM. = Formation; LS. = Limestone; GR. = Group; SUBGR. = Subgroup; MBR = Member.

De Witt et al., 1993). Dennison and Hasson (1976; also Hasson and Dennison, 1979) even extended the name Millboro into southwestern Pennsylvania.

Marcellus Lithology and Lithostratigraphy

Hall (1839) first used the name Marcellus for black and gray, thinly laminated shales exposed near the village of Marcellus in Onondaga County, New York, where it rests disconformably on the Seneca Member of the Onondaga Limestone. He described a variable formation, with a lower mass of black "slate" containing limestone nodules or concretions and an upper dark-colored, slaty, fossiliferous shale grading upward into compact blue shale and fissile olive shale. Hall marked the top of the Marcellus where a "true Hamilton fauna" first appeared (Cooper, 1930). Later, Hall (1843) further divided the Marcellus into two significantly different divisions. The lower division was very black and bituminous. Vanuxem (1840) described it as having the appearance of coal; Lesley (1892, p. 1196) stated that it was "so bituminous in places that it flames when thrown upon a fire of hot coals." These shales contained an abundance of pyrite and several beds of concretions and terminated upward in a thin limestone. The upper division started as a black, more fissile shale above the limestone and graded upward to somewhat lighter (olive or slate) color. Hall (1843) noted that the abundant fossils seen in the underlying Onondaga Limestone either ceased entirely or were succeeded by others of a totally different character.

In Pennsylvania, the First Geological Survey (1836–1858) referred to Marcellus-equivalent strata as the "Cadent Lower Black Slate" and described them as "a black and highly bituminous slate, graduating upward into a dark-blue argillaceous shale" (Rogers, 1858, p. 107–108). It took until the Second Geological Survey (1874–1889) before the name "Marcellus" came into general use in the state. Because of its relatively persistent lithology, the Marcellus is one of the easiest units recognizable in Pennsylvania outcrops. Willard (1939, p. 168) noted that "… its obviously distinctive features could hardly escape even the least observant of (Second

Survey State Geologist J. P.) Lesley's band" in the late 1800s.

Marcellus lithostratigraphy has undergone numerous changes during the past 170+ yr. Hall (1839) originally considered the Marcellus to include all of the rocks between the Seneca Limestone (uppermost Onondaga) and "Ludlowville shales." Vanuxem (1840) subsequently removed the upper rocks from the Marcellus and renamed them "Skaneateles shales." Cooper (1930) subdivided the Marcellus Formation in ascending order into the Union Springs, Cherry Valley, and Oatka Creek members in the western part of New York (additional members occur as eastern facies equivalents). This tripartite division of the Marcellus is generally accepted, although the stratigraphic ranks of the formation and its members have recently changed in New York as a result of highly detailed outcrop work (Ver Straeten et al., 1994; Ver Straeten and Brett, 2006; Brett et al., 2011) (see Figure 7 for the current standard nomenclature in western New York). These rank changes generally have not been accepted in the subsurface of New York, Pennsylvania, and Ohio (Lash and Engelder, 2011), however, because of the difficulty in recognizing and separating some of the very thin members and beds in drill cuttings and on wireline logs. In fact, Piotrowski and Harper (1979) made no stratigraphic distinction among any of the members of the Marcellus Formation and even included organic-rich black shales from overlying Hamilton Group formations in their "Marcellus facies." When Range completed the Renz No. 1 gas well in Washington County in 2004, they hydraulically fractured the black shales of both the Marcellus Formation and the overlying Skaneateles Formation (the Levanna Member of New York). Thus, the "Marcellus play" actually incorporated the "Marcellus facies" from the beginning. This section of the article, however, focuses only on true Marcellus Formation strata.

In this article, we use a modified version of the western New York terminology of Cooper (1930)—Marcellus Formation, Union Springs Member, Cherry Valley Limestone, and Oatka Creek Member. In addition to Cooper's (1930) members, Ver Straeten et al. (1994) recognized a new member, the Hurley, which they placed at the top of the Union Springs Formation. Brett et al. (2011), however, considered the Hurley to lie at the base of the Oatka Creek Formation (Figure 7). The Hurley, if it exists at all in Pennsylvania, appears to be inseparable from the Cherry Valley Limestone on wireline logs; therefore, it is not considered further herein.

Union Springs Member

Where it occurs in the subsurface of Pennsylvania, the Union Springs Member consists of all of the black organic-rich shale, with thin interbedded limestones and altered ash fall beds, occurring between the Onondaga Limestone and the Cherry Valley Limestone or its equivalent. It is, therefore, essentially identical with the Bakoven Member of the Union Springs Formation of New York (Figure 7). The Union Springs Member appears on wireline gamma-ray and density logs as much more radioactive and less dense than surrounding strata (Figure 9), making it very easy to recognize and correlate. The lower part is particularly radioactive as a result of both high TOC content and the occurrence of one or more K-bentonite beds that are part of the Tioga ash zone (Fettke, 1952b; Way et al., 1986).

Lash and Engelder (2011) mapped the extent of the Union Springs in the subsurface of the central Appalachians and showed that it thickens significantly in northeastern Pennsylvania to more than 160 ft (>49 m). They also suggested that the Union Springs is locally absent along a northeast-southwest–trending axis in western New York into northwestern Pennsylvania. We are preparing a series of preliminary cross sections across Pennsylvania that indicate that the Union Springs is essentially absent throughout much of western New York and westernmost Pennsylvania north of the Beaver-Washington County boundary. It typically overlies a "corrosional discontinuity" (Baird et al., 2000) that separates it from the Onondaga Limestone (Figures 7, 8). The discontinuity, juxtaposing the top of the Onondaga with increasingly younger strata from east to west, represents the beginning of a major basin deepening event, Ettensohn's (1985) "second tectophase." This marked the end of Onondaga carbonate deposition and the beginning of organic-rich shale deposition as a result of transgression and an associated sediment starvation (Ver Straeten et al., 1994) related to tectonically induced subsidence (Ettensohn, 1998; Brett et al., 2011).

Cherry Valley Limestone and Purcell Member

The Cherry Valley Limestone and, at least partially, equivalent Purcell Member of the Marcellus Formation are very good marker horizons where they occur. The Cherry Valley is a widespread relatively thin carbonate unit, typically dark colored, fossiliferous, and petroliferous (Cooper, 1930; Baird et al., 2000). The limestone truncates the upper Union Springs Member across western New York (Baird et al., 2000; Brett et al., 2011). Our preliminary cross sections indicate that the Cherry

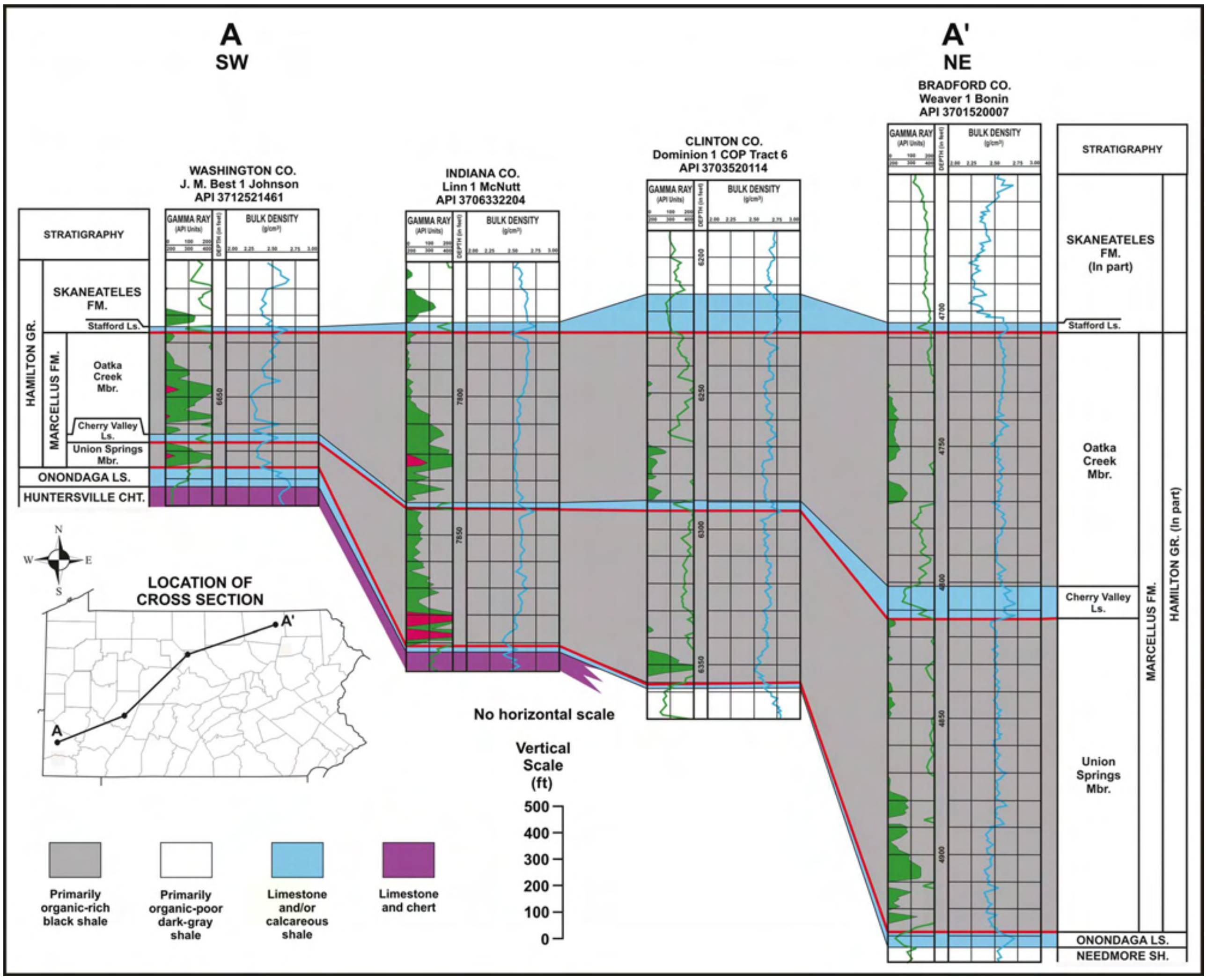


Figure 9. Generalized cross section of Marcellus Formation (FM.) and adjacent strata from Washington County to Bradford County, Pennsylvania, showing the general west-to-east thickening trend. Gamma-ray log signature is shown in green, with the most organic-rich radioactive sections colored in green and red. Bulk density signature is shown in blue. Heavy red lines indicate disconformities. GR. = Group; Mbr. = Member; Ls. = Limestone; Sh. = Shale; CHT. = Chert.

Valley log signature can be traced in the subsurface across most of Pennsylvania, making it an excellent marker horizon.

Relatively thin limestones or calcareous siltstone and shale packages as much as 45 ft (14 m) thick occur in the lower half of the Marcellus in south-central Pennsylvania. Gas operators found one of these to be a useful subsurface marker in wells drilled in Bedford County in the late 1950s and named it the "Purcell Limestone" (Cate, 1963). Dennison and Hasson (1976) changed the name to Purcell Member because of its varied lithology; this is the terminology we use here. Drill cuttings from the type well in Bedford County indicate that the interval consists of dark-colored, silty, calcareous shale essentially indistinct from much of the rest of the Marcellus, but drill cuttings are not especially valuable for detailed lithologic description and correlation because each sample typically represents a vertical distance of 10 ft (3 m) or more. De Witt et al. (1993) described the Purcell in outcrop as gray silty shale and mudrock, with some siltstone, an abundance of limestone nodules, and some barite nodules about 1 to 2 in. (2.5–5 cm) in diameter. Dennison (1963) traced a persistent zone of interbedded limestone and shale occurring between 40 and 100 ft (12–30 m) above the base of the Marcellus through outcrops in eastern West Virginia. He apparently was unaware that the zone had been named Purcell because that name does not appear anywhere in his report. Ver Straeten (1996) found the Purcell to be a distinctive interval visible in almost all mid-Marcellus outcrops from central Pennsylvania to Virginia, with the lithofacies in at least one locality being very similar to that of the Cherry Valley Limestone in New York. In fact, the Purcell typically is considered to be stratigraphically equivalent to the Cherry Valley (Figure 8).

