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Prepared in cooperation with the U.S. Department of Energy

Water Resources and Shale Gas/Oil Production in the Appalachian Basin—Critical Issues and Evolving Developments

Introduction

Unconventional natural gas and oil resources in the United States are important components of a national energy program. While the Nation seeks greater energy independence and greener sources of energy, Federal agencies with environmental responsibilities, state and local regulators and water-resource agencies, and citizens throughout areas of unconventional shale gas development have concerns about the environmental effects of high volume hydraulic fracturing (HVHF), including those in the Appalachian Basin in the northeastern United States (fig. 1). Environmental concerns posing critical challenges include the availability and use of surface water and groundwater for hydraulic fracturing; the migration of stray gas and potential effects on overlying aquifers; the potential for flowback, formation fluids, and other wastes to contaminate surface water and groundwater; and the effects from drill pads, roads, and pipeline infrastructure on land disturbance in small watersheds and headwater streams (U.S. Government Printing Office, 2012). Federal, state, regional and local agencies, along with the gas industry, are striving to use the best science and technology to develop these unconventional resources in an environmentally safe manner.

(Photograph courtesy of Dennis Risser, USGS)

Water intake and water-level monitoring station for surface-water withdrawal at Fall Brook Creek, Ward Township, Tioga County, Pennsylvania.

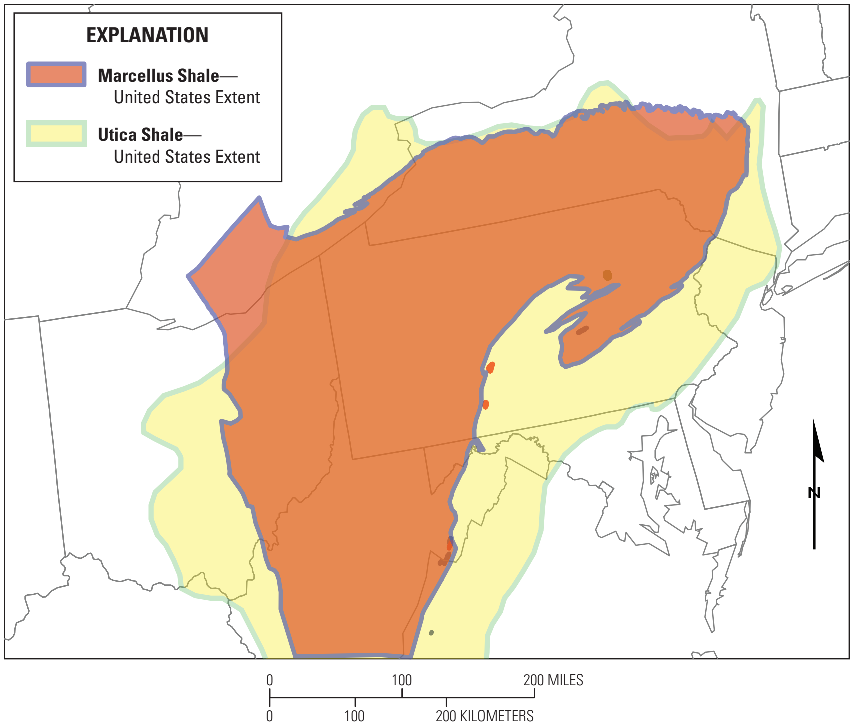


Figure 1. Map showing extent of the Marcellus Shale and Utica Shale in the Appalachian Basin in the northeastern United States.

Some of these concerns were addressed in U.S. Geological Survey (USGS) Fact Sheet 2009–3032 (Soeder and Kappel, 2009) about potential critical effects on water resources associated with the development of gas extraction from the Marcellus Shale of the Hamilton Group (Ver Straeten and others, 1994). Since that time, (1) the extraction process has evolved, (2) environmental awareness related to high-volume hydraulic fracturing process has increased, (3) state regulations concerning gas well drilling have been modified, and (4) the practices used by industry to obtain, transport, recover, treat, recycle, and ultimately dispose of the spent fluids and solid waste materials have evolved.

