GSA Critical Issue: Hydraulic Fracturing

Table of Contents:

Introduction

Hydraulic fracturing is a technological process used in the development of natural gas and oil resources. Used commercially since the 1940s, it has only relatively recently been used to extract gas and oil from shales and other tight reservoirs economically. Development of lower cost, more effective fracturing fluids (1), with horizontal wells drilling and subsurface imaging, created a technological breakthrough that is largely responsible for the increase in domestic production of shale oil, shale gas and other unconventional sources (fig. 2) [2, 3]. The continued use of hydraulic fracturing can be expected, given projections of future shale gas and tight gas contributions to total U.S. gas production (fig. 3), unless banned, replaced by other technologies or it becomes economically unviable [4, 5]. Hydraulic fracturing has expanded oil and gas development to new areas of the United States (fig. 4) and internationally, including Canada, Australia and Argentina (6, 742, 8, 943). In contrast, some governments have limited the use of hydraulic fracturing. For example, France and Bulgaria have banned its use, several U.S. cities and counties have restricted it, and in June 2015, New York banned high volume hydraulic fracturing [7, 8, 9, 10, 11, 12, 13, 74).

Figure 1: Drilling into Marcellus Shale (Google Images)

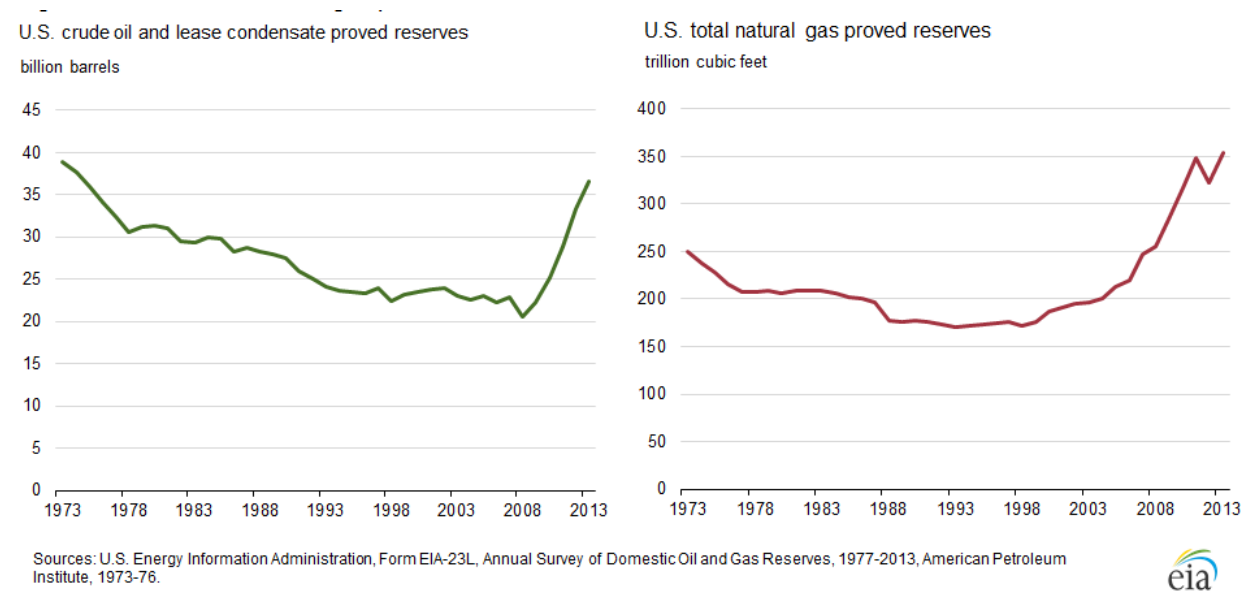
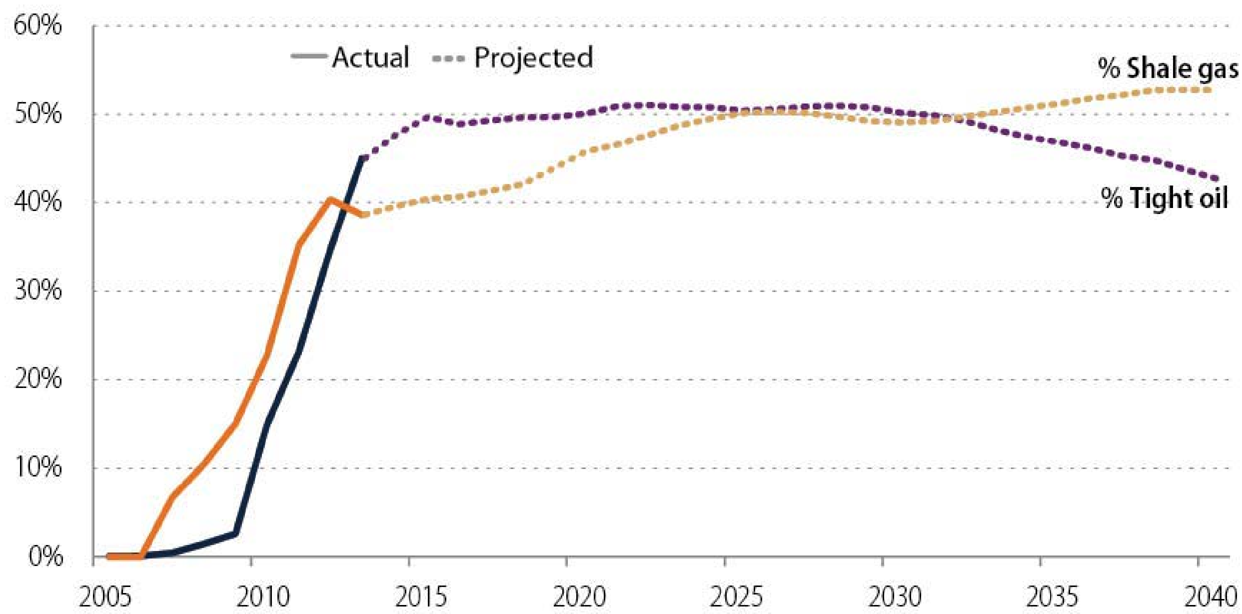


Figure 2: Proved U.S. reserves of crude oil and natural gas by December 2013 increased by 9.3% and 9.7% respectively over the previous year, driven primarily by shale and other unconventional sources. From: EIA, December 4, 2014. www.eia.gov/naturalgas/crudeoil/reserves.

Figure 3: Percentage of U.S. Oil and Gas from Tight Oil and Shale Gas, 2005 - 2040. Source: U.S. Energy Information Administration, *Annual Energy Outlook 2014*. Note: The EIA began reporting tight oil and shale gas data in 2007.



Hydraulic fracturing remains a highly contentious public policy issue because of concerns about the environmental and health effects of its use. What are the environmental risks of hydraulic fracturing? What are the health risks from the chemicals injected into the ground? Will it take away water needed for food production and cities? Does it trigger earthquakes? Does expansion of this technology for fossil fuels mean a decreased commitment to renewable energy technology? Are the environmental and health hazards well understood and managed? [14, 67, 68]

In many cases it is unclear whether concerns raised relate specifically to hydraulic fracturing, or more generally to the development of unconventional petroleum resources, or to other aspects related to all oil and gas development. While many of these concerns relate to policy, economics, and social areas that are outside the scope of this paper, the geoscience community is well suited to address some of the technical questions being asked.

The Geological Society of America does not have a position statement on hydraulic fracturing. This critical issue paper is written as a primer for the general public, journalists, and even resource professionals who may have difficulty finding objective, credible information about hydraulic fracturing of shales and other unconventional sources and related environmental concerns. This primer is also intended to furnish members of the Geological Society of America with a concise, clear, non-technical discussion of the process and the issue, and as a reference that they can provide to non-geologists to inform conversations on the topic.