Cate (1963) traced the Purcell Member into western Pennsylvania at least as far west as Laurel Hill anticline (coincident with the boundary between Somerset and Westmoreland counties). We have been able to trace the wireline log signature of the Cherry Valley–Purcell interval as far west as western Greene County, where it disappears as the result of the corrosional discontinuity that similarly affects the Union Springs Member. Based on the above research, the Purcell and Cherry Valley are very distinct lithologic units with only a small number of similarities. The larger issue is not whether they are equivalent but, instead, where does the Cherry Valley end and the Purcell begin? Drill cuttings are not particularly useful for answering this question, and the types of modern wireline logs that could be useful (e.g., photoelectric log) are generally not publicly available. As this issue is beyond the scope of this article, it will not be addressed here further.

Lash and Engelder (2011) mapped the Cherry Valley Limestone from less than 10 ft (<3 m) thick where it occurs in western New York and northwestern Pennsylvania to more than 140 ft (>43 m) thick in northeastern Pennsylvania and southeastern New York. Dennison (1963) found the Purcell Member to range from 6 to 29 ft (2–9 m) thick in his West Virginia outcrops. Based on our preliminary cross sections, the Cherry Valley–Purcell interval, where it occurs, ranges from 3 ft or less (≤1 m) near the zone of the corrosional discontinuity to 70 ft or more (≥21 m) in south-central Pennsylvania.

Oatka Creek Member

The Oatka Creek Member, as defined here, begins with a sharp, corroded, and mineralized boundary on top of the Cherry Valley Limestone that Brett et al. (2011) interpreted as a drowning unconformity. The Oatka Creek in the subsurface of most of the Appalachian Plateau of Pennsylvania is dominated by organic-rich shale (the Chittenango Member of the Oatka Creek Formation in New York; see Figure 7). Like the Union Springs Member, this shale has a high TOC value (up to 18%) (Baird et al., 1999) and displays high radioactivity and low density signatures, respectively, on gamma-ray and bulk density wireline logs (Figure 9) in most areas where it is developed.

In westernmost Pennsylvania, especially in those areas where the Union Springs and Cherry Valley limestones are missing, the Oatka Creek is most radioactive in the lowest 10 to 15 ft (3–4.5 m). Lash and Engelder (2011) found the Oatka Creek to be only about 30 ft (~9 m) thick in western New York and northwestern Pennsylvania but thickened greatly to the east, exceeding 550 ft (168 m) in northeastern Pennsylvania. Our own investigations indicate that this member is closer to 90 ft (27 m) thick in westernmost New York and westernmost Pennsylvania north of the Ohio River.

The top of the Oatka Creek Member (and of the Marcellus Formation) is marked by the base of the Stafford Member of the Skaneateles Formation, a fossiliferous carbonate unit that occurs throughout much of New York and Pennsylvania. We have traced the Stafford in the subsurface as far east as the Allegheny Front in central Pennsylvania and Susquehanna County in northeastern Pennsylvania. In south-central Pennsylvania, the Stafford appears to grade laterally, or be replaced entirely, by a zone of siltstone and shale equivalent to the Turkey Ridge Member of the Mahantango Formation.

Biostratigraphy and Fossil Content

Few or no data exist on the fossil content of the Hamilton Group and Marcellus Formation in the subsurface of Pennsylvania. The faunas are well known in outcrop in New York (e.g., Linsley, 1994) and in central Pennsylvania (e.g., Willard, 1932, 1939), however, and have been put to use in assessing the biota of the lower Middle Devonian in the Appalachian Basin.

Fossils are relatively sparse in the black-shale parts of the Marcellus Formation, which have been shown to have the highest geochemical signals for anoxia in the Devonian of eastern North America (Baird et al., 1999). As a result, most of the fossils found in these parts consist primarily of nektonic forms such as styliolinids, cephalopods, and conodonts, as well as microscopic fossils of both phytoplankton and zooplankton. The occasional benthic fossil specimens include bryozoans, brachiopods, tentaculitids, crinoids, trilobites, bivalves, and gastropods. The limestones and calcareous beds generally preserve a larger and more diverse fauna of benthic animals.

The Devonian has been zoned on a global scale using conodonts (e.g., Kaufmann, 2006). Conodont zonation for Devonian strata in the eastern United States, however, has been revised (Kirchgasser, 2000); the currently accepted zonation for Middle Devonian

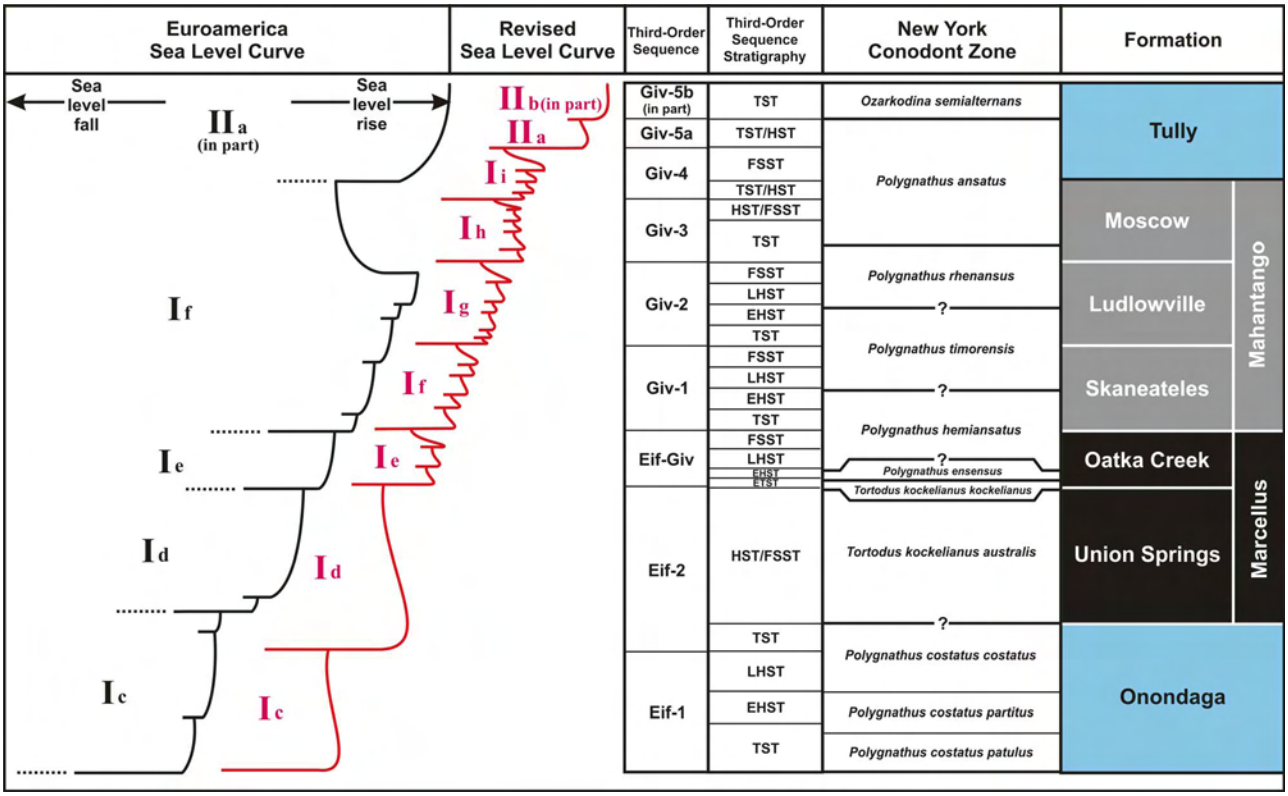


Figure 10. Sea level curves, conodont zonation, and sequence stratigraphy of Middle Devonian (Eifelian and part of the Givetian) rocks in New York and Pennsylvania (based on Ver Straeten, 1996, modified by Bartholomew et al., 2006, and Brett et al., 2011). Euramerica sea level curve (black) from Johnson et al. (1985). Revised sea level curve (red) interpreted from Brett et al. (2011): long bases = third-order sequence boundaries; short bases = fourth-order sequence boundaries. Eif = Eifelian; Giv = Givetian; EHST = early highstand systems tract; ETST = early transgressive systems tract; FSST = falling stage systems tract; HST = highstand systems tract; LHST = late highstand systems tract; TST = transgressive systems tract.

strata in the Appalachians is shown in Figure 10 (see also Bartholomew et al., 2006; Brett et al., 2011). In addition, other faunal groups (e.g., goniatite cephalopods) are also useful for correlation.

Sequence Stratigraphy

In a seminal article on Devonian eustatic cycles, Johnson et al. (1985) recognized and described a series of transgressive-regressive (T-R) cycles in the Devonian of the North American craton, combined into two larger cycles labeled I and II that are separated by the Taghanic unconformity (sensu Hamilton-Smith, 1993). A part of this is illustrated in Figure 10 (left side). These T-R cycles represent the third-order cycles of Vail et al. (1977); fourth-order cycles appear within those. Brett et al. (2011, p. 22) viewed this work as "a useful synthesis, correct in its main outline," but that it was only intended as a "work in progress." Unfortunately, as they pointed out, it has since become dogma despite some flaws. The cycles defined by Johnson et al. (1985) were not based on the modern concept of sequence stratigraphy. In an attempt at defining Devonian sequences and their component systems tracts in a consistent manner, Brett and Baird (1996; also Bartholomew et al., 2006, Brett et al., 2011) have subdivided the Middle Devonian section from the base of the Onondaga Limestone through the Tully Limestone into sequences that can be traced widely through the northeastern half of the United States, including within the Michigan, Iowa, Illinois, and Appalachian basins. A revised sea level curve, which we have interpreted from their work, is shown in red in Figure 10.

Each of the Middle Devonian third-order sequences (Ic–IIb) in the Appalachian Basin starts at the erosive base of a transgressive stratum indicating a sequence boundary (transgressive systems tract [TST]). This stratum typically is a limestone, although some of the widely recognized Hamilton limestones (especially the Centerfield and Tichenor, which are standard formation boundary markers) cannot be recognized in many places in the subsurface of Pennsylvania. In the Marcellus Formation of Pennsylvania, two TSTs represented by the Cherry Valley–Purcell interval and the beginning of deposition in the Oatka Creek interval exist. A third TST, defined by deposition of the Stafford Limestone of the Skaneateles Formation, marks the top of the Marcellus Formation.

Each TST is followed by a highstand systems tract (HST) that encompasses the time between still-stand and the beginnings of sea level fall. The HST strata typically record the deepest water in the cycle, although what is meant by "deepest" is relative. Many authors consider the Marcellus sea to have been "deep" in the sense of the Black Sea (that is, hundreds or thousands of meters of water column, e.g., Clarke, 1904; Rich, 1951; Potter et al., 1981; Broadhead et al., 1982; and Kepferle, 1993). Harper (1999), however, suggested that the Marcellus black shales were deposited in a variety of shallow-water anoxic environments, possibly as shallow as 150 ft (45 m). In such a case, the shallow-water column might have been stratified enough to keep warm oxygenated surface water from mixing with hypoxic (anoxic or euxinic) bottom water (Lash and Engelder, 2011). Modern hypoxic events have been documented in water as shallow as 16 ft (5 m) over areas as large as 6000 mi^2 (9500 km^2) resulting from a combination of increased nutrient input, decay of phytoplankton blooms, and water column stratification induced by warm water and a strong salinity gradient (Harper et al., 1991; Rabalais et al., 1991). Within the Marcellus, the most organic-rich black-shale facies of the Union Springs and Oatka Creek members represent the HST. On wireline logs, they exhibit the highest radioactivity and lowest bulk density signatures within the formation.

Basal black-shale facies of the HST tend to grade laterally and vertically into less organic-rich and coarser grained shales, siltstones, and even sandstones as pulses of continental sediment prograde seaward during still-stand. It should be noted that, although the flush of coarser clastics into the depositional basin during early progradation marks the beginning of a regressive phase within the rock section, this might be caused more by a tectonic than a purely eustatic event.

Falling stage systems tracts (FSST), above and seaward of the HST, can be difficult to recognize because of subsequent erosion. Bartholomew et al. (2006) found that FSSTs in the Devonian of the Appalachian foreland begin with a distinct shell bed that marks a shift to shallower water conditions. This condition is reflected twice in the Marcellus, within the Union Springs and Oatka Creek members, by a decrease in organic content and an increase in silt upward and eastward in Pennsylvania. In addition, an end-Marcellus FSST is recorded in outcrop in the Solsville and Pecksport members of the Oatka Creek Formation in central New York (Brett et al., 2011). In the subsurface of Pennsylvania, the FSSTs within the Union Springs and Oatka Creek members appear on wireline logs as decreasing radioactivity and increasing bulk density signatures in the upper few meters or tens of meters.

Continuing regression/progradation ultimately results in a lowstand systems tract (LST) that indicates the shallowest water conditions. Typically, this is recorded as an unconformity at the base of the next TST. Within the Marcellus Formation, the LSTs occur at the interface between the Union Springs Member and the Cherry Valley Limestone and between the Oatka Creek Member and the Stafford Limestone of the overlying Skaneateles Formation.