This report updates and expands on Fact Sheet 2009–3032 and presents new information regarding selected aspects of unconventional shale gas development in the Appalachian Basin (primarily Virginia, West Virginia, Maryland, Pennsylvania, Ohio, and New York). This document was prepared by the USGS, in cooperation with the U.S. Department of Energy, and reviews the evolving technical advances and scientific studies made in the Appalachian Basin between 2009 and the present (2013), addressing past and current issues for oil and gas development in the region.

Water Supply

Hydraulic fracturing of Appalachian Basin shales uses about 3 to 5 million gallons of water per horizontal well (King, 2012). Anecdotal information from drillers and the Susquehanna River Basin Commission indicates that approximately 10 percent of all HVHF water used is recovered from the drilled and fractured formation in northeastern Pennsylvania (Susquehanna River Basin Commission, 2013). Any water remaining downhole is considered to be a consumptive loss and is no longer part of the hydrologic cycle.

Sustainable water-supply practices for HVHF include the continual but low-rate (relative to streamflow) withdrawal of water from streams to onsite holding tanks or impoundments (fig. 2). This practice is designed to allow for adequate downstream flow for aquatic ecosystems and downstream water users. Permit requirements that prohibit water withdrawals during low-streamflow (drought) conditions have resulted in minimal additional stream and (or) groundwater impacts in Pennsylvania where intensive hydraulic fracturing has recently taken place (Pennsylvania Environmental Digest, 2010). Permitting of stream and groundwater withdrawals by state and regional agencies has proven to be an effective tool in mitigating the effects of HVHF water use during drought conditions. Consumptive loss of water over many decades by conventional or unconventional oil and gas development, among other consumptive uses, has yet to be quantified.

The gas industry has found that non-potable water sources may suffice in the HVHF process, at least in Appalachian Basin shales. The current best-management practice also recycles much of the flowback water into the next batch of HVHF fluid after treatment to remove suspended solids, thus reducing the amount of freshwater needed for drilling and hydraulically fracturing the next well. Non-potable water sources such as wastewater-treatment-plant effluent have been successfully used for HVHF with proper chemical treatment, and the Commonwealth of Pennsylvania has encouraged a study of mine wastewaters for such use (Pennsylvania Department of Environmental Protection, 2012).

A

B

C

(Photographs courtesy of the Susquehanna River Basin Commission)

Figure 2. *A,* Holding-tank facility; *B,* filling of the lagoon using tanker trucks; and *C,* a freshwater holding lagoon.

Potential Effects on Drinking Water

The U.S. Environmental Protection Agency (USEPA) is conducting a study on the potential impacts of hydraulic fracturing on drinking-water resources. Because of the increasing development of gas and oil resources in the United States and comments received from stakeholders during development of the Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources (U.S. Environmental Protection Agency, 2011), the scope of the research includes the full life cycle of water used in the hydraulic fracturing process, from acquisition of the water through the mixing of chemicals and well stimulation to the management of flowback and produced water and their ultimate treatment and disposal. The USEPA study is collecting and analyzing new and existing data to evaluate possible impacts to both surface water and groundwater (fig. 3). The data are provided by nine hydraulic fracturing service companies and nine well operators, and are found in publicly-available databases to better understand the products and chemicals used in hydraulic fracturing fluids, accidental releases of chemicals, well practices, water use, and wastewater treatment and disposal. Laboratory studies are being conducted to develop analytical methods for chemicals known to be used in hydraulic fracturing fluids and assess the treatability of hydraulic fracturing wastewaters. Case studies provide new information on potential impacts at existing well sites, and computer modeling estimates the conditions needed for possible groundwater impacts to occur during generalized well scenarios. The USEPA research team is working in consultation with other Federal agencies, state and interstate regulatory agencies, industry, non-governmental organizations, and others in the private and public sector. In December 2012, USEPA published a progress report (U.S. Environmental Protection Agency, 2012a) describing the research projects underway as part of the study and the progress made as of September 2012. The study plan and progress report are available on USEPA's website (http://www.epa.gov/hfstudy).