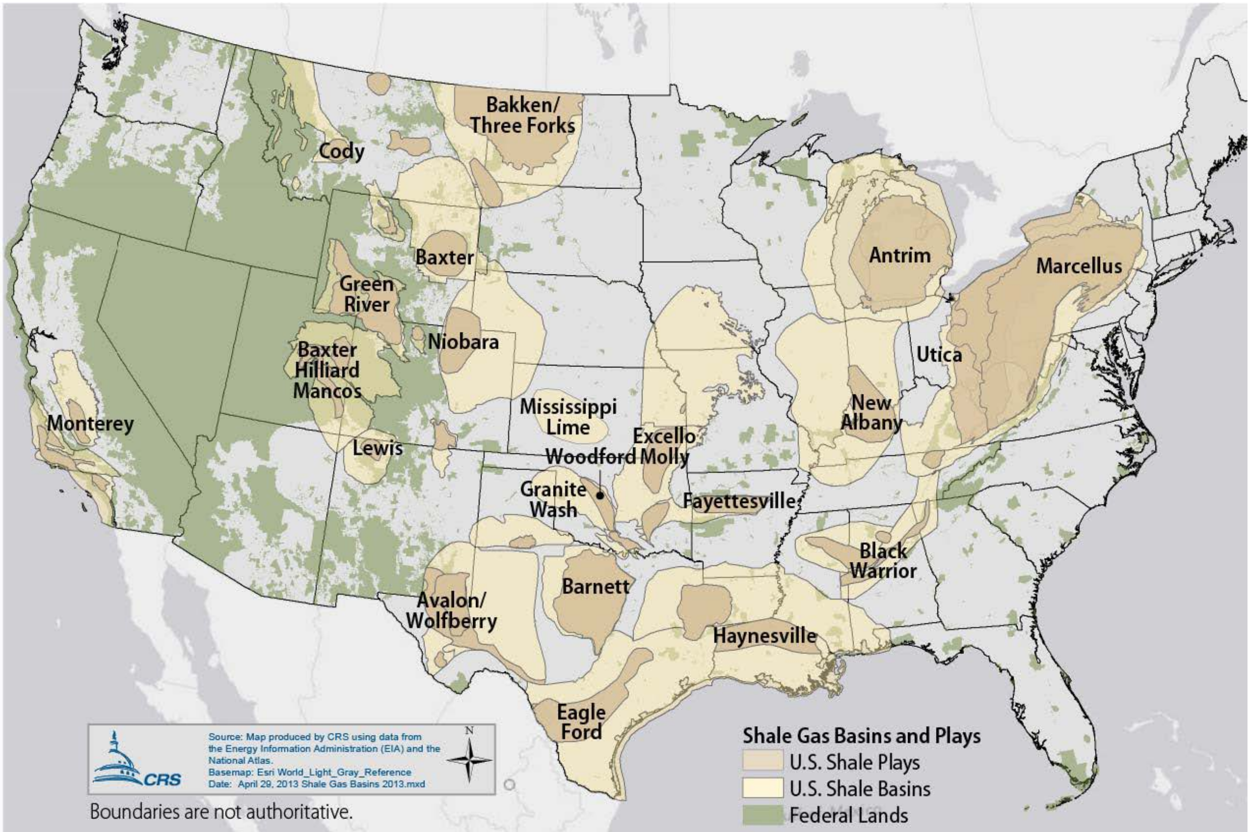


Figure 4: Unconventional Shale Plays in the Lower 48 States (with federal lands shown); From: Ratner and Tiemann, November 21, 2014, Congressional Research Service; An Overview of Unconventional Oil and Natural Gas: Resources and Federal Actions. Note: federal land coverage is over generalized in this image.

HYDRAULIC FRACTURING DEFINED

Oil and natural gas, which are hydrocarbons, reside in the pore spaces between grains of rock (called reservoir rock) in the subsurface. If geologic conditions are favorable, hydrocarbons flow freely from reservoir rocks to oil and gas wells. Production from these rocks is traditionally referred to as "conventional" hydrocarbon reservoirs. However, in some rocks, hydrocarbons are trapped within microscopic pore space in the rock. This is especially true in fine-grained rocks, such as shales, that have very small and poorly connected pore spaces not conducive to the free flow of liquid or gas (called low- permeability rocks)(fig. 5). Natural gas that occurs in the pore spaces of shale is called shale gas. Some sandstones and carbonate rocks (such as limestone) with similarly low permeability are often referred to as "tight" formations. Geologists have long known that large quantities of oil and natural gas occur in formations like these (often referred to as tight oil or gas). Hydraulic fracturing can enhance the permeability of these rocks to a point where oil and gas can economically be extracted.

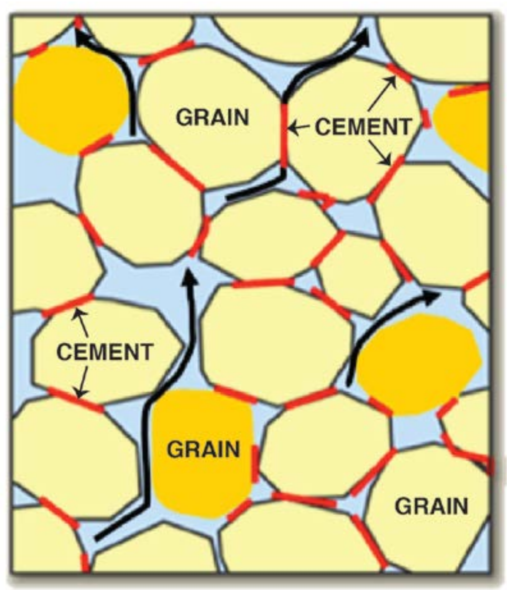


Figure 5: Schematic of rock grains, pore space and permeability. Interconnection of spaces between grains allows flow of gas or other fluid. Modified from Bureau of Economic Geology, University of Texas.

Hydraulic fracturing (also known colloquially as "fracing," or "fracking,") is a technique used to stimulate production of oil and gas after a well has been drilled [15]. It consists of injecting a mixture of water, sand, and chemical additives through a well drilled into an oil- or gas-bearing rock formation, under high but controlled pressure. The process is designed to create small cracks within (and thus fracture) the formation, and propagate those fractures to a desired distance from the well bore by controlling the rate, pressure, and timing of fluid injection. Engineers use pressure and fluid characteristics to restrict those fractures to the target reservoir rock, typically limited to a distance of a few hundred feet from the well. Proppant (sand or sometimes other inert material such as ceramic beads) is carried into the newly formed fractures to keep them open after the pressure is released and allow fluids (generally hydrocarbons) that were trapped in the rock to flow through the fractures more efficiently. Some of the water/chemical/proppant fracturing fluids remain in the subsurface. Some of this fluid mixture (called "flowback water") returns to the surface, often along with oil, natural gas, and water that was already naturally present in the producing formation. This natural formation water is known as "produced water" and much of it is highly saline [16]. The hydrocarbons are separated from the returned fluid at the surface, and the flowback and produced water is collected in tanks or lined pits. Handling and disposal of returned fluids has historically been part of all oil and gas drilling operations, and is not exclusive to wells that have been hydraulically fractured. Similarly, proper well construction is an essential component of all well-completion operations, not only wells that involve hydraulic fracturing. Well completion and construction, along with fluid disposal, are inherent to oil and gas development, and are specifically addressed in this paper because of concern about them and their relationship to hydraulic fracturing.

Hydraulic fracturing of shales and other tight rocks typically is through horizontal or directional (non-vertical) drilled wells (fig. 6) which typically involve longer boreholes and much greater volumes of water than conventional oil and gas wells.

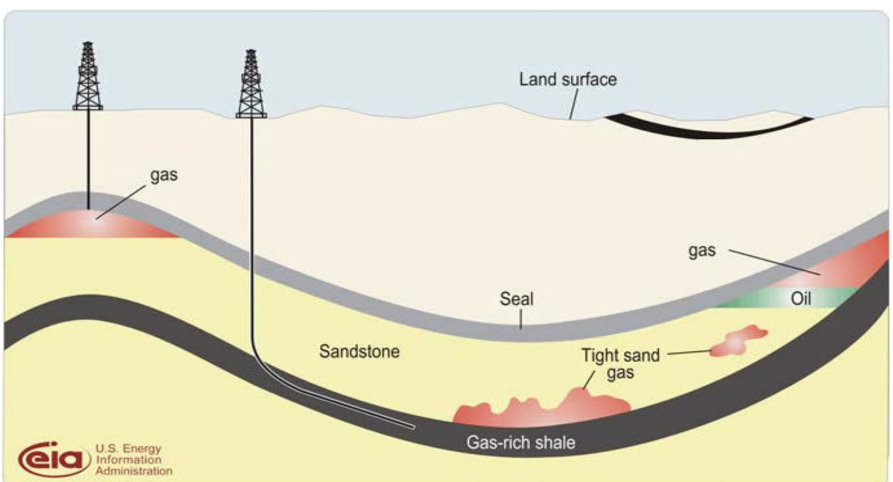


Figure 6: Schematic geology of natural gas resources. Modified from U.S. Energy Information Administration and U.S. Geological Survey Fact Sheet 0113-01.

HYDRAULIC FRACTURING'S HISTORY AND ROLE IN ENERGY DEVELOPMENT

Hydraulic fracturing has been commercially applied since the 1940s (fig. 7). Over a million wells in the U.S. have been subjected to hydraulic fracturing, most of them conventional vertical oil and gas wells [12]. Hydraulic fracturing became even more important in the 1990s, when improved technology allowed its application to horizontal wells in developing tight gas and oil reservoirs, particularly for shales[3]. The technological combination of hydraulic fracturing, the chemistry of the fracturing fluid, and the use of horizontal wells is rapidly evolving. Traditional wells are drilled vertically (usually several thousand feet) and penetrate only a few tens or hundreds of feet of the reservoir rock. Horizontal wells start vertically, but then at a kickoff point are directed laterally (or horizontally) within the reservoir rock. The horizontal legs of these wells may extend as much as 10,000 feet through a reservoir rock, thus accessing a far greater volume of the reservoir than a traditional vertical well that only taps one vertical thickness of the reservoir rock. This replaces the need for multiple, vertical wells spaced closely on the land surface to tap the same reservoir volume. Because multiple wells can be drilled from one horizontal well pad, this further decreases the total amount of land needed for the drilling platform (called the "footprint") and subsequent surface production equipment, although a horizontal well pad is typically much larger than a traditional vertical well pad. Because horizontal wells have both a vertical and a horizontal leg, and more contact with the reservoir rock than a traditional vertical well, horizontal wells typically require a larger volume of water than traditional vertical wells [6, 17, 18]. This may be due to larger volumes of oil produced and not just the hydraulic fracturing requirements; one study compared the ratio of water use to oil produced for two different shale plays and found it was within the typical range for vertical, conventional oil wells over their lifespans[19]. In a horizontal well, hydraulic fracturing usually occurs sequentially in several stages along the horizontal well bore (these are sometimes referred to as "staged treatments"), generally 10 to 15 pumping intervals, and sometimes as many as 50 [18]. Hydraulic fracturing of each stage may last from 20 minutes to four hours to complete [20].