Based on the above criteria, the Marcellus Formation represents all or part of two third-order cycles, labeled Eif-2 and Eif-Giv by Brett et al. (2011) (Figure 10) and MSS1 and MSS2 by Lash and Engelder (2011). Sequence Eif-2 actually starts in the underlying Onondaga Limestone but includes the entire Union Springs Member. Sequence Eif-Giv encompasses the Cherry Valley Limestone and Oatka Creek Member. The exact durations of these sequences is unknown but probably is on the order of 1 to 2 m.y. (Kaufmann, 2006; Lash and Engelder, 2011). If the smaller scale fourth-order subsequences shown in Figure 10 spanned approximately 400 k.y. each (based on the long eccentricity Milankovitch cycle), sequence Eif-Giv (= MSS2) would have been approximately 1.2 m.y. in duration. A similar assessment for sequence Eif-2 (= MSS1) is difficult because fourth-order subsequences have not yet been recognized within it in the Appalachian Basin. But what caused these T-R cycles? Although no overwhelming evidence exists for large-scale glaciation during the Middle Devonian, Elrick et al. (2006, 2009) found that the magnitude of changes in oxygen isotope values, determined from conodont apatite, matched the kinds of global temperature shifts associated with Carboniferous- and Pleistocene-type glacial cycles. The T-R cycles could also have resulted from tectonics, the initial collisional events in the early stages of the Acadian orogeny, but it is difficult to understand how mountain-building episodes could be regular enough to account for what appears to be Milankovitch cyclicity. It is obvious that a great deal more research is needed before this will be resolved.

THE MODERN MARCELLUS SHALE GAS PLAY

The Marcellus Shale covers approximately 95,000 mi^2 (~246,049 km^2) in several states throughout the Appalachian Basin, but more than one-third of this area (35,000 mi^2 [90,650 km^2]) is situated in Pennsylvania. This organic-rich rock exists throughout the subsurface of northern and western Pennsylvania, and it is approximately bounded to the east by the Topographic Front; beyond the front, in the Ridge and Valley province, the Marcellus crops out, exists in a structurally complex state in the subsurface, or is absent altogether (Figure 1).

The Marcellus Shale is a known source rock for most of the historical petroleum reservoirs in the Commonwealth. Furthermore, Pennsylvania operators have known for decades that the unit contained significant volumes of gas. As operators began exploring the Lower Devonian Oriskany Sandstone in the 1930s, they commonly encountered large gas shows in the overlying Marcellus. They sometimes attempted completions in the shale but, more commonly, they shut down drilling operations for a few hours or even days until the well blew down enough to continue drilling safely (Harper and Kostelnik, 2010). The difference between then and now is that much has changed with respect to our understanding of the Marcellus Shale's source and reservoir characteristics, not to mention the business, technology, and engineering resources available to the petroleum industry today. This section chronicles the modern Marcellus play, from its discovery in 2004 through mid-2011, and how geologic structure has played an important function in the drilling of Marcellus Shale gas wells permitted in different areas of the state.

The Discovery Well

In 2003, Range permitted and drilled the Renz No. 1 well (Figure 2). This vertical well was drilled to a depth of 8470 ft (2582 m) into the middle Silurian Rochester Shale. Large shows of gas were encountered when they penetrated the Middle Devonian organic-rich shales, and so Range returned to the well in October 2004, stimulating it in the organic-rich shales of the Marcellus and Skaneateles formations from 6174 to 6284 ft (1882–1915 m). The well was turned in line in 2005 and produced 5.5 mmcf in 31 days or an average of 300 mcf/day (Pennsylvania Internet Record Imaging System/Wells Information System, 2011).

Following the success of this discovery well, Range initiated a pilot horizontal program, drilling five horizontal wells into the Marcellus that reported initial flows ranging from 1.4 to 4.7 mmcf/day (Durham, 2008). Based on these results, Range began using horizontal drilling and slickwater hydraulic fracturing techniques developed in the Barnett Shale of Texas to maximize the economic viability of the Marcellus play in Pennsylvania. Continued refinement of drilling and stimulation technologies has propeled the Marcellus Shale play into its current position as a super giant gas field.

Drilling Activity: 2005–2011

We have tracked the drilling activity associated with the Marcellus Shale play in terms of both permitted and completed wells using the DEP Environment Facility Application Compliance Tracking System (eFACTS) and the Survey's PA*IRIS/WIS database, respectively. Although both systems track active oil and gas permits, information contained in PA*IRIS/WIS incorporates and archives critical paperwork associated with each oil and gas permit as obtained from DEP, which enables the Survey to determine when or whether a well has actually been completed by the operator. By the Survey's process, an oil or gas well is considered complete when an operator has submitted a well completion report to the Commonwealth that includes not only basic demographic and drilling data for the well, but also casing details, perforation and stimulation depths, water and proppant volumes used in hydraulic fracturing, and initial open-flow data.

As of June 2011, DEP had issued 6488 permits to drill Marcellus Shale gas wells (Department of Environmental Protection, 2011e); of these, 1098 have been interpreted as known Marcellus completions by the Survey (Pennsylvania Internet Record Imaging System/Wells Information System, 2011). The remainder of this section uses this completed wells data set to analyze the Marcellus Shale gas play with respect to geographic location, operator involvement, and drilling type.

Geographic Distribution

The modern Marcellus play discovery well was drilled in Washington County, Pennsylvania, and for the first several years (2005–2008), more permits were issued in Washington County than anywhere else in the state (Table 2). Marcellus exploration was initiated in the

Table 2. Summary and Distribution of Permits Issued and Wells Completed for Marcellus Shale Gas Activity in Pennsylvania, 2004 to June 2011

	Completion Event		County				
	H*	V*					
2004							
Total Permits			Westmoreland	Elk	Somerset		
3	0	3	1	1	1		
Total Completions			Westmoreland	Elk	Somerset		
3	1	2	1	1	1		
2005							
Total Permits			Washington	Armstrong	Butler	Greene	Warren
13	0	13	8	1	1	1	2
Total Completions			Washington			Fayette	
2	1	1	1			1	
2006							
Total Permits				Washington	Potter	Lycoming/Butler	McKean
41	2	39		23	4	3	2
Total Completions			Washington	Butler	Mckean	Armstrong, Brad, Elk Fayette, Jefferson, Susquehanna	
12	0	12	2	2	2	1	
2007							
Total Permits			Washington	Butler	Lycoming	Potter/Susquehanna	Elk/Armstrong
98	13	85	41	12	8	6	5
Total Completions			Greene	Washington	Butler	Lycoming	Potter/Fayette
59	9	50	12	7	7	6	5
2008							
Total Permits			Washington	Susquehanna	Greene	Bradford	Fayette
411	136	275	68	56	51	46	36
Total Completions			Washington	Susquehanna	Greene	Fayette	Bradford
167	64	103	41	25	20	19	12
2009							
Total Permits			Bradford	Tioga	Susquehanna	Washington	Lycoming
1702	1310	392	422	257	144	161	86
Total Completions			Washington	Bradford	Susquehanna	Fayette	Greene
411	249	162	63	62	58	51	42
2010							
Total Permits			Bradford	Tioga	Susquehanna	Lycoming	Washington
2986	2602	384	791	538	222	222	220
Total Completions			Bradford	Tioga	Susquehanna	Lycoming	Greene
426	340	86	95	82	44	38	38
as of June 2011							
Total Permits			Washington	Susquehanna	Tioga	Bradford	Lycoming
1229	1138	91	74	98	130	280	150
Total Completions			Washington	Susquehanna	Greene	Fayette	Bradford
0	0	0	0	0	0	0	0

*Horizontal = horizontal; V = vertical.

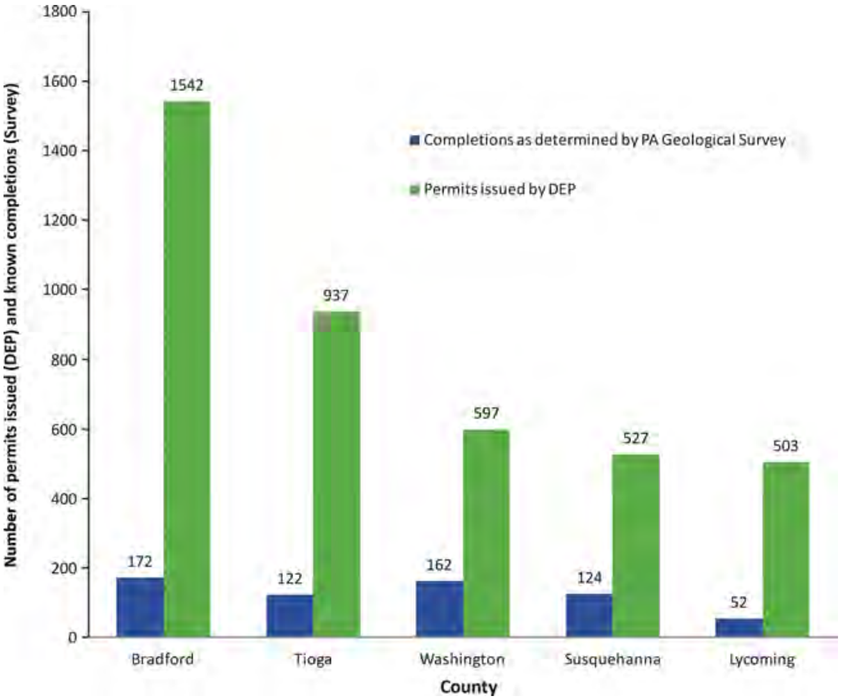


Figure 11. Comparison of number of Marcellus Shale gas permits issued by the Pennsylvania (PA) Department of Environmental Protection (DEP) and number of known completions, as interpreted by the PA Geological Survey, for the most active counties in the Commonwealth (Department of Environmental Protection, 2011e; Pennsylvania Internet Record Imaging System/Wells Information System, 2011).

northeastern part of the state in 2006 when the first permit was issued in Lycoming County, but it was not until 2008 that drilling activity became more evenly split between these two regions (i.e., southwestern and northeastern Pennsylvania). Specifically, in 2008, 155 permits were issued in Washington, Greene, and Fayette counties and 148 permits were issued in Tioga, Bradford, Susquehanna, Wayne, and Lycoming counties. Since 2009, most of the permits have been issued in northeastern Pennsylvania, although several hundred continue to be issued in Greene, Washington, and Fayette counties every year (Table 2). Of the 6488 Marcellus permits issued by DEP as of June 2011, the most were issued in Bradford County. Specifically, 1542 permits have been issued in Bradford County, 937 in Tioga County, 597 in Washington County, 527 in Susquehanna County, and 503 in Lycoming County (Figure 11).

Activity by Operator

As of June 2011, 76 operators had applied for permits to drill Marcellus Shale gas wells in Pennsylvania (Department of Environmental Protection, 2011e). The five most active Marcellus Shale operators, as determined by the number of permits issued by the DEP to date, include Chesapeake Appalachia LLC (1268), Talisman Energy USA, Inc. (620), Range (588), Shell Western Exploration and Production Inc. LP (SWEPI, formerly East Resources LLC, 525), and Chevron (formerly Atlas Resources LLC, 326) (Figure 12). Of these, Chesapeake, Talisman, and SWEPI work in northeastern Pennsylvania, and Range and Chevron have been focusing most of their efforts in southwestern Pennsylvania (Pennsylvania Internet Record Imaging System/Wells Information System, 2011).