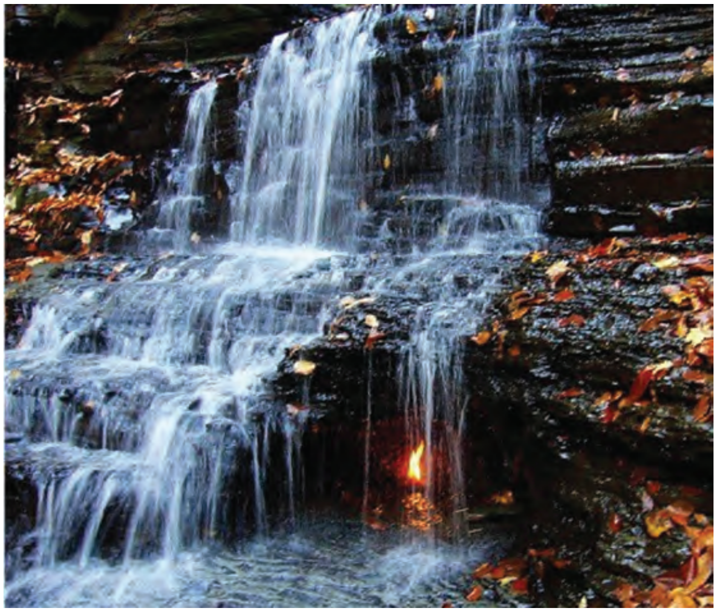
Figure 3. Research activities and objectives from the 2012 U.S. Environmental Protection Agency's progress report (table 8, p. 24).

Activity	Objective
Analysis of existing data	Gather and summarize existing data from various sources to provide current information on hydraulic fracturing activities; includes information requested of hydraulic fracturing service companies and oil and gas operators.
Scenario evaluations	Use computer modeling to assess the potential for hydraulic fracturing to impact drinking water resources.
Laboratory studies	Conduct targeted experiments to test and develop analytical detection methods and to study the fate and transport of selected chemicals during wastewater treatment and discharge to surface water.
Toxicity assessment	Identify chemicals used in hydraulic fracturing fluids or reported to be in hydraulic fracturing wastewater and compile available chemical, physical, and toxicological properties.
Case studies	
Retrospective	Study sites with reported contamination to understand the underlying causes and potential impacts to drinking water resources.
Prospective	Develop understanding of hydraulic fracturing processes and their potential impacts on drinking water resources.

The recent (2011–13) slowdown in natural gas drilling resulting from low natural gas prices has reduced the demands for water withdrawals for natural gas drilling in Pennsylvania. If this diminished gas well development rate continues, the use of water resources for HVHF likely will decrease in the short term. The need to address water-resource issues remains, however. The current slowdown will increase the total duration for HVHF water consumption because it leads to a longer time frame for the full development of the oil/gas resource in the Appalachian Basin. The longer time frame necessitates development of effective management strategies for the region's water resources in light of the increasingly variable climate.

Stray Gas

When methane gas appears where it is not wanted it is called stray gas. Incidents of stray gas occurrences in freshwater aquifers, specifically the presence of methane in water wells, have been documented during shale-gas development in localized areas of northern Pennsylvania (Osborn and others, 2011; Jackson and others, 2013). The likely mechanism for the occurrence of stray gas in areas of active gas development is leaky cement seals that do not effectively isolate freshwater aquifers from shallow gas zones penetrated by the gas well (Bruffato and others, 2003). Determination of cause and effect for incidents of stray gas migration is not straightforward



(Photograph courtesy of Matthew Conheady (www.nyfalls.com))

Figure 4. Natural gas seep at Chestnut Ridge County Park, Eternal Flame Falls, Erie County, New York.

(fig. 4), especially without local background information (Ground Water Protection Council, 2012). Thermogenic (geologically derived) methane is known to occur naturally throughout the Upper Devonian strata overlying the Marcellus Shale, including the fractured rocks that serve as aquifers used for drinking water (Molofsky and others, 2011). Samples from water wells overlying oil and gas bearing formations commonly show the presence of methane gas, perhaps from multiple sources, even in areas that have not yet been drilled (Molofsky and others, 2013; Mulder, 2012; Kappel and Nystrom, 2012). In 2011, in recognition of the threat to public health and safety as well as the environment, the Commonwealth of Pennsylvania revised the regulations concerning the design, installation, and cementing of surface and intermediate casings to help minimize gas migration and protect water supplies (The Pennsylvania Bulletin, 2011).