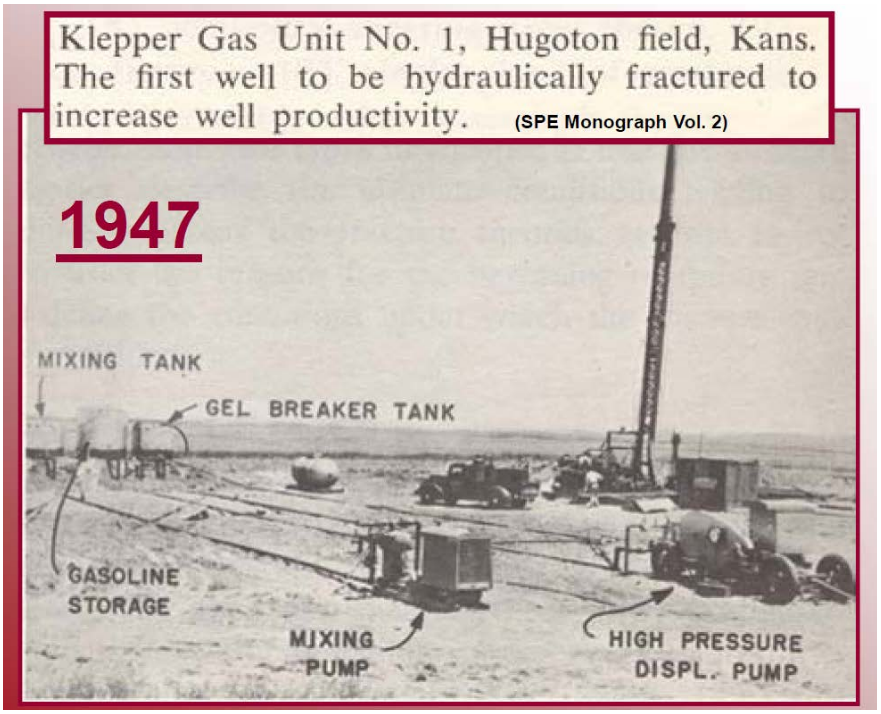


Figure 7: Photo of first hydraulically fractured well, from Howard, G.C. and Fast, C.R., 1970. Reproduced with permission of SPE; further reproduction prohibited without permission.

In the past three decades, hydraulic fracturing has been increasingly used in formations that were known to be rich in natural gas that was locked so tightly in the rock that it was technologically and economically difficult to produce [3]. The application of hydraulic fracturing to tight sands revitalized old fields and allowed establishment of new fields. Subsequently, the application of hydraulic fracturing to shale opened up huge new areas to development, including the Marcellus Shale in the eastern U.S, the Barnett Shale in Texas, and the Fayetteville Shale in Arkansas (Figs. 4, 8). The rise in production of natural gas from these and other shale plays was dramatic, to the point that natural gas prices have dropped and become more stable. Natural gas has become a major source of electrical power, and the U.S. may become a net natural gas exporter [21], if markets and regulations are favorable. [57, 58, 59]

While hydraulic fracturing has had a huge impact on natural gas production, the same techniques have been applied to oil fields [18, 19, 21], leading to increased production from formations such as the Bakken and Three Forks Formations in North Dakota and Montana, and the Eagle Ford Formation in Texas. U.S. oil production from tight formations grew rapidly over the past several years. Future growth projections are uncertain, as the industry is influenced by global demand, prices, a social license to operate, regulations, well production life spans, and technological improvements that increase the percentage of recoverable hydrocarbons [22].

Figure 8: Well drilling into Marcellus Shale, from Pennsylvania Independent Oil &Gas Association; www.pioga.org

WATER QUALITY

Fluids used in hydraulic fracturing are a mixture of water, proppant, and chemical additives. Additives typically include gels to carry the proppant into the fractures, surfactants to reduce friction, hydrochloric acid to help dissolve minerals and initiate cracks, inhibitors against pipe corrosion and scale development, and biocides to limit bacterial growth (23). The exact mix of additives depends on the formation to be fractured. Chemical additives typically make up about 0.5% by volume of well fracturing fluids, but may be up to 2% [17, 23]. Some potential additives are harmful to human health, even at very low concentrations (24). Unless diesel is used, the fracturing fluids are not regulated by the Safe Drinking Water Act (SDWA). Underground disposal of oil and gas wastes, however, is regulated by the SDWA(25).

Figure 9: Water Cycle in Hydraulic Fracturing, from U.S. EPA's Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources, Progress Report, 2012

Potential pathways for the fracturing fluids to contaminate water include surface spills prior to injection, fluid migration once injected, and surface spills of flowback and produced water (fig. 9). Because the fracturing fluids are injected into the subsurface under high pressure, and because some of the fluids remain underground, there is concern that this mixture could move through the well bore or fractures created in the reservoir rock by hydraulic pressure, and ultimately migrate up and enter shallow formations that are sources of freshwater (aquifers)[26]. There is also concern that geologic faults, previously existing fractures, and poorly plugged, abandoned wells could provide conduits for fluids to migrate into aquifers [27].

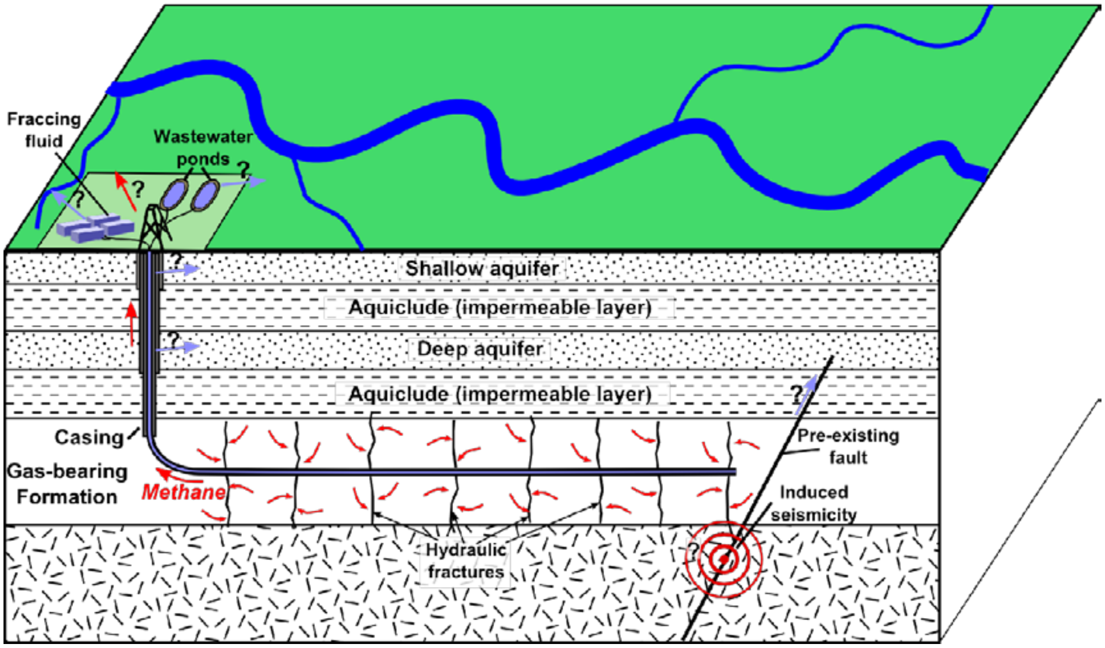


Figure 10: Diagram of possible fluid migration pathways and other environmental concerns with hydraulic fracturing. Source: Mike Norton, Wikimedia Commons

The potential to contaminate groundwater due to hydraulic fracturing is an environmental risk being studied (figure 10)[26, 28, 29]. At present, there have been possibly two confirmed cases of groundwater contamination caused directly by the hydraulic fracturing process; in one location the fractured rock is within 420 feet of the aquifer[6, 20, 30]. One challenge is to distinguish natural contaminants that seep into groundwater unrelated to oil and gas development, from contamination due to oil and gas development. There often are no water quality samples prior to hydraulic fracturing to provide a baseline comparison [6, 32, 33].

For example, methane has been detected in some water wells in areas with oil and gas development [33, 34]. Some researchers suggested hydraulic fracturing may be responsible for methane in water wells in northeastern Pennsylvania and upstate New York, although leaky well casings is a more likely possibility [29, 32]. In some geologic settings, methane can naturally originate from gas-producing rock layers below and close to the aquifer and be unrelated to the deeper fractured zone [20, 31]. Analysis of the gas can be used to identify the origin of gas occurring in groundwater [31, 35]. In one study of drinking water wells near shale gas well sites in Pennsylvania and Texas, wells were sampled for hydrocarbon gas to determine if contamination had occurred. [36]. The researchers concluded that contamination has locally occurred, and, for those wells with elevated gas levels, the fugitive gas appeared to have migrated from shallower rocks through cracks in the cement around the well (annulus), leaks in the well casing, or from other well failures [36], rather than from the artificial hydraulic fractures in the reservoir rock. An analysis of a large database on dissolved methane in domestic wells and proximity to pre-existing oil and gas wells in Pennsylvania indicated no statistically significant relationship [75], although the study had criticism for its industry support for the study [76].