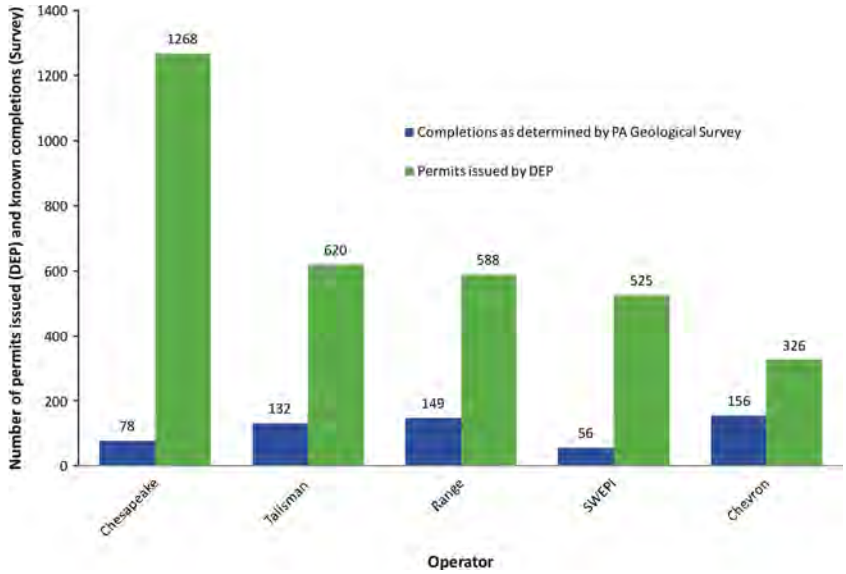
Drilling Type

The use of horizontal well drilling technologies in the Marcellus Shale gas play has played a major part in its widespread success. Compared with historical shale gas well production (where shale gas was produced from shallow low-pressure wells that lasted for many years but returned less than notable production volumes), the modern Marcellus play has exceeded all expectations for shale gas production in the state. Horizontal well drilling technology clearly emerged as the most popular drilling approach in 2009 when 1310 horizontal permits were issued by the DEP, exceeding the number of vertical well permits (392) by nearly 3.5 times (Figure 13). As of June 2011, a total of 1287 Marcellus wells had been permitted by DEP to be vertical completions, and 5201 had been permitted to be horizontal completions. Of the 1098 well completion reports received and processed by the Survey as of this same date, 664 were horizontal wells and the remaining 434 were vertical completions.

Effects of Geologic Structure on Marcellus Shale Gas Drilling and Production

The structural grain of the rocks in western and northern Pennsylvania roughly parallels the structural grain

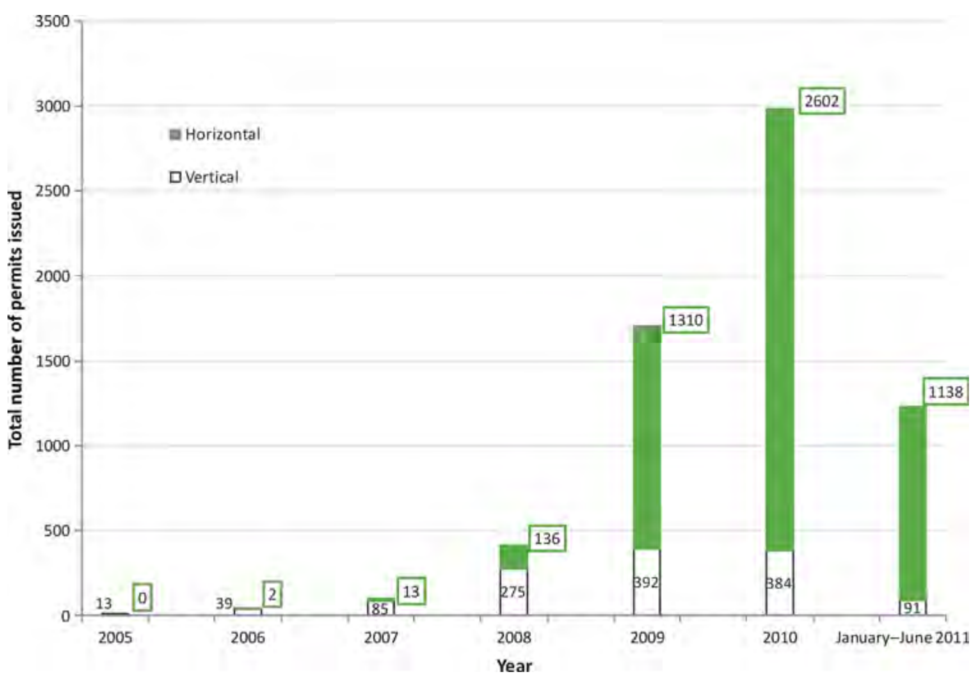
Figure 12. Comparison of number of Marcellus Shale gas permits issued by the Pennsylvania (PA) Department of Environmental Protection (DEP) and number of known completions, as interpreted by the PA Geological Survey, for the most active operators in the Commonwealth (Department of Environmental Protection, 2011e; Pennsylvania Internet Record Imaging System/Wells Information System, 2011). SWEPI = Shell Western Exploration and Production, Inc.



of the Ridge and Valley province of central Pennsylvania (Figure 14). Orientations of fold axes and faults do not specifically relate to Marcellus Shale gas production, however, because the primary pathway for fluid flow in the shale is along a set of joints that are oriented essentially parallel with the contemporary tectonic stress field. The Marcellus, like most shales, has very low permeability (100–500 nanodarcys). Success in producing shale gas, therefore, depends mostly on the presence of both naturally occurring joint sets and fractures induced by the hydraulic fracturing process, instead of on folds, faults, and/or tectonic fractures, as is the case for conventional reservoirs. In fact, the presence of intense fracturing caused by folding and faulting is considered undesirable for effective production from the shale, and the industry tends to avoid them if at all possible. As such, seismic surveying for the purpose of identifying tectonic fractures to be avoided has become an integral part of the shale-gas exploration process.

Engelder (2004; also see Engelder and Whitaker, 2006; Engelder, 2008; Lash and Engelder, 2009) recognized a pre- or early Alleghanian joint set (J1) that has the same approximate east-northeast–west-northwest orientation as neotectonic joints (J3) and the contemporary

Figure 13. Comparison of vertical and horizontal Marcellus Shale gas well permits issued by the Pennsylvania Department of Environmental Protection over time (Department of Environmental Protection, 2011e).



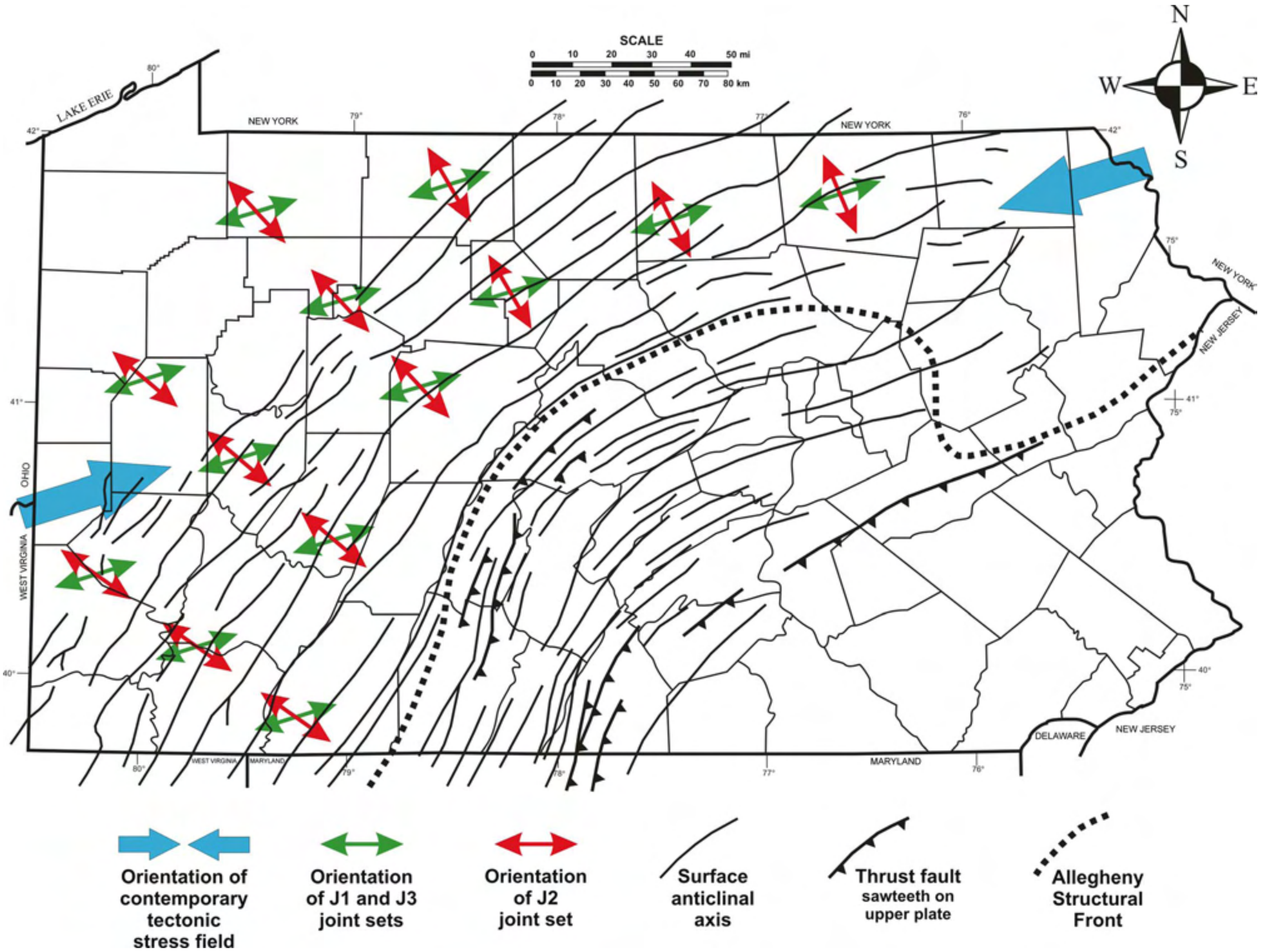


Figure 14. Map of Pennsylvania showing general orientations of structure axes, contemporary tectonic stress field, and J1, J2, and J3 joint sets of Engelder (2008).

tectonic stress field (Figure 14). The J1 joints were created by fluid pressure during hydrocarbon generation within the Devonian organic-rich source rocks such as the Marcellus (Lash and Engelder, 2009), as evidenced by the occurrence of J1 joints folded along with bedding in the Ridge and Valley province of the Appalachians (Engelder, 2004). The J1 and J3 joints intersect a set of Alleghanian cross-fold joints (J2) that are very prominent both at the surface (e.g., Nickelsen and Hough, 1967; Bench et al., 1977) and in Devonian shales in the subsurface (Evans, 1980, 1994).

Successful drilling and production programs in the Marcellus have occurred in vertical as well as horizontal holes. Vertical holes, however, are essentially hit or miss in terms of the number and extent of J1 joints they encounter. Assuming that a vertical hole intersects a set of J1 joints, production will be limited to the area encompassing that set (Figure 15A). Similarly, a horizontal well-oriented parallel with J1 will have limited production (Figure 15B). The most successful wells have been horizontal wells drilled normal to J1 (Figure 15C) because, in this manner, the lateral leg will intersect numerous joint sets and take full advantage of the interconnectedness that otherwise would not exist.

WATER MANAGEMENT ISSUES IN PENNSYLVANIA

Typically, a petroleum geology developments article might conclude here after having discussed the discovery, geology, extent, and drilling activity of the subject reservoir. In this case, however, water management has become a very important component of the Marcellus Shale gas play and is integral to the discussion of how the play is progressing in Pennsylvania. Specifically, water management is an essential part of the play for the following reasons: scale, logistics, and contending uses.

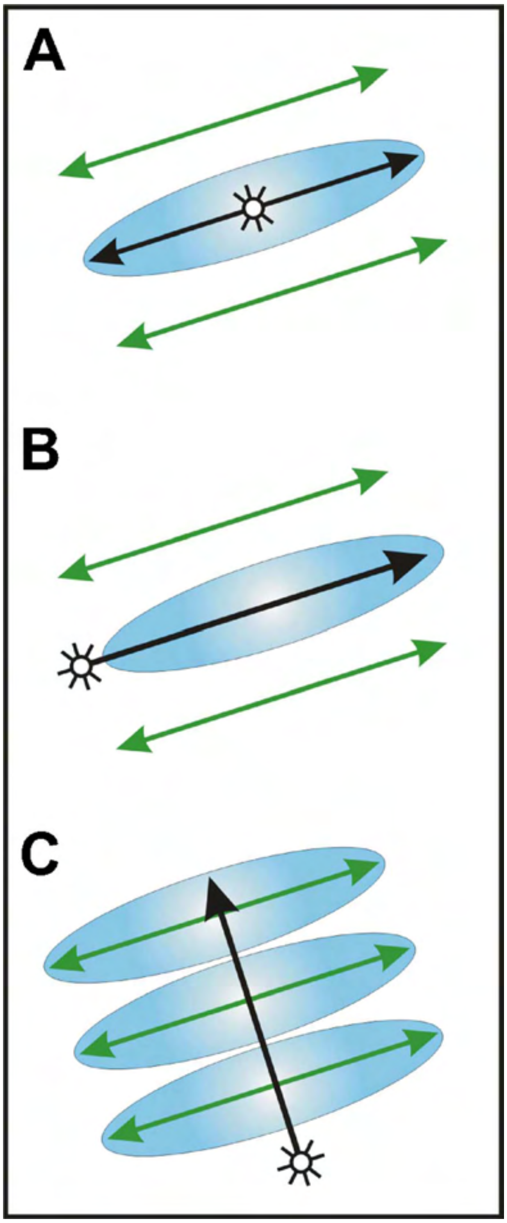


Figure 15. Diagrams showing the results of vertical versus horizontal drilling in the Marcellus Shale: (A) drainage area for a vertical well, assuming it intersects a set of J1 joints; (B) drainage area for a horizontal well drilled along a set of J1 joints; (C) drainage area for a horizontal well drilled normal to the J1 joint orientation. Green arrows indicate the direction of J1 joint orientation.

