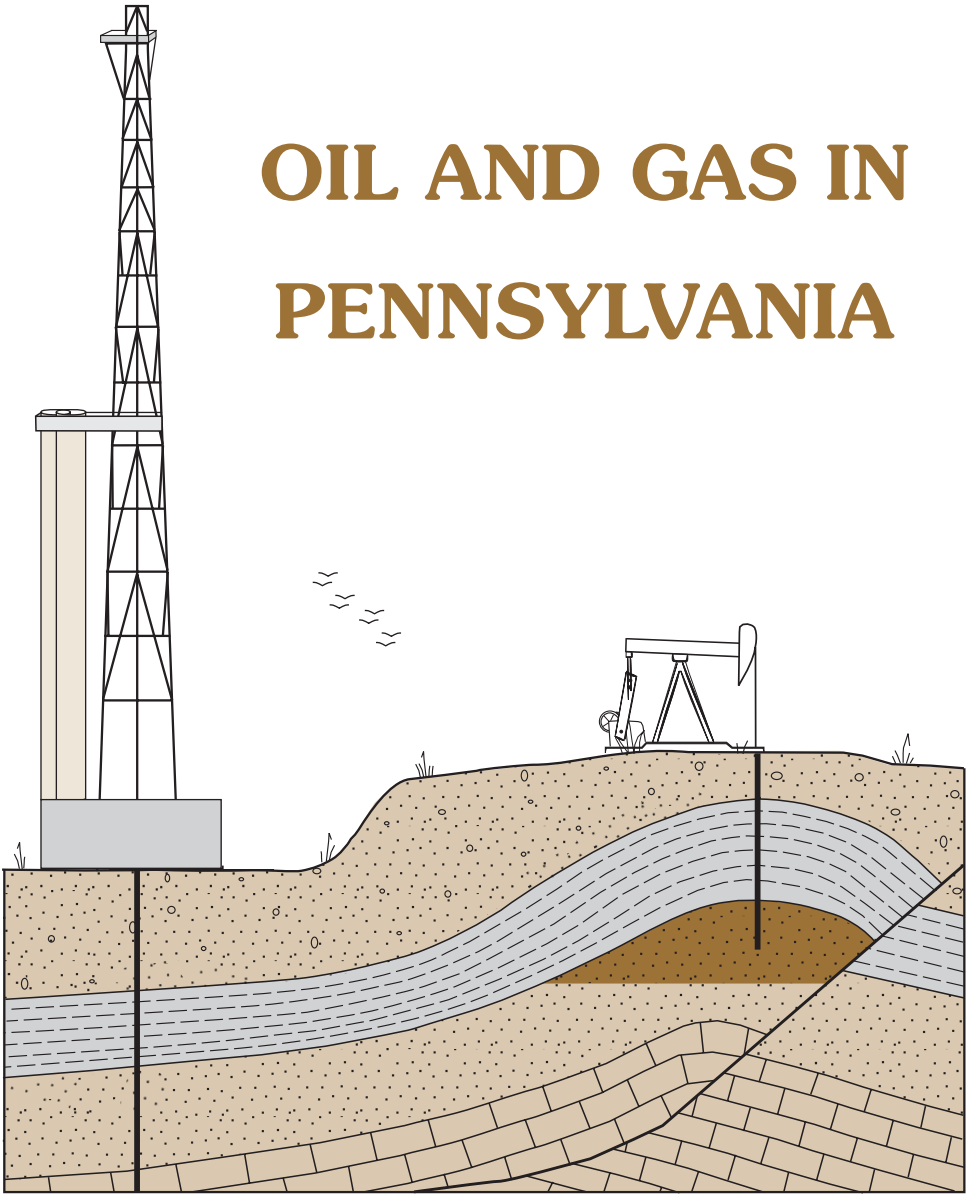
pennsylvania
DEPARTMENT OF CONSERVATION
AND NATURAL RESOURCES

Educational Series 8

OIL AND GAS IN PENNSYLVANIA



COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF
CONSERVATION AND NATURAL RESOURCES
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TOPOGRAPHIC AND GEOLOGIC SURVEY

COMMONWEALTH OF PENNSYLVANIA
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DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES
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FRONT COVER: Improvements in directional drilling and hydraulic fracturing have helped to make it economically desirable to produce oil and gas from deeper formations. Now shale gas fields are being developed at great depths across much of Pennsylvania, even within areas already producing from shallow reservoirs. The sketch (not to scale) illustrates a modern rig (left) drilling to a shale layer, which is far below the rock units shown. On a nearby hill, a pump jack produces oil from a shallow structural trap.

Educational Series 8

Oil and Gas in Pennsylvania

by Kathy J. Flaherty
ABARTA Energy
and Thomas Flaherty, III
Pennsylvania Department of
Environmental Protection

PENNSYLVANIA GEOLOGICAL SURVEY
FOURTH SERIES
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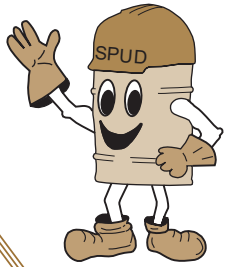
Hi! I'm Spud. "Spud" is a word used by oil and gas drillers. It means "to begin to drill a well." I'll be taking you on a tour of the oil and gas, or petroleum, industry. We'll look at many aspects of oil and gas, such as how it is found and produced, and how it is used.