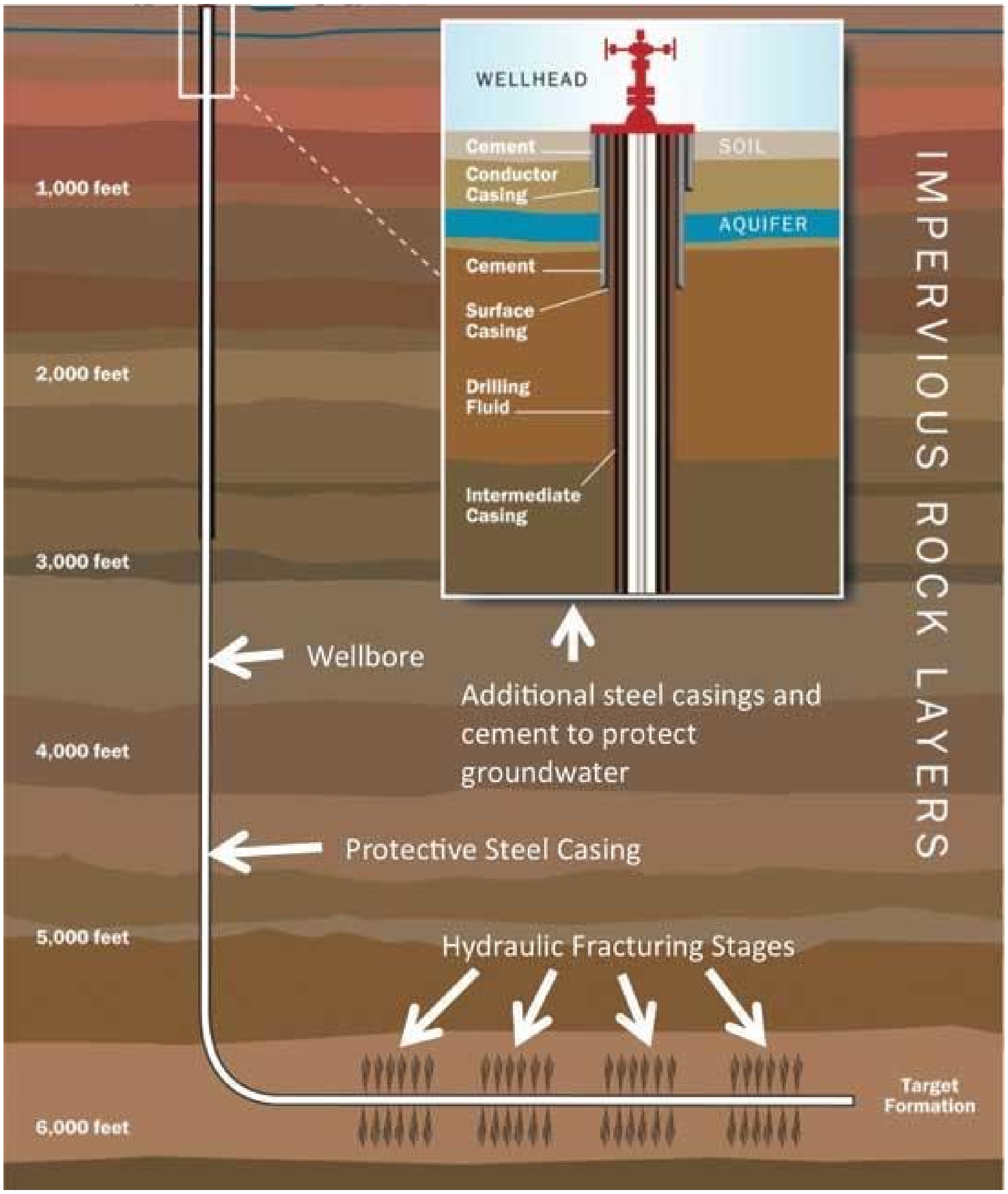


Figure 11: Horizontal Well Construction, From U.S. EPA Study Progress Report, December 2012, modified by Kansas Geological Survey (26)

There have been confirmed cases of groundwater contamination from improperly constructed oil and gas wells[27]. To protect groundwater, proper well design, construction, and monitoring are essential. During well construction, multiple layers of telescoping pipe (or casing) are installed and cemented in place, with the intent to create impermeable barriers between the inside of the well and the surrounding rock [17]. It is also common practice to pressure test the cement seal between the casing and rock or otherwise examine the integrity of wells. Wells that extend_through a rock formation that contains high-pressure gas require special care in stabilizing the well bore and stabilizing the cement or its integrity can be damaged [6]. As with any mechanical device or barrier, failures can occur. There is significant variability in the estimated failure rates of the integrity of oil and gas wells [60, 61]. Local regulations, the technology, the geologic setting and the prevailing operational culture influence the well completion, abandonment and monitoring[60, 61], and these evolve over time. Differences in the type and sizes of well integrity datasets add to the challenge of generalizing well integrity failure rates [60, 62, 63].

The physical separation between the relatively shallow freshwater aquifer and the typically much deeper oil- and gas-producing rock layer provides protection to shallow aquifers. Typically there are thousands of feet of mostly low- to very low-permeability rock layers between an aquifer and oil or gas reservoir rocks that prevent fracturing fluids and naturally migrated hydrocarbons from reaching the aquifer. In areas where there is concern about faults, fractures, or plugged wells, various geophysical methods can be used to locate and avoid faults[37], although such surveys are time consuming and expensive. There is also renewed interest in the need to locate and plug abandoned or "orphaned" oil and gas wells, and unused water wells, as a further measure to protect near-surface aquifers. It will also be prudent to develop technologies to monitor deep groundwater[56]. In some regions, identifying and properly plugging all the abandoned wells is a significant undertaking [38].

Proper storage and disposal of fracturing fluids and produced water is important to ensure that both surface water and groundwater are protected. Most fracturing fluids and produced water are re-injected into Class II wells [25] drilled specifically for deep disposal, treated in wastewater treatment facilities, or recycled [32]. Wastewater treatment facilities, designed primarily for municipal waste, can be overwhelmed with the volume and treatment of fracturing fluids and produced water; a number will not accept such waste [39, 40]. Disposal wells inject waste water deep into formations that originally produced the oil and gas, or into different formations that generally contain highly saline and otherwise unusable water. Water is generally co-produced in equal or larger volumes than petroleum throughout the life of a well. Fluid handling and disposal are important issues for all oil and gas activity.

Appropriate management practices and regulatory oversight help assure that accidental leaks and spills are minimized.

Figure 12: Groundwater Water Quality Sampling from a small diameter, temporary borehole. Kansas Department of Health and Environment, 2012

Baseline water-quality testing, carried out prior to oil and gas drilling, helps to document the quality of local natural groundwater and may identify natural or pre-existing contamination, or lack thereof, before oil and gas activity begins [37, 41, 42]. Without such baseline testing, it is difficult to know if contamination existed before drilling, occurred naturally, or was the result of oil and gas activity. Many natural constituents, including methane, elevated chlorides, and trace elements occur naturally in shallow groundwater in oil- and gas-producing areas and are unrelated to drilling activities [34]. The quality of water in private wells is not regulated at the state or federal level, and many owners do not have their well water tested for contaminants. States handle contamination issues differently. For instance, Colorado and Ohio require baseline sampling of wells in oil- and gas-producing regions as part of its regulatory process [23, 41, 43]. Pennsylvania places the presumptive burden of proof on oil and gas companies if groundwater contamination of drinking-water sources is found [16]. In most states, however, such baseline sampling is not required [42].

Figure 13: Measuring groundwater depth before sampling, from a non-pumping well installed to monitor water quality conditions, Kansas Department of Health and Environment, 2012

Although there is little evidence of groundwater contamination due to hydraulic fracturing itself, there are still many questions about the risks to aquifers with the rapidly expanding industry developing tight oil and gas reservoirs using modern hydraulic fracturing techniques [6, 20, 26, 27, 28, 30]. There are few long term, peer-reviewed scientific studies. The U.S. Environmental Protection Agency's (EPA) Scientific Advisory Board study *Potential Impacts of Hydraulic Fracturing on Drinking Water Resources* (projected to be finalized in 2016) will be an important contribution. Local baseline testing of groundwater quality prior to hydraulic fracturing operations can provide valuable data for later assessing claims of contamination.

Contamination risks to surface water during development of tight oil and gas plays has led to increased regulations in some U.S. states. Potential pathways for contamination include surface spills, waste disposal, and surface spreading of well cuttings. A study of the gas shale development in Pennsylvania documented increased chlorides downstream of the waste treatment plant and elevated total suspended solids downstream of shale gas wells [44]. The elevated suspended solids appear related to the land clearing for the well pad, roads, and related infrastructure.