First and foremost, the magnitude of water usage by the industry for Marcellus Shale gas development is considerable. The volume of water needed to complete the hydraulic fracturing of a single horizontal gas well is measured in millions of gallons, instead of the thousands of gallons typical for vertical wells completed in Pennsylvania. Using publicly available data for horizontal Marcellus wells completed between 2005 and 2010, we have determined that an average Marcellus frac job uses 2.9 millions of gallons (109,777 L) of water (Pennsylvania Internet Record Imaging System/Wells Information System, 2011).

Also very important is logistics. The extraction, transport, handling, reuse, and ultimate disposal of water and produced formation waters from the fracing process have been argued to impact the state's infrastructure, surface water and groundwater supplies, and overall environmental health. For reasons such as these, the state's basin commissions have become very active in the Marcellus Shale gas play.

Last but not the least is contending uses. Pennsylvania does not regulate private water supplies, so the use of groundwater by operators for fracing in some areas has raised concerns by citizens who are responsible for their own drinking water supply's quantity and quality. In addition, some operators are extracting surface waters in areas of the Commonwealth where Pennsylvanians fish, boat, and otherwise enjoy certain recreational uses of water. The use of water resources for hydraulic fracturing has created a perceived competition for these resources, even when wise water management practices are being used or drought conditions do not exist.

The remainder of this section focuses on key legal constructs and private water resource issues specific to Pennsylvania, which we would argue are mostly responsible for the existing water management "landscape" that must be navigated by operators drilling shale gas wells in the Commonwealth.

Legal Issues

It is true that the Commonwealth of Pennsylvania is fortunate to have abundant natural resources, from wide open spaces and state forests, to water and wildlife, to those treasures beneath our feet—rich soils, mineral deposits, and fossil fuels. The Pennsylvania State Constitution (1968) addressed these natural resources and the public estate in article 1, section 27:

"The people have a right to clean air, pure water, and to the preservation of the natural, scenic, historic and esthetic [sic] values of the environment. Pennsylvania's public natural resources are the common property of all the people, including generations yet to come. As trustee of these resources, the Commonwealth shall conserve and maintain them for the benefit of all people."

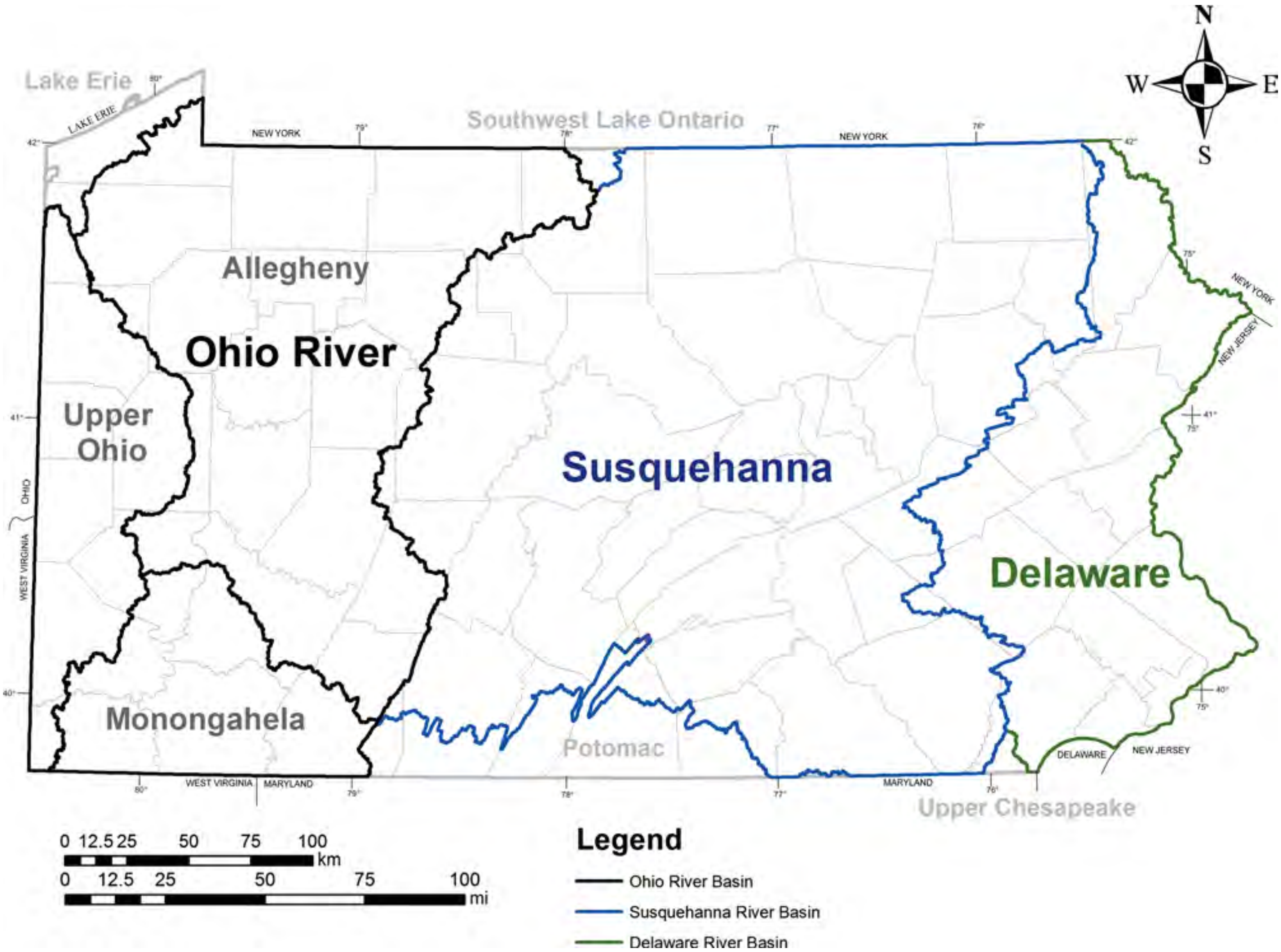


Figure 16. Location and extent of the three major river basins in Pennsylvania: the Ohio River, Susquehanna, and Delaware.

Water, essential for life, and arguably the most important of these resources, has been subject to various rules and management practices since the 1800s (Department of Environmental Protection, 2009b). The progression of water management approaches to the current day could be referred to as a "patchwork quilt" of state and federal statutes stitched together by common law. An understanding of how these statutes and legal concepts relate to issues of water management is important for evaluating how productive the Marcellus Shale gas play may ultimately be, and is, therefore, an important chapter in the Marcellus backstory.

Common Law

Common law provides the basis for Pennsylvania's earliest water management decisions and remains at the core of its water management practices even today (Weston, 2008). Common law, or case law, is built over time through judicial rulemaking that generally addresses matters of nuisance, trespass, and negligence. In other words, common law is not based on scientific principles, always subject to change, and inherently incomplete—that is, rulemaking voids remain because the body of common law is aggregated from individual legal decisions (Bishop, 2006; Weston, 2006).

Common law, as applied to water resource management, has defined four categories of water resources: diffused surface waters, surface waters, groundwaters in subterranean streams, and percolating groundwaters (Weston, 2008). These admittedly awkward classifications result from the limited knowledge of hydrogeologic concepts that existed in the 1800s when this terminology was developed (Weston, 2008). In the simplest of terms, however, water occurs as surface water and groundwater, and different rules apply to the allocation of each under common law.

The "riparian rights" doctrine applies to the use of surface water, that is, the use of water flowing in a stream on or adjacent to riparian land. In Pennsylvania, the riparian rights doctrine also incorporates the "reasonable

Table 3. Number of Private Wells and Population Served by Pennsylvania Counties*

County	No. Wells	County Population	HU**	Population per HU**	No. People Served by Private Wells†	People Served by Private Wells† (%)
Adams	15,655	78,274	30,141	2.60	40,655	51.9
Allegheny	10,676	1,336,449	580,738	2.30	24,569	1.8
Armstrong	10,774	73,478	31,757	2.31	24,928	33.9
Beaver	14,271	186,093	76,336	2.44	34,790	18.7
Bedford	13,472	47,919	21,738	2.20	29,698	62.0
Berks	38,847	336,523	134,482	2.50	97,209	28.9
Blair	12,790	130,542	54,349	2.40	30,721	23.5
Bradford	15,113	60,967	27,058	2.25	34,053	55.9
Bucks	45,507	541,174	199,934	2.71	123,177	22.8
Butler	27,073	152,013	59,061	2.57	69,681	45.8
Cambria	7149	163,029	67,374	2.42	17,299	10.6
Cameron	1602	5913	4399	1.34	2153	36.4
Carbon	11,793	56,846	27,380	2.08	24,484	43.1
Centre	6986	123,786	46,195	2.68	18,720	15.1
Chester	49,316	376,396	139,597	2.70	132,971	35.3
Clarion	6946	41,699	18,022	2.31	16,072	38.5
Clearfield	6842	78,097	34,300	2.28	15,578	19.9
Clinton	3119	37,182	16,478	2.26	7038	18.9
Columbia	11,292	63,202	25,598	2.47	27,880	44.1
Crawford	24,671	86,169	40,462	2.13	52,540	61.0
Cumberland	19,587	195,257	77,108	2.53	49,599	25.4
Dauphin	21,655	237,813	102,684	2.32	50,152	21.1
Delaware	6757	547,651	211,024	2.60	17,536	3.2
Elk	3312	34,878	17,249	2.02	6697	19.2
Erie	22,122	275,572	108,585	2.54	56,142	20.4
Fayette	7523	145,351	61,406	2.37	17,807	12.3
Forest	4664	4802	8445	0.57	2652	55.2
Franklin	14,455	121,082	48,629	2.49	35,992	29.7
Fulton	4444	13,837	6184	2.24	9944	71.9
Greene	3938	39,550	15,982	2.47	9745	24.6
Huntingdon	10,118	44,164	19,286	2.29	23,170	52.5
Indiana	13,180	89,994	34,770	2.59	34,113	37.9
Jefferson	7548	46,083	21,242	2.17	16,375	35.5
Juniata	5364	20,625	8505	2.43	13,008	63.1
Lackawanna	12,055	219,039	91,707	2.39	28,793	13.1
Lancaster	50,966	422,822	156,462	2.70	137,730	32.6
Lawrence	12,937	96,246	38,844	2.48	32,055	33.3
Lebanon	13,034	113,744	44,634	2.55	33,215	29.2
Lehigh	17,465	291,130	118,335	2.46	42,968	14.8
Luzerne	23,307	328,149	138,724	2.37	55,132	16.8
Lycoming	17,441	118,710	49,580	2.39	41,759	35.2
McKean	6321	47,131	21,454	2.20	13,886	29.5
Mercer	17,996	121,003	48,689	2.49	44,724	37.0
Mifflin	6729	46,197	19,641	2.35	15,827	34.3
Monroe	36,569	95,709	54,823	1.75	63,841	66.7
Montgomery	30,716	678,111	265,856	2.55	78,346	11.6
Montour	3315	17,735	6885	2.58	8539	48.1

Table 3. Continued

County	No. Wells	County Population	HU**	Population per HU**	No. People Served by Private Wells†	People Served by Private Wells† (%)
Northampton	17,456	247,105	95,345	2.59	45,241	18.3
Northumberland	9482	96,771	41,900	2.31	21,899	22.6
Perry	11,112	41,172	17,063	2.41	26,813	65.1
Philadelphia	486	1,585,577	674,899	2.35	1142	0.1
Pike	16,511	27,966	30,852	0.91	14,967	53.5
Potter	5273	16,717	11,334	1.47	7777	46.5
Schuylkill	14,685	152,585	66,457	2.30	33,717	22.1
Snyder	6913	36,680	13,629	2.69	18,605	50.7
Somerset	11,228	78,218	35,713	2.19	24,591	31.4
Sullivan	4254	6104	5458	1.12	4757	77.9
Susquehanna	12,682	40,380	20,308	1.99	25,217	62.4
Tioga	9955	41,126	18,202	2.26	22,493	54.7
Union	6178	36,176	12,886	2.81	17,344	47.9
Venango	9757	59,381	26,961	2.20	21,490	36.2
Warren	10,285	45,050	22,236	2.03	20,837	46.3
Washington	13,849	204,584	84,113	2.43	33,684	16.5
Wayne	16,997	39,944	28,480	1.40	23,839	59.7
Westmoreland	22,460	370,321	153,554	2.41	54,166	14.6
Wyoming	7804	28,076	11,857	2.37	18,479	65.8
York	43,441	339,574	134,761	2.52	109,464	32.2

*Data based on 1990 U.S. Census report.
**HU = Housing units.
†Estimated values.

use" doctrine. This means that within the Commonwealth's borders, people have certain nonexclusive rights of use, otherwise known as "usufructuary" rights, with respect to water but they cannot claim absolute ownership (Cunningham et al., 1993; Marquitz, 2003; Bishop, 2006; Dismukes, 2006; Weston, 2008; Department of Environmental Protection, 2009b). Along these same lines, riparian rights cannot be severed from the land with which it is associated (Bishop, 2006).