Abandoned and orphaned wells are another environmental resource concern related to stray gas. The number of abandoned wells ranges in the tens to hundreds of thousands in various states, and generally, only a small percentage of these wells have been field located. Additional attention by state and Federal regulators is being given to characterization of the distribution and condition of abandoned wells that penetrate drinking-water aquifers and that may be another avenue for stray gas and groundwater migration (Texas Railroad Commission, 2000; U.S. Geological Survey, 2013). For instance, in June 2012, an abandoned gas well drilled in 1932 erupted with water and methane related to the drilling of a nearby gas well in Union Township, Tioga County, Pennsylvania. (StateImpact Pennsylvania, 2012). This issue has been and will continue to be addressed by the gas industry and by the states regulating oil and gas development.

Radioactivity in Shale Waste

Radium (Ra) is a naturally occurring radioactive material (NORM) that is present as a component of the Marcellus Shale and is produced from the radioactive decay of high concentrations of uranium and thorium found naturally within black shales (Schmoker, 1981; Bank and others, 2010). Uranium is poorly soluble in water under the anoxic (oxygen-poor) conditions typical of black shales, but radium is readily dissolved and transported (Rowan and others, 2011; Szabo and others, 2012). Although two of the radium isotopes (^{223}Ra and ^{224}Ra) have short half-lives (a few days), the other two isotopes, ^{226}Ra and ^{228}Ra, have 1,622 and 5.75 year half-lives, respectively; if dispersed in the environment, these isotopes will persist for long periods of time. Chemically, radium behaves similarly to calcium (Ca), strontium (Sr), and barium (Ba). Radium can readily precipitate along with salts of Ca, Sr, and Ba in groundwater or produced brines having high total dissolved solids to form scale in or on drilling equipment (fig. 5) or in on-site storage tanks or brine pits. The scale precipitate is rich in radium, and that may emit radiation to those working near such equipment over time. The scale may eventually be removed from the pipe and then is added to the waste stream from drilling that must go to a landfill or can be dispersed to the local soil. Leachates from these materials may contain radium that may eventually reach the local water table or run off to the local watershed.

The concentrations of NORM present in black shale drill cuttings, drilling mud, scale and sludge build-ups, fluids from spills, treatment residuals, and other waste products may be greater than background environmental levels. Disposal of these waste products on-site or in landfill burial

[Photo courtesy of Creative Commons.org. Scale bar at bottom in centimeters]

Figure 5. Barium sulfate scale in drilling pipe. Radium can readily precipitate with these barium salts and may emit radiation to those working near such equipment, and may be potentially released to the environment if improperly disposed.

Radium in Groundwater

Data on radium distribution and occurrence in the freshwater aquifers of the Appalachian region are limited (Szabo and others, 2012), but median total (combined) radium activity in six samples of brine from oil and gas wells in western Pennsylvania was about 1,200 picocuries per liter (pCi/L) (Dresel and Rose, 2010). Radium (Ra) concentrations in Marcellus Shale fluids are distinctly higher than those from those brines—typically between 5,000 and 15,000 pCi/L (Rowan and others, 2011). The high concentrations of Ra from the "produced water" (formation brines) can potentially exceed drinking-water standards even after treatment and dilution with fresh water. Radium dispersed to soils, sludges, and sediments from the brines can undergo long-term low-level leaching into water bodies, but release can be accelerated with sudden changes in soil or water chemistry. The disposition of Ra-enriched waste fluids and solids in relation to drinking water supplies has yet to be quantified, but the health risk of radium ingestion, from any source, is associated with increased human cancer risk (U.S. Environmental Protection Agency, 1999). The health risk is proportional to the exposure as radium is readily stored in bone from where it emits radioactivity into bone and surrounding tissue. The Maximum Contaminant Level (MCL) in drinking water for combined radium isotopes ^{226}Ra and ^{228}Ra and the alpha particles emitted during radium decay is not to exceed 5 and 15 (pCi/L), respectively (U.S. Environmental Protection Agency, 2000). The establishment of an MCL is based on the Maximum Contaminant Level Goal (MCLG), whereby EPA considers the risk to sensitive subpopulations (infants, children, the elderly, and those with compromised immune systems) of experiencing a variety of adverse health effects. Further information on these goals and levels can be found at http://water.epa.gov/lawsregs/rulesregs/regulatingcontaminants/basicinformation.cfm.