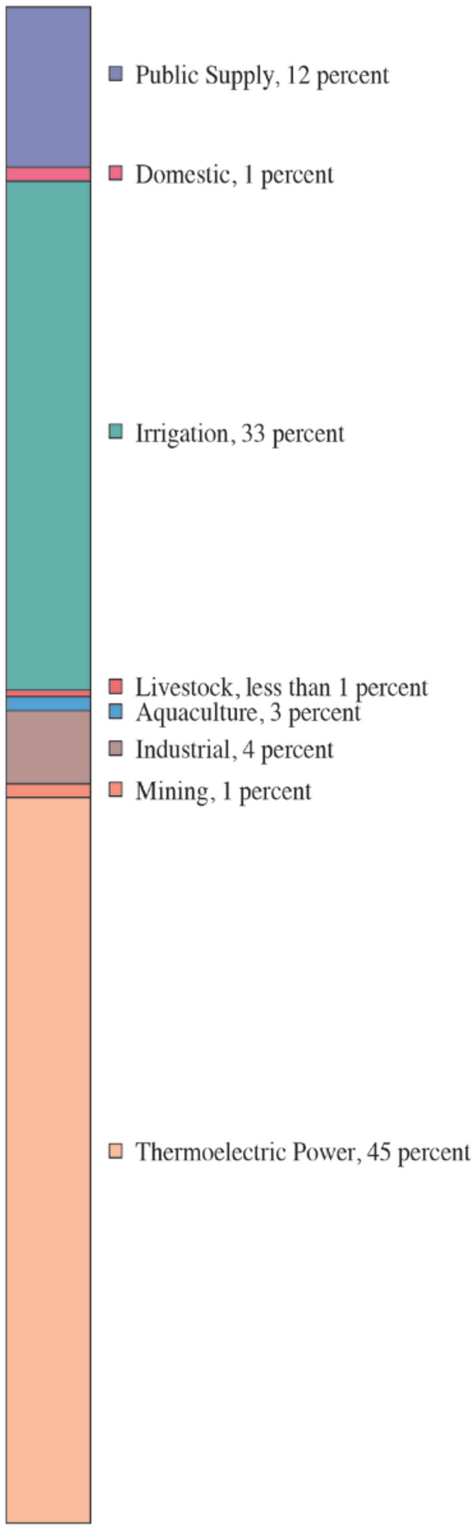


Figure 14, Estimated Water Use in the United States in 2010; USGS Circ 1405. Water for hydraulic fracturing included in mining category.

WATER USE

Hydraulic fracturing, particularly when applied to horizontal wells, can use 13 million gallons or more water per well, though two to five million gallons is typical [23, 40]. However, the ratio of "water used" to "oil produced" in hydraulically fractured wells in the Eagle Ford Shale, Texas, and Bakken Shale, North Dakota, is on the low end of what is typically used in a conventional, vertical oil well over the life of the well [19]. The study concluded that the higher water use reflects an increase in oil production, and not that hydraulic fracturing uses more water per unit of oil produced than conventional wells. Water used in oil and gas development is relatively small in comparison to other recurring uses (Fig. 14) [23, 42, 45]. However, where drilling rates are high, and particularly in water-poor areas, water use for oil and gas development is significant. The U.S. EPA is studying the current and future potential competition between hydraulic fracturing and drinking water supplies in two basins, one humid (Susquehanna River Basin, Pennsylvania) and one semi-arid (Upper Colorado River Basin, Colorado)[26]. Water needs 30 years out are based on drilling trends, natural gas production, and population growth.

Drilling companies are working on improved methods to recycle water used in hydraulic fracturing, or to use saline water that is unsuitable for drinking [40]. Some energy companies are treating and reusing produced and flowback water; the feasibility depends on economics and the quantity, quality, and duration of water generated [46]. Some companies are trying water-free, nonflammable propane fracking fluid [47]. However, because of chemical mixing considerations and costs, freshwater continues to be the preferred and primary source of water for hydraulic fracturing in most areas. In December, 2015, the Governor of Oklahoma formed a task force to find economic treatment and uses for the produced water [73].

Induced Seismicity

Induced seismicity is an earthquake caused by human activities. One way this can occur is from injection of fluids deep into the earth. The increase in underground disposal of produced and flowback water from oil and gas wells are associated with a large increase in triggered small and moderate earthquakes in some regions, such as central and northern Oklahoma [69, 70]. Oil and gas operations are responsible for two types of fluid injection: 1) injection of hydraulic fracturing fluids into the reservoir rock; and 2) disposal of waste fluids through deep well injection.

Hydraulic fracturing imparts pressures of several thousand pounds per square inch on reservoir rocks. The resulting fractures may extend several hundred feet away from the borehole (Fig. 15), but generally no more than that due to physical and technological limitations on the hydraulic fracturing process[38, 49]. The hydraulic fracturing process creates very small seismic events or earthquakes. Such microseismicity is generally too small for humans to feel or to cause surface damage [26], although it can be detected by monitoring instruments that are designed to precisely determine where the fractures have propagated. A number of studies, including one by the National Academy of Sciences, have determined that hydraulic fracturing does not create a significant earthquake risk [48]. Alberta and British Columbia, Canada, have had moderate earthquakes that appear related to the hydraulic fracturing process itself [71, 72].

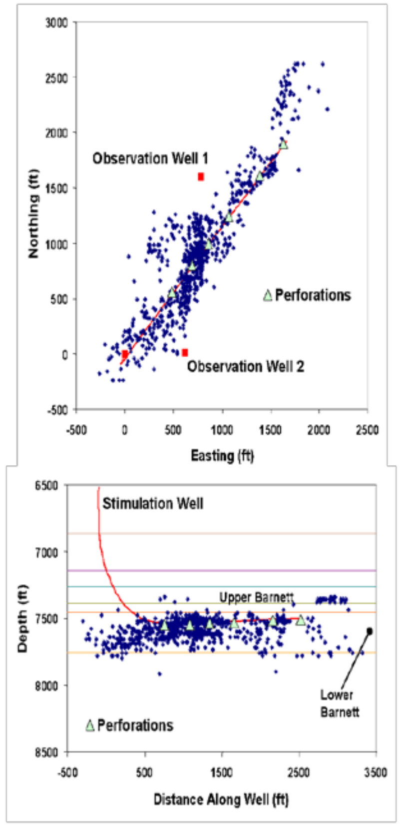


Figure 15: Seismic Expression from Hydraulic Fracturing; Warpinski et al, 2005. Reproduced with permission of SPE; further reproduction prohibited without permission.

Disposal of large volumes of waste fluids produced from hydraulically fractured rocks through deep-well injection has been documented to produce small earthquakes, generally less than magnitude 2.0 [48]. However, in areas with high volumes and rates of injection into disposal wells, there have been dramatic increases in earthquakes magnitude 3.0 and greater [50, 70]. Horizontal wells that have been hydraulically fractured typically produce large volumes of waste fluids (produced and flowback water). Deep disposal of any fluids can trigger earthquakes [48, 51]. Most, although not all, of such earthquakes have occurred in areas of long-term or continuous injection of wastewater. Fluids injected near a subsurface fault may reduce the frictional resistance that keeps faults from slipping. These small movements allow energy already stored in brittle rock to be released in earthquakes [52]. In some locations, sites of slowly accumulating forces in the earth resulting from natural geologic processes are already susceptible to seismic events (which is why it is referred to as "triggered seismicity"). The increase in pore pressure on stressed fault surfaces appears to be the main physical reason for injection-induced earthquakes in the central and eastern United States [69, 72].

Deep well injection of fluids has likely caused earthquakes in excess of magnitude 2.0 over the past several decades, including a magnitude 5.7 earthquake in 2011 in Oklahoma[54] and a sharp increase of earthquake frequency from 2012 to 2015 in Oklahoma [65, 72]. Kansas has also experienced a marked increase in seismic activity in the last two years, including the state's largest earthquake recorded at magnitude 4.9 in November 2014[64]. The potential for triggered seismicity with the increasing volume of wastewater disposal is unknown [48, 40, 55]. States are implementing strategies to mitigate risks of induced seismicity associated with disposal injection wells. This includes a screening protocol to determine what response strategies may be appropriate [69]. Mitigation actions can include changing the allowable rates and pressures of injection, partial plugback of the injection well, and stopping all injections and shutting the well [69].

Regulation Issues

Oil and gas exploration and production activity is regulated at the federal, state, and local level. Although the EPA Scientific Advisory Board is studying issues related to hydraulic fracturing, and has investigated complaints of possible groundwater contamination related to hydraulic fracturing, most regulation resides with state agencies, many of which have experience in oil and gas regulation. The Interstate Oil and Gas Compact Commission (IOGCC), a multi-state commission ratified by Congress, helps states establish and coordinate regulation of the oil and gas industry. The Ground Water Protection Council (GWPC) and the State Review of Oil and Natural Gas Environmental Regulations (STRONGER) also assist in this effort. In addition, acquisition of water for hydraulic fracturing is subject to state regulations and laws.

Disclosure of chemicals used in hydraulic fracturing is exempt from federal regulations associated with the Safe Drinking Water Act, and composition restrictions and reporting requirements of injected fluid vary between states [66]. In response to public requests for disclosure of the composition of fluids used in hydraulic fracturing, the IOGCC and the GWPC established a publicly accessible hydraulic fracturing chemical registry website called FracFocus 3.0 (FracFocus.org) (Fig 16). At least 18 states require companies to disclose the identity of chemicals used in hydraulic fracturing, although all of these states protect proprietary trade secrets from disclosure.