The American doctrine of reasonable use (commonly referred to as the "American Rule" or "reasonable user" doctrine) applies to the use of groundwater in Pennsylvania. According to this doctrine, a landowner can use as much groundwater beneath his property as needed for "natural and ordinary use," regardless of impact to neighboring groundwater supplies (Cunningham et al., 1993; Marquitz, 2003; Bishop, 2006 Dismukes, 2006; Department of Environmental Protection, 2009b). This usage would only be restricted if it were found by the courts to be negligent or have caused malicious damage to another's property (Marquitz, 2003; Bishop, 2006; Department of Environmental Protection, 2009b).

State Legislation

Not one comprehensive piece of legislation regulates water resources allocation in Pennsylvania. Over the years, however, a short list of state laws has been interpreted to require permits, registration, and/or reporting of withdrawals for certain uses and from specific water sources, including the Water Rights Act of 1939, the Pennsylvania Safe Drinking Water Act of 1971 (and subsequent amendments), the Water Well Drillers License Act of 1956, and Water Resources Planning Act of 2002 (Weston, 2008).

Perhaps the most relevant of these to the current discussion are the Safe Drinking Water Act and the Water Resources Planning Act—the former being directly applicable to water withdrawals that industry pursues with respect to the extraction of Marcellus Shale gas and the latter likely becoming a major influence on water management policy (and perhaps even natural gas drilling and production practices) in the future. Based on the 1996 court ruling in the case of Oley Township et al. versus DEP and Wissahickon Spring Water, Inc., DEP is obligated under the Safe Drinking Water Act to

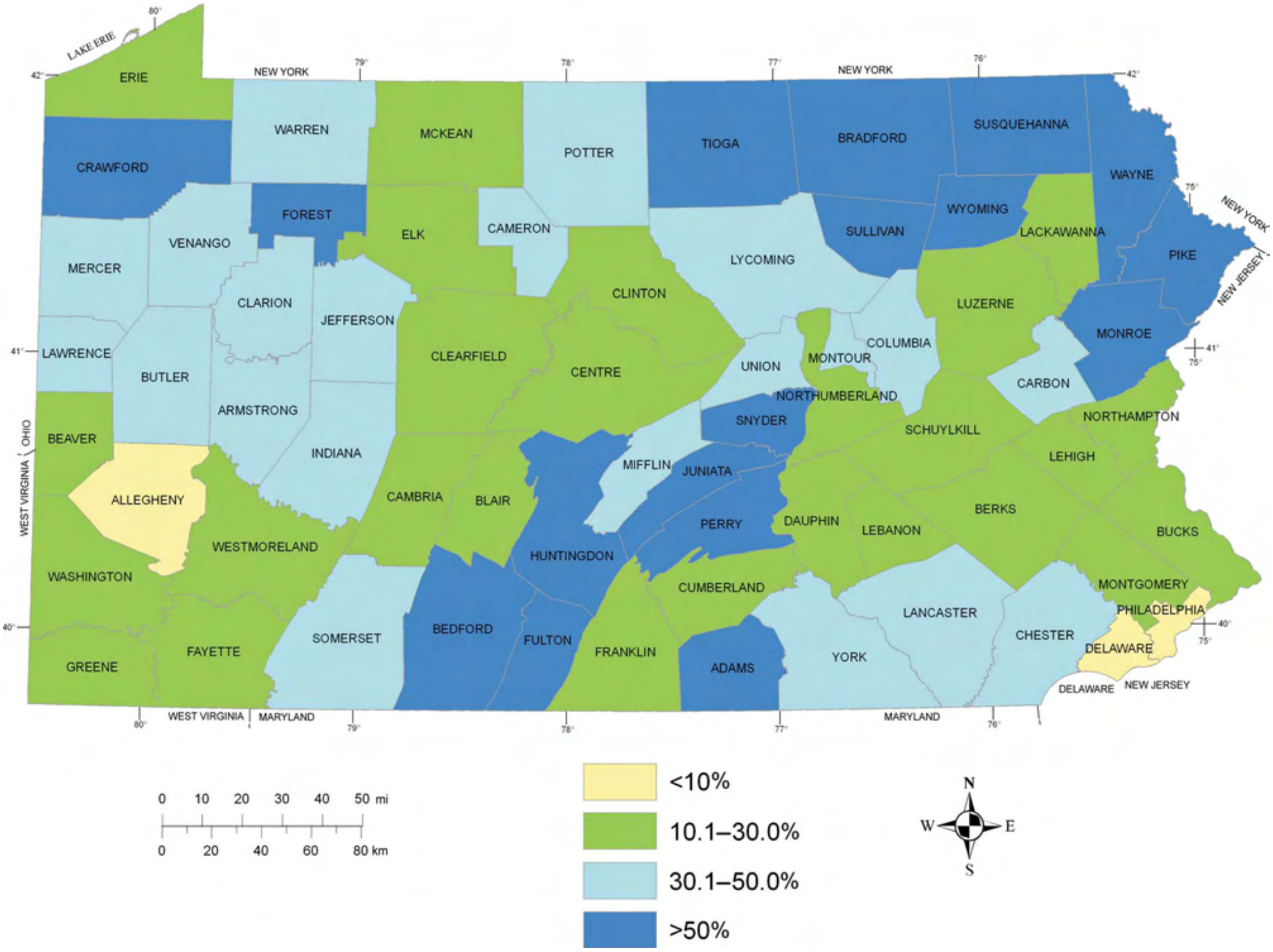


Figure 17. Estimated percent of Pennsylvania population relying on private water wells (based on 1990 U.S. Census data; S. Reese, Pennsylvania Geological Survey, compiler).

ensure that none of the water withdrawals it permits will impact other water resources (Bishop, 2006), a very specific directive. The Water Resources Planning Act requires that the existing State Water Plan be periodically updated and expanded to address matters of water budget, sustainable usage, and future water resource planning. To this end, the DEP and various stakeholders formed regional and statewide committees in 2003 and began working to develop a new State Water Plan that would replace the one created in 1983. The new document was signed into law in March 2009 (Department of Environmental Protection, 2009b). One of the derivative products of the new State Water Plan is an online basin-based water atlas for water resource planning. In addition, the Plan has incorporated certain registration and reporting requirements to track water usage; as an example, all water withdrawals in excess of 10,000 gal/day (37,854 L/day) must be reported to the Commonwealth (Carter, 2010). The reporting, management, and planning elements of the new State Water Plan could very well be used as a model for oil and gas permitting, unitization, and production in the future.

Federal Law: Implications for State Activities

In Pennsylvania, there exists an additional level of oversight when it comes to water resource allocation and planning. Three different organizations associated with the major river basins in the Commonwealth (Figure 16) provide guidance and water resource management support: the Delaware River Basin Commission, the Susquehanna River Basin Commission, and the Ohio River Valley Sanitation Commission.

The Delaware River Basin Commission (DRBC) was created in 1961 by the federal government's adoption of the Delaware River Basin Compact (Weston, 2006). As stated in the Compact, the DRBC's charge is to manage, regulate, allocate, and safeguard the water resources in the Delaware Basin.

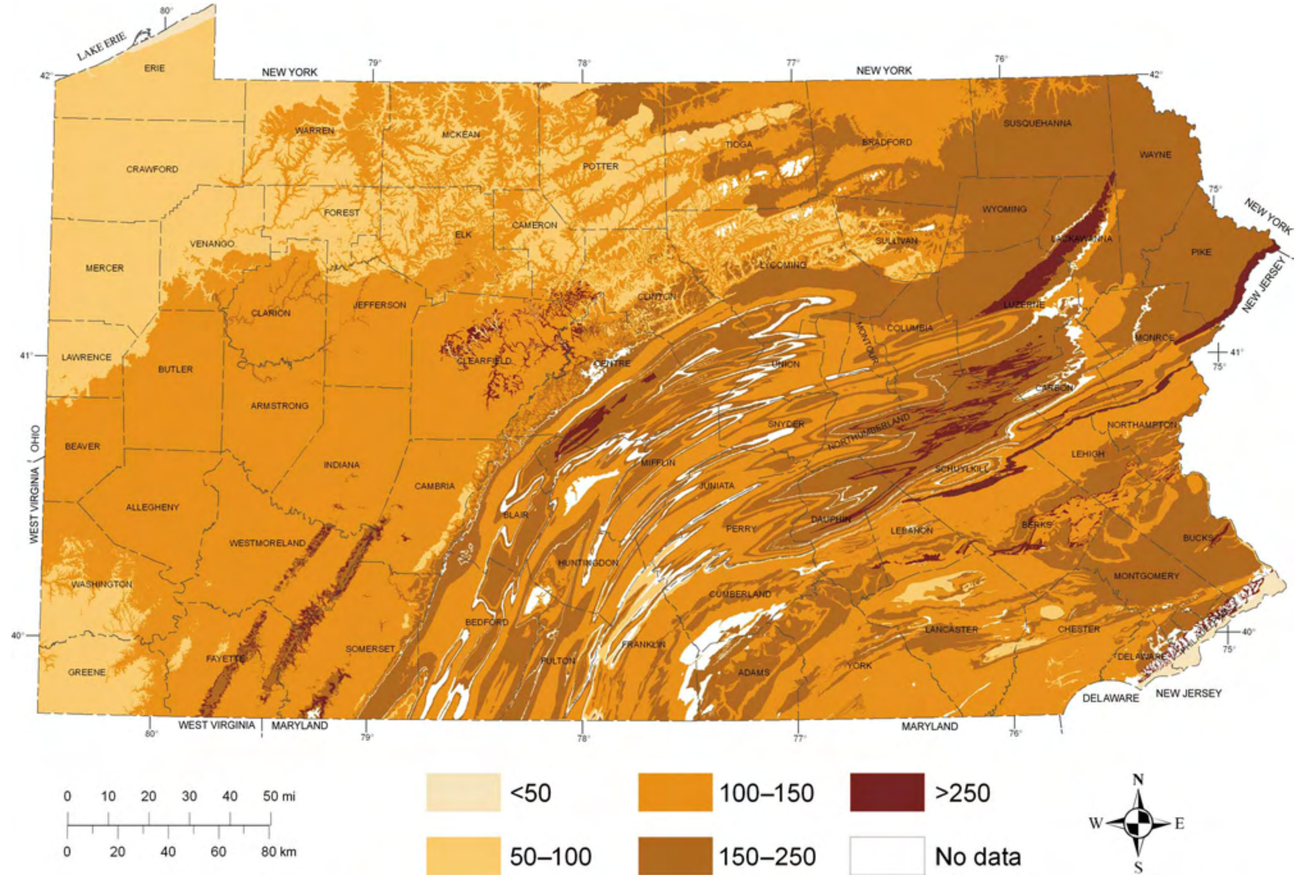


Figure 18. Median water well depth (feet below surface) by geologic unit of Pennsylvania (modified from Reese, 2010).

In December 1970, the Susquehanna River Basin Compact was signed by then President Nixon. The Susquehanna River Basin Commission (SRBC) appointed its first commissioners, chairman, and executive director in 1971 and so has been active in managing this basin, which incorporates New York, Pennsylvania, and Maryland, for 40 yr (Susquehanna River Basin Commission, 2011). The mission and current work of the SRBC are described by Heicher (see "Susquehanna River Basin Commission research related to natural gas development," also this issue).

A third commission that has a vested interest in the water resources of Pennsylvania is the Ohio River Valley Water Sanitation Commission (ORSANCO). The commission was created in 1948 via federal compact among eight states located in the Ohio River Valley Basin—New York, Pennsylvania, West Virginia, Virginia, Ohio, Kentucky, Indiana, and Illinois—to improve water quality by controlling and abating pollution (Ohio River Valley Water Sanitation Commission, 2011). The mission and regulatory purview of ORSANCO are presented by Schulte (see "The Ohio River Valley Sanitation Commission," also this issue).