sites will require assessments of both gamma radiation emissions and radionuclide concentrations in solids and liquids (U.S. Environmental Protection Agency, 2008). Dispersal of radium into soils may have several effects in addition to the potential increase in gamma radiation exposures and the potential for leaching into water resources. The ^{226}Ra emits radon gas as a decay product; structures built on the soil that contains ^{226}Ra-bearing waste may have high levels of indoor-air radon that require monitoring due to this type of exposure. Plants may also take up the ^{226}Ra from soil. Recently (2013), the Commonwealth of Pennsylvania has initiated a study of the radioactivity of the Marcellus Shale through all aspects of the gas drilling, extraction, and waste disposal (Pennsylvania Department of Environmental Protection, 2013).

Fluid Waste Treatment and Disposal

Flowback fluid is recovered following HVHF and during the initial stages of gas production in the first 2 to 3 weeks following HVHF; it consists mostly of the water and chemical additives which have been modified during the hydrofracturing process. The flowback fluid can be treated at the well and recycled for use in the next HVHF well (Maloney and Yoxtheimer, 2012). Eventually though, as dissolved salts and minerals accumulate, this recovered fluid must receive proper treatment, transportation, and disposal.

During the early development of the Marcellus Shale in 2008, local municipal wastewater-treatment plants in Pennsylvania were used to process these waste fluids (Soeder and Kappel, 2009). These plants were not designed to treat the complex chemistry of flowback fluids, especially the high total dissolved solids (TDS), halides, metals, chemical additives, organic compounds, and radiological materials produced during and following the HVHF process. Most of these dissolved materials can pass untreated through the wastewater plant and into the receiving water, creating water-quality problems downstream from the plant outfall (StateImpact Pennsylvania, 2013). In 2010, the Commonwealth of Pennsylvania strongly requested that only advanced industrial wastewater-treatment facilities capable of handling the various types of flowback fluid be used (Indiana Gazette, 2011). The gas industry complied with this request, which in turn, caused many drillers to recycle flowback fluids to reduce disposal volumes and expenses.

The high-salinity formation fluids (Blauch and others, 2009; Haluszczak and others, 2013) present an additional wastewater-treatment and disposal challenge (Lutz and others, 2013). These formation waters, called brines, may contain relatively high concentrations of sodium, chloride, bromide, and other inorganic constituents, such as arsenic, barium, other heavy metals, and associated radionuclides that substantially exceed drinking-water standards (Lutz and others, 2013). When these materials are removed at advanced wastewater-treatment facilities, they create a concentrated solid waste (sludge residual) that requires special handling and disposal in properly designed and regulated landfills. The radiological constituents pose problems even for the advanced treatment facilities, and any residual wastes that are created may have gamma radiation emissions greater than background levels (U.S. Environmental Protection Agency, 2008).

Deep Well Injection of Fluid Waste

The cost of disposal of residual waste from hydraulic fracturing operations using deep-well injection to underground injection control (UIC) wells compared favorably to advanced wastewater-treatment costs. UIC wells have been used for hydraulic fracturing wastewater disposal for conventional and unconventional oil and gas development across the United States. These UIC wells are regulated by some states and the USEPA and have been an important means of waste disposal for many years (U.S. Environmental Protection Agency, 2012b). The disposal formations are generally deep, saline aquifers below drinking-water aquifers and in some cases below gas/oil-producing horizons. Unfortunately, the geologic formations capable of accepting these fluids are limited in Pennsylvania and New York (Pennsylvania State Extension, 2011; McCurdy, 2011). Wastewater from many shale gas wells in Pennsylvania is transported to UIC wells in Ohio and Kentucky for disposal; these UIC wells at present have the capacity to accept wastes.