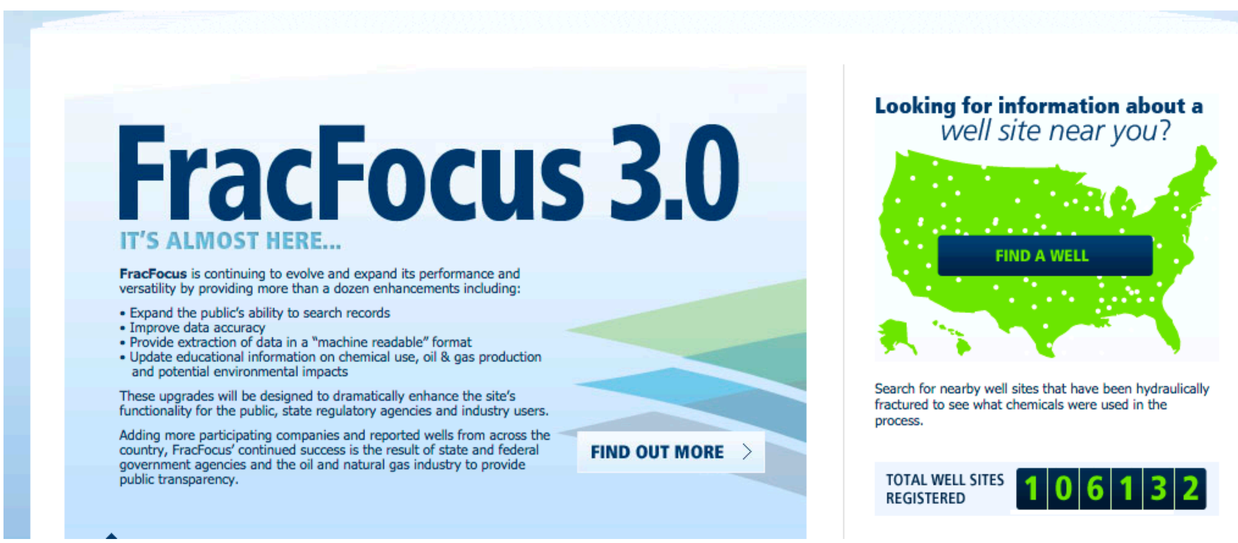


Fig.16. Frac Focus home webpage

STAYING INFORMED

Hydraulic fracturing of tight rocks has become a growing component of oil and gas energy production in the U.S., particularly in terms of natural gas production from shale. There are potential impacts from hydraulic fracturing itself, however, most of the environmental concerns relate to long established processes used in nearly all oil and gas drilling—such as well construction or fluid disposal—and are not unique to the process of hydraulic fracturing itself. There are also serious concerns related to the rapid industrialization of unconventional oil and gas development, of which hydraulic fracturing is a critical component. There remains a significant need for accurate information dissemination, improved dialogue between consumers and producers, and ongoing research on hydraulic fracturing and its potential environmental impact. Meanwhile, peer-reviewed professional publications remain the most reliable source of scientific and technical information about hydraulic fracturing and unconventional oil and gas development. Geologists involved in aspects of the hydraulic fracturing technology, whether in exploration and development, regulation, natural resource management or environmental protection, are encouraged to share their knowledge with the general public and policy makers.

References

1. Sharma, Mukul MK. and Phani B. Gadde, R. Sullivan, R. Fielder, D. Copeland, L. Griffin, and L. Weihers; September 2004, Slick Water and Hybrid Fracs in the Bossier: Some Lessons Learnt. Society of Petroleum Engineers, Inc. SPE 89876 (access at: http://faculty.engr.utexas.edu/sharma/pdfs/conference/Conf-86.pdf)

2. Wang, Zhongmin and Alan Krupnick, April 2013, A Retrospective Review of Shale Gas Development in the United States What Led to the Boom? Resources for the Future, RFF DP 13-12 (access at: http://www.rff.org/RFF/Documents/RFF-DP-13-12.pdf)

3. Trembath, Alex, Jesse Jenkins, Ted Nordhaus, and Michael Shellenberger, May, 2012; Where the Shale Gas Revolution Came From: Government's Role in the Development of Hydraulic Fracturing in Shale. (access at: http://thebreakthrough.org/blog/Where_the_Shale_Gas_Revolution_Came_From.pdf)

4. United States Energy Information Administration, December 2012, What is Shale gas and Why is It Important? Energy in Brief. (access at: http://www.eia.gov/energy_in_brief/article/about_shale_gas.cfm)

5. United State Geological Survey, May 2013, Assessment of Undiscovered Oil Resources in the Bakken and Three Forks Formations, Williston Basin Province, Montana, North Dakota, and South Dakota, 2013 National Assessment of Oil and Gas Fact Sheet 2013-3013. (access at: http://pubs.usgs.gov/fs/2013/3013/fs2013-3013.pdf)

6. Vidic, R.D., S.L. Brantley, S.L., J.M. Venderbossche, D.Yoxtheimer, and J.D. Abad, May 17, 2013, Impact of Shale Gas Development on Regional Water Quality. Science, Vol 340, No 6134. (access at: http://www.sciencemag.org/content/340/6134/1235009.abstract)

7. The Economist, June 2, 2012, Gas Goes Boom. (access at: http://www.economist.com/node/21556291)

8. New York Times, October 21, 2013, An Odd Alliance in Patagonia. (access at: http://www.nytimes.com/2013/10/22/business/energy-environment/argentinas-oil-ambitions-create-unlikely-alliance-with-chevron.html?_r=0)

9. Christian Science Monitor, October 2012; South Africa OKs fracking for natural gas. (access at http://www.csmonitor.com/Environment/Energy-Voices/2012/1002/South-Africa-OKs-fracking-for-natural-gas

10. Bloomberg Businessweek, January 19, 2012; Bulgaria Bans Gas Fracking, Thwarting Chevron Drilling Plan. (Access at: **http://www.businessweek.com/news/2012-01-19/bulgaria-bans-gas-fracking-thwarting-chevron-drilling-plan.html**)

11. New York Times, October 11, 2013; France Upholds ban on Hydraulic Fracturing (access at: http://www.nytimes.com/2013/10/12/business/international/france-upholds-fracking-ban.html)

12. BloombergBusiness, June 29, 2015; N.Y. Officially Bans Fracking with Release of Seven-Year Study. (access at: http://www.bloomberg.com/news/articles/2015-06-29/n-y-officially-bans-fracking-with-release-of-seven-year-study)

13. New York State Department of Health, December 2014, A Public Health Review of High Volume Hydraulic Fracturing for Shale Gas Development. (access at: http://www.health.ny.gov/press/reports/docs/high_volume_hydraulic_fracturing.pdf)

14. Stern, Paul C., Rapporteur, 2014, Risks and Risk Governance in Shale Gas Development: Summary of Two Workshops, National Research Council, National Academies Press (Access at: http://www.nap.edu/catalog.php?record_id=18953)

15. United States Environmental Protection Agency, May 9, 2012, Hydraulic Fracturing Background Information, (access at: http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/wells_hydrowhat.cfm)

16. Gregory, Kelvin, Radisav Vidic and David Dzombak, June 2011, Water Management Challenges Associated with the Production of Shale Gas by Hydraulic Fracturing. Elements, Geoscience World, pgs 181-186. (access at: http://171.66.125.216/content/7/3/181.full)

17. Ground Water Protection Council, 2009, Modern Shale Gas Development in the United States: A Primer, Prepared for U.S. Department of Energy, Office of Fossil Energy, and National Energy Technology Laboratory, U.S. DOE Grant DE-FG26-04NT15455, 98 p. (access at: http://www.netl.doe.gov/technologies/oil-gas/publications/EPreports/Shale_Gas_Primer_2009.pdf)

18. Fisher, Kevin, 2012, Trends Take Fracturing "Back to the Future": American Oil and Gas Reporter, 55 (8): 86-97.

19. Scanlon, B.R., R.C. Reedy and J.P.Nicot, 2014. Comparison of Water Use for Hydraulic Fracturing for Oil and Gas versus Conventional Oil. Environmental Science Technology, vol 48, pg 12386-12393.

20. King, George E., 2012, Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know about Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells: Society of Petroleum Engineers, Society of Petroleum Engineers, Document 152596 (access at: www.onepetro.org/mslib/app/Preview.do?paperNumber=SPE-152596-MS&societyCode=SPE)

21. United States Energy Information Administration, May 7, 2014, Annual Energy Outlook 2014 (access at http://www.eia.gov/forecasts/aeo/index.cfm).

22. United States Energy Information Administration, December 9, 2014, Short Term Energy Outlook (access at: http://www.eia.gov/forecasts/steo/)

23. FracFocus: Chemical Disclosure Registry, National Groundwater Association, Interstate Oil and Gas Compact Commission: FracFocus.org. (access at: http://fracfocus.org)

24. United States House of Representatives Committee on Energy and Commerce, Minority Staff, April 2011. Chemicals Used in Hydraulic Fracturing. (access at:

http://democrats.energycommerce.house.gov/sites/default/files/documents/Hydraulic-Fracturing-Chemicals-2011-4-18.pdf)

25. United State Environmental Protection Agency, Regulation of Hydraulic Fracturing Under the Safe Drinking Water Act. (Access at: http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/wells_hydroreg.cfm)

26. United States Environmental Protection Agency, December 2012 progress report, Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources; (accessed at http://www.epa.gov/hfstudy/pdfs/hf-report20121214.pdf)

27. Cooley, Heather, and Kristina Donnelly, 2012, Hydraulic Fracturing and Water Resources: Separating the Frack from the Fiction, Pacific Institute, 34 p.