Implications for Private Water Resource Management

Private water supplies, in the form of wells, springs, or cisterns, have been used by Pennsylvanians for centuries. In fact, it is estimated that 1.025 million Pennsylvanians currently rely on private water wells (S. Reese, 2011, personal communication) and that half of the Commonwealth's population is directly reliant on groundwater as their drinking water source, whether directly from these private wells or through larger community or municipal supplies that tap groundwater aquifers (Fleeger, 1999). Statistics compiled using private water supply data collected by the 1990 U.S. Census (the last one that specifically captured such data) indicate that for most counties in the Commonwealth, anywhere from about 10 to 80% of residents use private groundwater wells as their drinking water supply (Table 3;

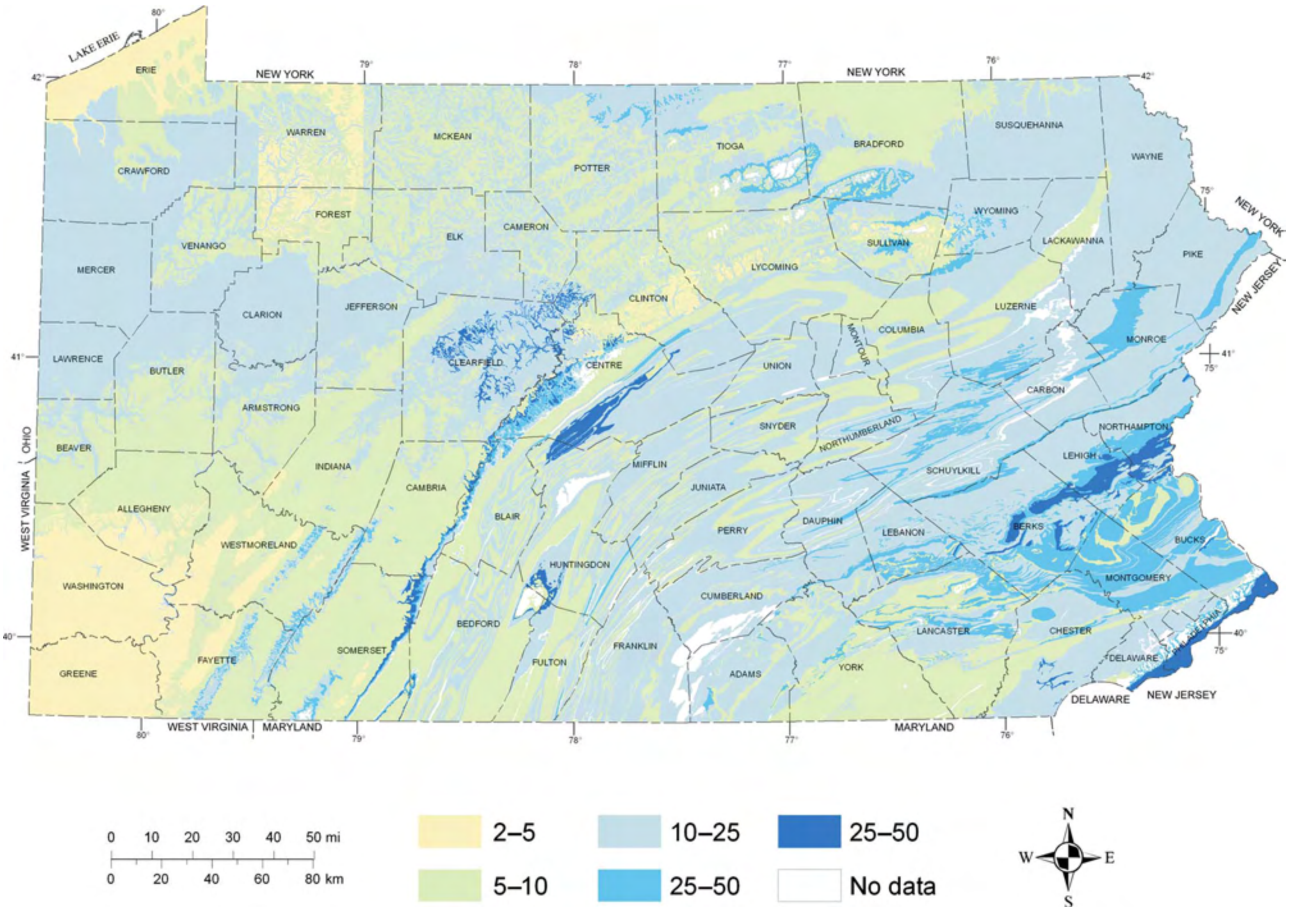


Figure 19. Median water well yield (in gallons per minute) by geologic unit of Pennsylvania (modified from Reese, 2010).

Figure 17). The only counties for which private water wells serve less than 10% of the population include Allegheny, Delaware, and Philadelphia. Six more counties, Cambria, Fayette, Lackawanna, Lehigh, Montgomery, and Westmoreland, have an estimated 10 to 15% of residents relying on private water wells. The remaining 58 counties in the Commonwealth have 15% or more of their residential populations relying on private groundwater wells for their water supply (Figure 17). Needless to say, groundwater quantity and quality are important issues to those living in the Commonwealth.

The Pennsylvania Groundwater Information System (PAGWIS), the state's online digital database of water well, spring, and water quality data, was created by the Survey under the auspices of the Water Well Drillers License Act of 1956. This act, also referred to as Pennsylvania Act 610, imposed a legislative mandate on the Survey to license water well drillers, collect data on the drilling and abandonment of water wells, and make these data available to the public. The Survey's procedures for collecting and sharing these water well data with the public have evolved substantially during the past several decades, with perhaps the most important being digital data submission requirements and public data sharing via the Web.

Based on data extracted from PAGWIS in October 2010, the average water well depth in Pennsylvania ranges between 65 and 340 ft (20–104 m; Figure 18), with bed rock encountered at depths of about 15 to 60 ft (5–18 m). The average static water level in these wells range from 20 to 105 ft (6–32 m), and average yields range from about 5 to 100 gal/min (19–379 L/min) (Figure 19) (Carter, 2010; Reese, 2010). These data indicate that Pennsylvanians using a water well as their drinking water source are obtaining that water from relatively shallow groundwater aquifers, that is, within the uppermost 200 to 300 ft (61–91 m) of bed rock. The issue of just how deep the deepest fresh groundwater occurs in the subsurface in Pennsylvania is currently being evaluated by the DEP through a collaborative work group of state agencies, research institutions, and oil and gas companies that evolved from other Marcellus Shale gas regulatory discussions between the DEP and industry (E. Pine, 2011, personal communication).

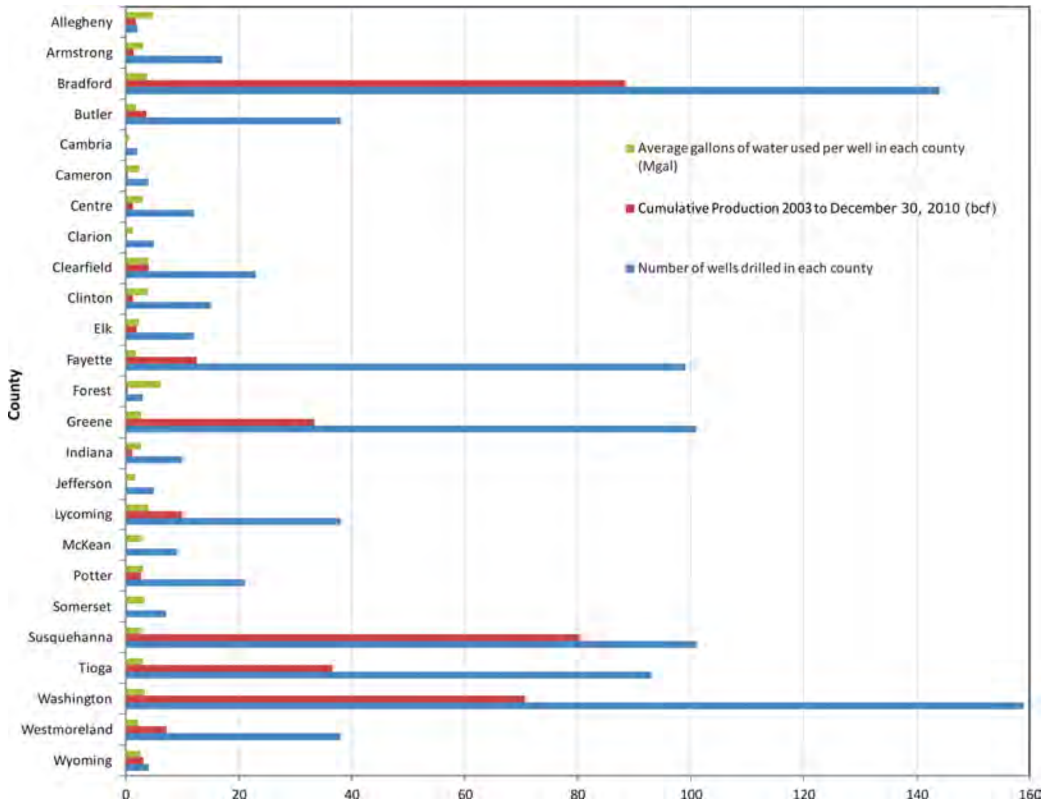


Figure 20. Comparison of Marcellus drilling, completion, and production statistics by county (Department of Environmental Protection, 2011e; Pennsylvania Internet Record Imaging System/Wells Information System, 2011).

Figure 20 illustrates the average frac water usage per well in each county that has experienced Marcellus Shale gas drilling. Based on the water well statistics cited above, it is not surprising that most of the counties where Marcellus Shale gas drilling is occurring have residents who rely on private water supplies. Although we do not presume to know the exact source(s) and proportions of surface water and/or groundwater used by Marcellus Shale operators in different parts of the Commonwealth, the sheer magnitude of private water wells across the state (Figure 21) suggests that water quantity and quality are particularly important to Pennsylvania residents and that there might be times or places during which a perceived competition exists among multiple users.

WATER MANAGEMENT AND SHALE GAS PRODUCTION

When it comes to the Marcellus Shale gas play, prudent water management is not only important for conserving water supplies but also for maximizing gas well production. The intent of this section is to discuss frac water usage relative to shale gas production using publicly available data for known Marcellus-producing wells. To this end, we gathered Marcellus Shale well completion information for the period of 2005 through 2010 from PA*IRIS/WIS and evaluated these data in collaboration with Mr. Austin Mitchell of Carnegie Mellon University, who assisted with quality control and statistical evaluations of hydraulic fracturing data garnered from well completion reports. We obtained Marcellus Shale well production data for the period of 2003 through 2010 from two different sources: PA*IRIS/WIS and the DEP Oil and Gas Reporting-Electronic (OGRE) Web site (Department of Environmental Protection, 2011e; Pennsylvania Internet Record Imaging System/Wells Information System, 2011). Specifically, annual production data for Marcellus-producing wells for the period of 2003 to 2008 were obtained from PA*IRIS/WIS, and more recently acquired Marcellus production data, including semiannual production reports required by Pennsylvania Act 15 of 2010, were obtained from OGRE.