Induced seismicity can occur when fluids are injected into deep bedrock formations penetrated by the UIC wells, where they may lubricate pre-existing geologic faults and cause the faults to slip, creating small earthquakes. Although most UIC wells have been used successfully over many decades, a number of earthquakes occurred near Youngstown, Ohio, in 2012 as a result of shale flowback fluid disposal into a new, deep-injection well (Ohio Department of Natural Resources, 2012). A similar situation occurred in Arkansas from UIC wells used for disposal of residual wastewater from Fayetteville Shale wells (Horton, 2012). UIC well operators, state regulatory agencies, and the USEPA have been re-evaluating the capacity of these disposal wells to handle wastes in a manner that will avoid induced seismic activity in the future.

Solid Waste Disposal

Horizontal drilling of black shales creates long boreholes within the organic-rich layers and generates hundreds of tons of drill cuttings (Maloney and Yoxtheimer, 2012). Black shales like the Marcellus Shale contain reduced sulfide minerals that can oxidize when exposed to air and rainwater, producing acidic, metals-rich leachate. The oxidized forms of some of these metals from the minerals are much more water-soluble and thus more mobile than in the original reduced state, especially under acidic conditions. Drill cuttings in West Virginia are typically disposed of on-site by burial in the mud pit (West Virginia Department of Environmental Protection, 2010). In Pennsylvania, it has been observed that the drill cuttings are mixed with wood chips/sawdust or absorbent polymer to reduce water content (fig. 6) and then are taken to secured landfills or are reprocessed for other uses (Drilling Waste Management Information System, 2013).

The potential for oxidation and leaching of radionuclides and toxic metals associated with organic matter in black shale cuttings led to a preliminary assessment of the geochemistry of a number of black shales by U.S. Department of Energy (DOE) in 2010. The results of this initial study indicate that black shales like the Marcellus Shale contain minor, but detectable, amounts of heavy metals and other elements that can be detrimental to the environment if mobilized and concentrated in the soil or shallow groundwater (Soeder, 2011; Fortson and others, 2011). The results of the Soeder (2011) study were inconclusive but did indicate that additional analyses are needed to better define the fate and transport of leachate from black shale cuttings and evaluate the potential environmental hazards. Additional research by DOE is currently underway (Dan Soeder, DOE, written commun., February 2013).

Figure 6. Mixing of drill cuttings with absorbent polymer prior to shipping and disposal in a secured landfill.

(Photograph courtesy of Curtis Schreffler, USGS)

Pipeline construction in the Endless Mountain region near Trout Run, Pennsylvania.

Summary

Unconventional natural gas and oil resources in the United States are important components of a national energy program that seeks both greater energy independence and greener sources of energy. Unconventional high volume hydraulic fracturing (HVHF) shale gas and oil development in the Marcellus Shale and Utica Shale is underway in the Appalachian Basin within Pennsylvania, West Virginia, and eastern Ohio and is proposed in New York, Maryland and Virginia. Compared to conventional gas production, the scale of shale gas operations may be much larger and has the potential to create significantly greater effects on landscapes, watersheds, water supplies, and water quality. Because of the potential effects, some states (New York and Maryland as of spring 2013) have placed moratoriums on development until these issues are resolved. At the same time, development of the shale gas resource is considered a major component of America's energy supplies for the foreseeable future.

Although the technology for directional or horizontally drilled wells used in combination with sophisticated hydraulic fracturing processes to extract gas resources has improved over the past few decades, the knowledge of how this extraction might affect water resources has not kept pace. Federal and state water-resource and regulatory agencies, the gas industry, and citizens desire a better understanding of the potential environmental effects from the hydraulic fracturing process. Advancements in the science can provide that understanding and lead to the development of best-management strategies for limiting adverse effects of shale gas development in the Appalachian Basin, as well as improvements in monitoring strategies designed to insure environmental quality.