28. Davies, Richard J., October 25, 2011, Methane Contamination of Drinking Water Caused by Hydraulic Fracturing Remains Unproven, Proceedings of National Academy of Science. (access at: http://www.pnas.org/content/108/43/E871.short)

29. Jackson, Robert B., S.G. Osborn, A. Vengosh, and N.R. Warner, October 25, 2011, Reply to Davies: Hydraulic Fracturing Remains a Possible Mechanism for Observed Methane Contamination of Drinking Water, Proceedings of the National Academy of Sciences of the United States. (access at: http://www.pnas.org/content/108/43/E872.full.pdf+html)

30. U.S. Environmental Protection Agency, December 8, 2011, Draft Investigation of Ground Water Contamination Near Pavillion, Wyoming. (access at: http://www2.epa.gov/region8/pavillion)

31. Molofsky, Lisa, John A. Conner, Albert S. Wylie, Tom Wagner, and Shahla Farhat, May 2013; Evaluation of Methane Sources in Groundwater in Northeast Pennsylvania. Groundwater, Vol 51, No. 3, pgs 333--349. NGWA.

32. Osborne, Stephen G., A. Vengosh, N. R. Warner, and R. B. Jackson, 2011, Methane Contamination of Drinking Water Accompanying Gas-Well Drilling and Hydraulic Fracturing: Proceedings of the National Academy of Sciences, 108 (20): 8172-8176. (access at: http://biology.duke.edu/jackson/pnas2011.html)

33. Anderson, Fred, January 2013, Natural Gas Occurrence in Private Water Supply Wells Confirmed in North Dakota, *in* GeoNews, North Dakota Department of Mineral Resources.

34. Kappel, William M., and E.A. Nystrom, 2012, Dissolved Methane in New York Groundwater, 1999-2011, U.S. Geological Survey Open-file Report 2012-1162, 6 p. (access at: http://pubs.usgs.gov/of/2012/1162/pdf/ofr2012-1162_508_09072012.pdf)

35. Warner, N.R., R.B. Jackson, T.H. Darraha, S.G. Osborn, A. Down, K. Zhao, A. White, and A. Vengosh, 2012, Geochemical Evidence for Possible Natural Migration of Marcellus Formation Brine to Shallow Aquifers in Pennsylvanian, Proceedings of the National Academy of Science, 109 (30): 11961-11966.

36. Darrah, T.H., A. Vengosh, R.B Jackson, N.R. Warner, and R.J. Poreda, September 2014; Noble gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales, Proceedings of the National Academy of Sciences, 111 (39): 14076-14081.

37. Suchy, Dan R. and K.D. Newell, 2013, Hydraulic Fracturing of Oil and Gas Wells in Kansas. Public Information Circular (PIC) 32, Kansas Geological Survey. (access at: http://www.kgs.ku.edu/Publications/PIC/pic32.html)

38. Kansas Corporation Commission, January 2013, Abandoned Oil and Gas Wells Status Report (access at: http://biology.duke.edu/jackson/pnas2011.html)

39. Associated Press, April 16, 2012, More water protection from Marcellus shale suggested for Pennsylvania (access at: http://triblive.com/x/pittsburghtrib/s_791491.html#axzz2VBC04TFR)

40. Maloney, Kelly O., and D. A. Yoztheimer, December, 2012, Production and Disposal of Waste Materials form Gas and Oil Extraction from the Marcellus Shale Play in Pennsylvania: Environmental Practice, Vol 14, Issue 4, pp 278-287. (access at: http://journals.cambridge.org/action/displayAbstract?fromPage=online&aid=8789192)

41. Colorado Oil and Gas Conservation Commission, May 1, 2013, Model Sampling and Analysis Plan, State of Colorado. (access at: http://cogcc.state.co.us/RR_HF2012/Groundwater/FinalRules/Model_SAP_05012013.pdf

42. National Ground Water Association, July 2014, Hydraulic Fracturing: Meeting the Nation's Energy Needs While Protecting Groundwater Resources (access at http://www.ngwa.org/Documents/PositionPapers/Hydraulic%20Fracturing.pdf

43. ALS, Fracking regulations by State. (access at: http://www.alsglobal.com/en/Our-Services/Life-Sciences/Environmental/Capabilities/North-America-Capabilities/USA/Oil-and-Gasoline-Testing/Oil-and-Gas-Production-and-Midstream-Support/Fracking-Regulations-by-State)

44. Olmstead, Sheila, L. Muehlenbachs, J. Shih, Z. Chu, and A. Krupnick, March 26, 2013. Shale Gas Development Impacts on Surface Water Quality in Pennsylvania. Proceedings of the National Academy of Sciences, Vol. 110, No. 13, pg 4962-4967. (access at: http://www.pnas.org/content/110/13/4962.full)

45. Maupin, Molly, J.F. Kenny, S.S.Hutson, J.K.Lovelace, N.L. Barber, and K.S. Linsey, November, 2014. Estimated Use of Wter in the United States in 2010, Circular 1405, United States Geological Survey. (Access at: http://pubs.usgs.gov/circ/1405/)

46. Mantell, Mark, Chesapeake Energy Corporation, March 2011, Produced Water Reuse and Recycling Challenges and Opportunities Across Major Shale Plays, presentation at EPA Hydraulic Fracturing Study Technical Workshop #4, Water Resources Management, March 29-30, 2011 (access at: http://www2.epa.gov/sites/production/files/documents/09_Mantell_-_Reuse_508.pdf)

47. The Globe and Mail, August 21, 2013. Taking the water out of fracking. (access at: http://www.theglobeandmail.com/report-on-business/breakthrough/taking-the-water-out-of-fracking/article13876363/).

48. National Research Council of the National Academies, 2012, Induced Seismicity Potential in Energy Technologies: National Academies Press, 225 p.

49. Warpinski, N.R., R.C. Kramm, J.R. Heinze, and C.K. Waltman, 2005, Comparison of Single- and Dual-Array Microseismic Mapping Techniques in the Barnett Shale, Society of Petroleum Engineers international, From SPE 95568. Copyright 2005, SPE.

50. Ellsworth, William, J. Robertson, and C. Hook, January 17, 2014, Man Made Earthquake (access at: http://www.usgs.gov/blogs/features/usgs_top_story/man-made-earthquakes/)

51. Healy, J.H., W.W. Rubey, D.T. Griggs, and C.B. Raleigh, 1968, The Denver Earthquakes: Science, v. 161, no. 3848: 1301-1310. (access at: http://geosurvey.state.co.us/hazards/Earthquakes/Documents/ERC/THE%20DENVER%20EARTHQUAKES-HEALY%20AND%20OTHERS%201968.pdf)

52. Buchanan, Rex, K.D. Newell, C.S. Evans and R.D. Miller, April 2014, Induced Seismicity: The Potential for Triggered Earthquakes in Kansas. Kansas Geological Survey, Public Information Circular 36 (Access at: http://www.kgs.ku.edu/Publications/PIC/pic36.html)

53. Keranen, Katie, H. Savage, G. Abers, and E. Cochran, March 26, 2013. Potentially induced earthquakes in Oklahoma, USA: links between wastewater injection and the 2011 Mw 5.7 Earthquake. Geology,

54. Howard, G.C., and C.R. Fast, 1970, Hydraulic Fracturing: Monograph 2 of the Henry L. Doherty Series, Society of Petroleum Engineers of AIME, New York, 210 p. ISBN 0-89520-201-8

55. Ellsworth, William L., July 12, 2013. Injection-Induced Earthquakes. Science, Vol 341, no. 6142. (Access at: https://www.sciencemag.org/content/341/6142/1225942)

56. Alley, W.M, Bair, E.S., and Wireman, M., October 2013, “Deep” groundwater: Groundwater, v. 51, no. 5, pg. 653-654.

57. U.S. Government Accountability Office, October 1, 2014; Natural Gas: Federal Approval Process for Liquefied Natural Gas Exports GAO-14-762: Published: Sep 26, 2014. Publicly Released: Oct 1, 2014. **(**Access at: http://www.gao.gov/products/GAO-14-762**)**

58. Bloomberg Business, November 6, 2014; U.S. Natural Gas Exports Will Fire Up in 2015. (Access at: http://www.bloomberg.com/bw/articles/2014-11-06/u-dot-s-dot-natural-gas-exports-will-fire-up-in-2015)

59: The Christian Science Monitor, November 19, 2014. How Russia could derail US natural gas exports. (Access at: http://www.csmonitor.com/Environment/Energy-Voices/2014/1119/How-Russia-could-derail-US-natural-gas-exports)

60. Brufatto C, Cochran J, Power LCD, El-Zeghaty SZAA, Fraboulet B, Griffin T, Munk S, Justus F, Levine J, Montgomery C, Murphy D, Pfeiffer J, Pornpoch T, Rishmani L., Autumn 2003; From Mud to Cement: Building Gas Wells. Schlumberger OilField Review, pgs. 62–76.