Water Usage

As of this writing, obtaining water to drill and hydraulically fracture Marcellus wells has not been an impediment to operators in Pennsylvania (Veil, 2010). The volume of water used while drilling a Marcellus well depends on both the drilling method and the well's total depth. Wells drilled on air will use less water than

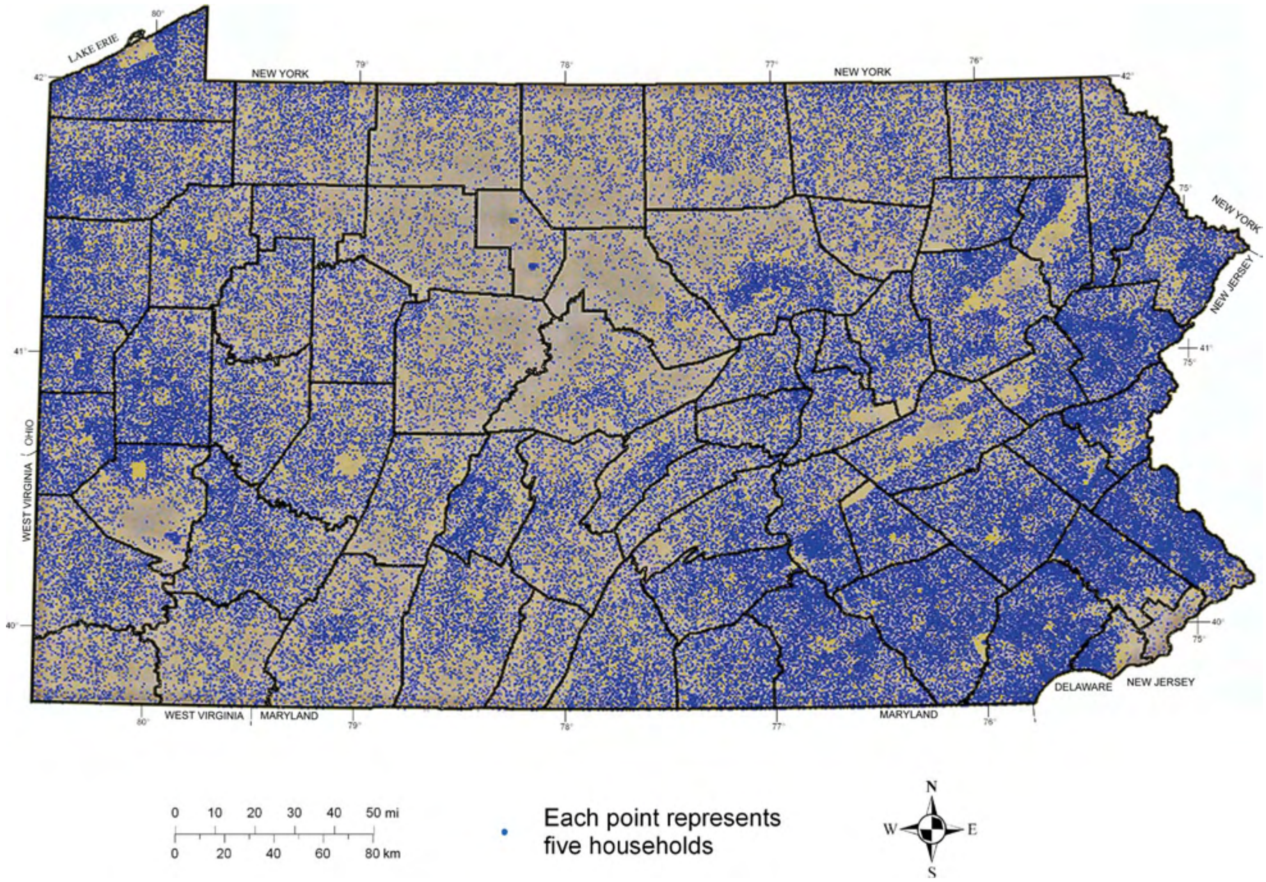


Figure 21. Private water supplies in use across Pennsylvania (based on 1990 U.S. Census data; M. Moore and S. Reese, Pennsylvania Geological Survey, compilers).

wells drilled with mud but tend to experience more hole-caving problems. Veil (2010) estimates that on average, 80,000 gal (302,833 L) are needed to drill a typical Marcellus well. Additional water is required, however, to hydraulically fracture that well and complete it for production. Based on available Marcellus well completion records, the amount of water used in frac jobs ranged from 25,000 to 15.9 millions of gallons (94,635–60 million liters) of water and averaged 2.9 millions of gallons (109,777 L) (Pennsylvania Internet Record Imaging System/Wells Information System, 2011).

Shale Gas Production

Table 4 lists the number of wells and cumulative production for each of the 27 Pennsylvania counties where Marcellus wells have been completed. Most of the Marcellus wells completed between 2005 and 2010 were drilled in Bradford, Fayette, Greene, Susquehanna, Tioga, and Washington counties. Based on these publicly available data reported by operators to the state, a Marcellus Shale gas well in Pennsylvania produces, on average, 1.3 mmcf/day (Department of Environmental Protection, 2011e; Pennsylvania Internet Record Imaging System/Wells Information System, 2011).

Clearly, shale gas production is not uniform across the state. Although Washington County has the longest history of Marcellus-producing wells (2005 to present), Bradford and Susquehanna counties have each produced more gas from the Marcellus even though they only began to experience Marcellus exploration in 2009 (Figure 20). Specifically, Bradford and Susquehanna counties report a cumulative production of 88.4 and 80.5 bcf of gas, respectively, compared with 70.7 bcf for Washington County. In Tioga and Greene counties, cumulative Marcellus production through 2010 was 36.45 and 33.4 bcf, respectively. The cumulative Marcellus production reported in each of the remaining counties is less than 20 bcf (Figure 20).

Looking at Pennsylvania as a whole, the U.S. Energy Information Administration (EIA) has reported that as of mid-2011, daily Marcellus Shale gas production exceeds 2.8 bcf. Two core areas of the state, northeastern and southwestern Pennsylvania, are responsible for

Table 4. Summary of Marcellus Well Distribution and Average Production by County

County	No. Marcellus Wells	No. Producing Marcellus Wells	Average Daily Production (mcf/day)
Allegheny	2	2	3467
Armstrong	17	15	273
Blair	1	0	–
Bradford	144	126	3137
Butler	38	27	277
Cambria	2	1	38
Cameron	4	3	186
Centre	12	10	510
Clarion	5	5	82
Clearfield	23	18	993
Clinton	15	12	1084
Elk	12	6	736
Fayette	99	85	280
Forest	3	1	609
Greene	101	97	806
Indiana	10	10	456
Jefferson	5	4	228
Lycoming	38	17	1570
McKean	9	5	53
Potter	21	17	423
Somerset	7	1	25
Sullivan	2	0	–
Susquehanna	101	83	2942
Tioga	93	77	2397
Washington	159	151	1176
Westmoreland	38	34	455
Wyoming	4	3	7372

this impressive figure, with roughly 2 bcf being produced in the northeastern part of the Commonwealth and the remaining 0.8 bcf coming from southwestern Pennsylvania (U.S. Energy Information Administration, 2011). Based on the EIA's report, Pennsylvania's daily Marcellus production in these two regions (southwestern and northeastern) has increased threefold and fivefold, respectively, since the beginning of 2010 (U.S. Energy Information Administration, 2011).

Hydraulic Fracturing Methods

As of June 2011, operators have reported various types of frac jobs on Marcellus well completion records they have filed with the state. These include water, slickwater, backflow water, linear gel, gelled water, and cross-linked gel (Figure 22). Slickwater fracs are composed of approximately 99.5% water based on a report by the Groundwater Protection Council and ALL Consulting (2009). Regardless of the nomenclature used, then, it is evident that the most of the Marcellus well stimulations are using water-based fracs.

In general, Marcellus wells produce more gas when more water is used in the frac job. This trend is far from linear, however, because many other factors also impact the amount of natural gas produced from a Marcellus well, such as the drilling and fracing methods used, reservoir heterogeneities, the numbers of frac stages completed, and the length of each stage. A geostatistical assessment of how and to what extent these factors may influence shale gas production, although scientifically intriguing and certainly worthwhile, is beyond the scope of this article.

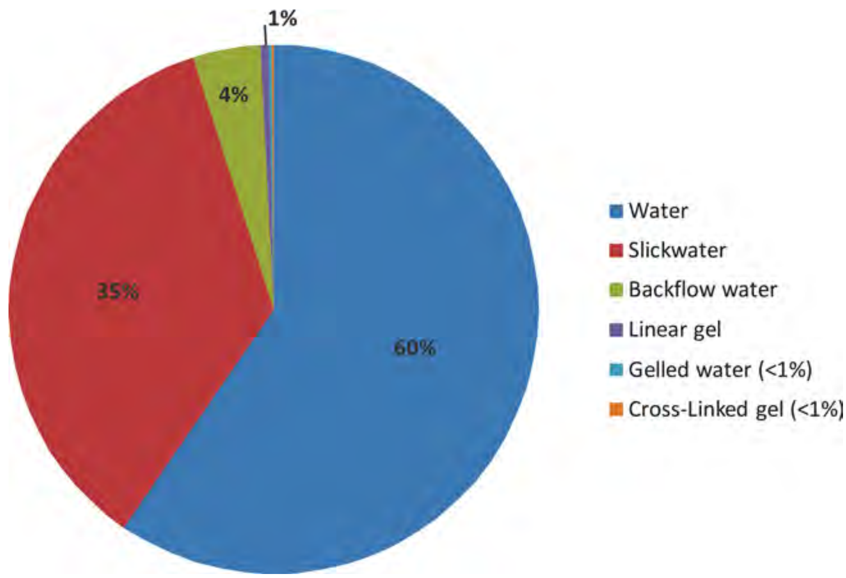
According to the Groundwater Protection Council (Groundwater Protection Council and ALL Consulting, 2009), less water should be needed per shale gas frac job as technology and methods improve during time. We have not yet seen this trend in Pennsylvania (Figure 23) (Pennsylvania Internet Record Imaging System/Wells Information System, 2011), but perhaps as more completion data become publicly available and hydraulic fracturing techniques are further refined, the average reported water usage per frac job will stabilize.

SUMMARY AND CONCLUSIONS

Pennsylvania has a rich history of petroleum exploration and production and has served as the proving ground for many of the industry's drilling and completion methods. The Commonwealth has seen historically notable wells such as the Newton, Haymaker, and Speechley produce millions of cubic feet of gas per day, serving communities and industries throughout western Pennsylvania. In addition, hydraulic fracturing of deep gas reservoirs has been used in the state for almost 60 yr, first being used in Punxsutawney-Driftwood field at the Oriskany-producing State of Pennsylvania Tract 28 No. 3 well (Elk County).

Pennsylvania's modern oil and gas regulations postdate oil and gas drilling activities by roughly 100 yr. In fact, it could be said that today's regulations have "grown up" with the petroleum industry in Pennsylvania

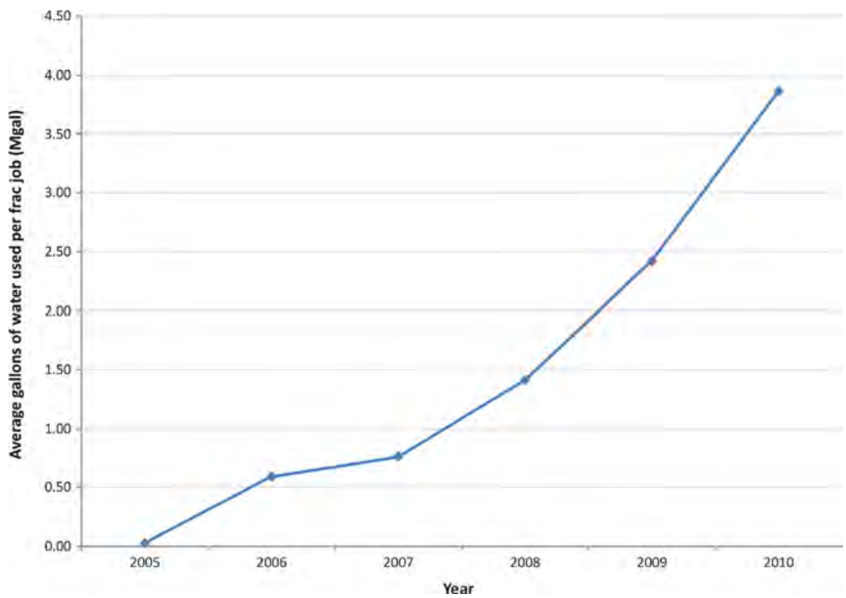
Figure 22. Pie chart showing frac fluids used by operators in Pennsylvania (Pennsylvania Internet Record Imaging System/Wells Information System, 2011).



and continue to evolve with the changing landscape of unconventional gas resource exploration and development. As of June 2011 (and almost 7 yr into the Marcellus Shale gas play), the DEP has permitted 6488 Marcellus wells, 1098 of which have been interpreted as known Marcellus completions by the Survey. Publicly available completion and production data indicate that the average volume of water used to hydraulically fracture a Marcellus well is 2.9 millions of gallons and that an average Marcellus well produces 1.3 mmcf/day. The overwhelming majority of Marcellus completions are horizontal wells.

Within the past couple of years, water management issues have been brought to the forefront of discussions among regulators, the shale gas industry, and citizens because matters of scale, logistics, and sometimes contending uses affect Pennsylvanians in one way or another. The volumes of water needed to complete Marcellus frac jobs, the prevalence of private water supply wells across the state, the State Water Plan, and oversight by river basin commissions are just a few of the reasons why water supply issues must be an integral part of the regulation and development of unconventional shale gas in Pennsylvania.

Figure 23. Usage of water for hydraulic fracturing of Marcellus Shale gas wells by year (Pennsylvania Internet Record Imaging System/Wells Information System, 2011).



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