Construction and Transportation

Hydraulic fracturing operations in the Appalachian Basin involve moving large amounts of heavy equipment, trucks, supplies, storage tanks, and fluids into mostly rural areas. Transporting all this materiel to and from drill sites has caused damage to some of the rural, steep, two-lane Appalachian Mountain roads. Many of the roads have been repaved or totally rebuilt by the gas drilling industry (Marcellus Shale Coalition, 2011). Such intensive construction may result in considerable land and wildlife disturbance within small watersheds (U.S. Fish and Wildlife Service, 2013; Intermountain Oil and Gas BMP Project, 2013). The gas drilling industry has recently adopted practices to help reduce truck traffic, including the transport of freshwater by pipeline (fig. 7) and the reuse of flowback water. Local governments have worked with the gas industry to implement management practices to reduce well-pad construction and transportation impacts (Marcellus Shale Coalition, 2012).

Some of the management practices include keeping trucks off roads during specific times and finding alternate routes to well pads on roads that can accommodate heavy equipment. The road restrictions are accomplished through road-use agreements with the municipalities (Pennsylvania State University, 2012). However, even with agreements between the gas companies and state regulators, some local environmental impacts might occur (Slonecker and others, 2012; Drohan and others, 2012); therefore, regulatory agencies and the gas industry continue to support research to improve management practices

Figure 7. Pipeline construction in northeastern Pennsylvania.

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(Photograph courtesy of the Susquehanna River Basin Commission)

Rig used for drilling the horizontal leg of a Marcellus gas well.

Exposure of the Marcellus shale in central New York showing the Cherry Valley limestone (grey-colored rock) between the Union Springs and Oatka Creek shales of the Marcellus.

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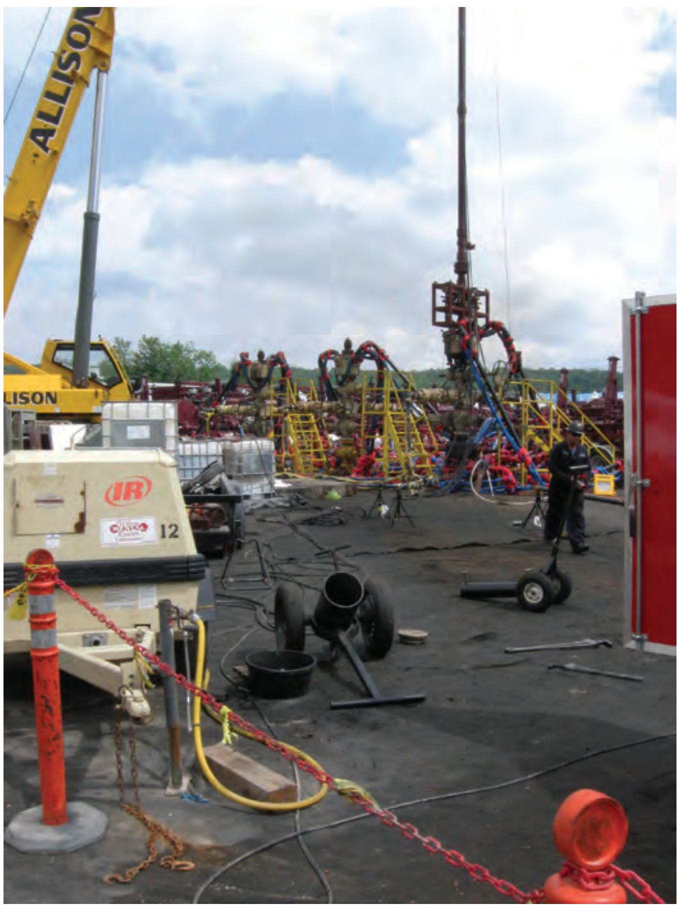
Fault in Upper Devonian bedrock near Towanda, Bradford County, Pennsylvania.

Completed well pad with brine holding tanks (green) with nearby wind turbines near Gleason, Tioga County, Pennsylvania.



Three well heads on a drilling pad, the closest well head being prepared for hydraulic fracturing.

Typical well drilling tower with associated equipment.

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