61. Richard J. Davies, S. Almond, R. S. Ward, R.B. Jackson, C. Adams, F. Worrall, L.G. Herringshaw, J.G. Gluyas, M.A. Whitehead, September 2014; Oil and gas wells and their integrity: Implications for Shale and unconventional resource exploitation. Marine and Petroleum Geology, vol. 56, pgs. 239-254.

62. John L. Thorogood, P.L Younger, January 2015; Discussion of "Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation" by R. J. Davies, S. Almond, R.S. Ward, R.B. Jackson, C. Adams, F. . Worrall, L.G. Herringshaw, J.G. Gluyas, M.A. Whitehead. (Marine and Petroleum Geoogy 2014). Marine and Petroleum Geology, vol. 59, pgs. 671-673.

63. R.J. Davies, S. Almond, R. Ward, R.B. Jackson, C. Adams, F. Worrall, L.G. Herringshaw, J.G. Gluyas, January 2015; Reply: "Oil and gas wells and their integrity: implications for shale and unconventional resource exploitation". Marine and Petroleum Geology, vol. 59, pgs .674-675.

64. Rex Buchanan, January 26, 2015; Kansas Geological Survey Testimony. Kansas Legislature, House Standing Committee on Energy and Environment. With attachments. (Access at: http://www.kgs.ku.edu/PRS/Seismicity/2015/01-26-15_KGS_Seismic_Testimony.pdf)

65. U.S. Geological Survey and Oklahoma Geological Survey, joint press release, May 2 2014. Record Number of Oklahoma Tremors Raises Possibility of Damaging Earthquakes. (access at: http://earthquake.usgs.gov/contactus/golden/newsrelease_05022014.php)

66. United States Government Accountability Office, Sept 23, 2014; Characterization of Injected Fluids Associated with Oil and Gas Production. (Access at: http://www.gao.gov/products/GAO-14-857R).

67. National Association of County & City Health Officials, November 2014. Hydraulic Fracturing: What Local Health Departments Need to Know. Issue Brief, 8 pgs.

68. Trevor M. Penning, P. Breysse, K.Gray, M. Howard and B. Yan, 2014, Environmental Health Research Recommendations from the Inter-Environmental Health Sciences Core Center Working Group on Unconventional Natural Gas Drilling Operations. Environmental Health Perspectives, National Institute of Environmental Health Sciences, 23p.

69. StatesFirst Induced Seismicity by Injection Work Group (ISWG), 2015, Potential Injection-Induced Seismicity Associated with Oil & Gas Development: A Primer on Technical and Regulatory Considerations Informing Risk Management and Mitigation. Interstate Oil and Gas Compact Commission and the Ground Water Protection Council, 139 p.

70. M. Weingarten, S. Ge, J.W. Godt, B.A. Bekins, J.L. Rubinstein, June 18, 2015, High-rate injection is associated with the increase in U.S. mid-continent seismicity. Science magazine, Vol 348, Issue 6241, pg 1336-1339.

71. Amir Mansour Farahbod, H. Kao, J.F. Cassidy, and D. Walker, June 2015, How did hydraulic fracturing operations in the Horn River Basin change seismicity patterns in northeastern British Columbia, Canada? The Leading Edge, Special Section: Injection-induced seismicity. Pp. 658-663.

72. Gail Atkinson, K. Assatourians, B. Cheadle and W. Greig, June, 2015, Ground Motions from Three Recent Earthquakes in Western Alberta and Northeastern British Columbia and Their Implications for Induced-Seismicity Hazard in Eastern Regions. Seismology Research Letters, vol 86, No 3.

73. State Impact, NPR, December 2, 2015, Fallin Directs Officials to Discuss Alternatives for Quake-Linked Wastewater. (access: https://stateimpact.npr.org/oklahoma/2015/12/02/fallin-directs-officials-to-discuss-alternatives-for-earthquake-linked-wastewater/)

74. High Volume Hydraulic Fracturing, Revised Summary of Expressed Terms, June 2015, Department of Environmental Quality, State of New York. 6 NYCRR Parts 52, 190, 550-556, 560, 750 (access at: www.dec.ny.gov/docs/administration_pdf/summaryrevisedhvhfexpressterms.pdf)

75. Donald Siegel, N. Azzolina, B. Smith, A.E. Perry, R. Bothun, March 12 2015, Methane Concentrations in Water Wells Unrelated to Proximity to Existing Oil and Gas Wells in Northeastern Pennsylvania, Environmental Science and Technology, vol 49, p. 4106-4112.

76. Neela Banerjee, April 2015, Study on water contamination under ethics review, Inside Climate News.

GLOSSARY

aquifer: A body of permeable rock or sediment that is saturated with water and yields useful amounts of water.

biocide: A chemical substance capable of destroying some life forms. In hydraulic fracturing, biocides are used to inhibit growth of bacteria and mold.

carbonate rock: A rock composed primarily of carbonate minerals (minerals containing the CO3 anionic structure, such as calcite). Common carbonate rocks are limestones and dolomites.

casing: The hard metal or plastic pipe that lines the well, prevents a borehole from caving in, and provides a barrier to the outside rock and groundwater.

chloride: A chemical compound with one or more chlorine atoms bonded within the molecule; a salt of hydrochloric acid. Table salt is sodium chloride (NaCl).

fault: A fracture or fracture zone along which rock layers have moved.

fine-grained: A geologic term to describe a rock texture, referring to its mineral or rock fragment components.

formation: A basic unit of rock layers distinctive enough in appearance, composition, and age to be defined in geologic maps and classifications.

flowback water: The fracturing fluid that returns to the surface through the wellbore during and after a hydraulic treatment.

fracture: A crack or break in the rock.

fracturing fluids: The water and chemical additives used to hydraulically fracture the reservoir rock, and proppant (typically sand or ceramic beads) pumped into the fractures to keep them from closing once the pumping pressure is released.

frictional resistance: The force that inhibits the relative motion of two solid objects in contact. It is usually proportional to the force which presses the surfaces together.

hazard: Any sort of potential damage, harm, or adverse impact on something or someone.

high volume hydraulic fracturing: When more than 300,000 gallons are injected as base fluid in a well.

hydraulic fracturing: A process to propagate fractures in a subsurface rock layer with the injection of pressurized fluid through a wellbore, especially to extract oil or gas.

hydrocarbon: An organic compound made of carbon and hydrogen, found in coal, crude oil, natural gas and plant life.

kick off point: The depth at which the vertical drill hole is deviated for directional drilling so the well bore can enter the target zone roughly horizontal.

Mercalli intensity scale: Used by scientists to measure the size of an earthquake in terms of effects at the earth's surface (e.g., levels of damage to buildings and their contents).

moment magnitude scale: Used by scientists to measure the size of earthquakes in terms of the energy released. The scale was developed in the 1970s to improve upon the Richter magnitude scale, particularly to describe large (M>7) earthquakes and those whose epicenter is over 370 miles away.

microseismic: A faint earth tremor, typically less than Richter Magnitude zero, which was the detection limit in 1935.

methane: A colorless, odorless and flammable gaseous hydrocarbon (CH_4).

permeability: The capacity of a rock for transmitting a fluid. Permeability depends on the size and shape of pores in the rock, along with the size, shape, and extent of the connections between pore spaces.

pore space: The spaces between grains in a rock that are unoccupied by solid material.

produced water: The naturally occurring fluid in a formation that flows to the surface through the wellbore, throughout the entire lifespan of an oil or gas well. It typically has high levels of total dissolved solids with leached out minerals from the rock.

proppant: Solid material used in hydraulic fracturing to hold open the cracks made in the reservoir rock after the high pressure of the fracturing fluids is reduced. Sand, ceramic beads or miniature pellets "prop" open the cracks to allow for freer flow of oil or gas.

reservoir rock: The oil or gas bearing rock, typically a fractured or porous and permeable rock formation.

Richter magnitude scale: A numerical scale previously used by scientists to measure the size of an earthquake, ranging from less than zero to greater than 9.

risk: The chance or probability that a person or property will be harmed if exposed to a hazard.

seismic event: An earth vibration, such as an earthquake or tremor.

shale: A fine-grained sedimentary rock that formed from the compaction of finely layered silt and clay-sized minerals ("mud").

shale gas: Natural gas locked in tiny bubble-like pockets within shale or other layered, sedimentary rock.

shale oil: A shale or tight silty limestone which contains oil that formed in place. Oil is extracted by technologies such as horizontal wells and hydraulic fracturing. (Not to be confused with "oil shale" a rock that contains kerogen, an early stage of organic matter processing into petroleum. Oil shale requires a destructive distillation of the rock to yield oil.)

tight oil or gas reservoirs: Hydrocarbons dispersed in rocks of low permeability and porosity, which makes it more difficult to recover than conventional hydrocarbon deposits.

trace element: A chemical element present in minute quantities; especially ones used by organisms and essential to their functioning.

unconventional reservoir: Tight deposits such as shale and other rocks with low porosity and permeability. The gas or oil remains in the layer in which it was created or migrates short distances and requires stimulated production to extract.

well bore: A hole that is drilled to explore and recover natural resources, such as oil, gas or water.