Turn to the back cover of this booklet. Take a few minutes to look at the chart, which shows the kinds of rocks that lie underground in western Pennsylvania. The symbols for the different rock types are also used in other figures in this booklet. This figure will be a handy reference as you read about oil and gas in Pennsylvania. Let's get started!

OIL AND GAS IN PENNSYLVANIA

by Kathy J. Flaherty[1] and Thomas Flaherty, III[2]

WELCOME TO THE OIL AND GAS PATCH!

Think fast! Paint, acrylic carpets, and deodorant have something in common. Do you know what it is? Suppose we add gasoline and WD–40 to the list? Got it now? They are all by-products of oil and gas, or petroleum. You may not realize just how much your life is affected by petroleum.

Let's take an example from part of your typical day. You woke up this morning and stepped onto the *acrylic carpet*. You reached for your *eyeglasses* and *toothpaste tube,* then headed down the freshly *painted* hallway. You popped a *CD* into your *stereo* to sing along with as you closed the *shower curtain* and reached for a *plastic bottle* of shampoo. After a refreshing shower of *hot* water brought to you through *plastic water pipes,* you applied your *deodorant,* a dab of *perfume* or *aftershave,* and dressed in *synthetic running shoes* and a *sweater.* You used a *hair dryer, comb, brush,* and *lip balm,* and headed for the kitchen. You put your sandwich in *plastic wrap* and some soup in a *thermos bottle.* You pulled up a *vinyl* chair to the *Plexiglas®* table, ate your breakfast, and sipped orange juice from a *plastic cup.* On your way out the door, you swished your dishes in *dishwashing liquid* and unwrapped a piece of *bubble gum.* You put your *pen* and *tennis racket* in your *backpack* and grabbed your *boots, umbrella,* and *waxed-paper-bag* lunch. After placing a quick *telephone* call, you started your *car* or jumped onto the *bus,* all set for the day, thanks to petroleum!

Oil goes into nearly everything. It is a key ingredient in a wide variety of products essential to modern everyday life. Look around your home, school, or office, and try to imagine life without the benefits of petroleum.

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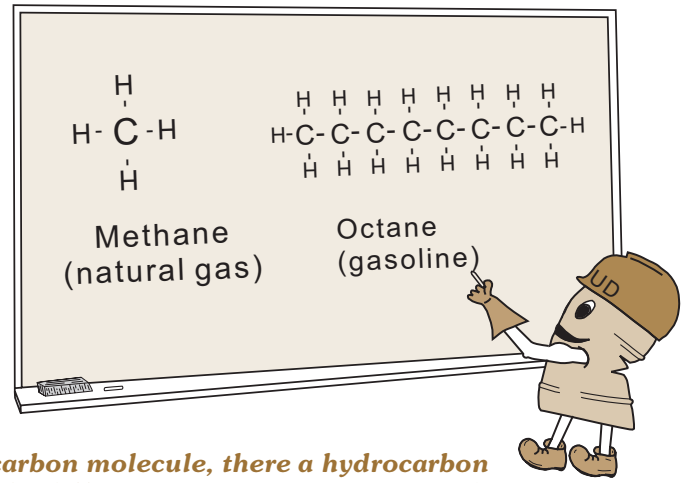
WHAT IS PETROLEUM?

So what is this substance called petroleum that seems to be everywhere in our daily lives? To answer that question, we need to start at the beginning. The basic building blocks of the world are tiny particles known as ***atoms.*** Everything is made of atoms. Each atom has a nucleus that is surrounded by at least one electron. The number and arrangement of the electrons around the nucleus are different for each element. Clusters of two or more atoms are called ***molecules.*** The elements hydrogen and oxygen, for example, combine to form water molecules. Petroleum molecules are made mostly of the elements hydrogen and carbon. Hydrogen and carbon can combine in many different ways to form these ***hydrocarbon*** molecules, which vary greatly in size and shape. Carbon atoms can connect with up to four other atoms, and hydrogen atoms can connect to only one. Therefore, hydrocarbons usually form as carbon chains surrounded by hydrogen atoms.

Hydrocarbons make up petroleum, which occurs naturally. Petroleum is found in two forms: oil, commonly called crude oil, and gas, commonly referred to as natural gas. Typical crude oil consists of 85 percent (by weight) carbon, 13 percent hydrogen, 1 percent sulfur, 0.5 percent nitrogen, and 0.5 percent oxygen. Natural gas may consist of 75 percent carbon, 20 percent hydrogen, 0.1 percent sulfur, and 4.9 percent nitrogen. However, crude oil or natural gas from different locations are never exactly the same.



Here a hydrocarbon molecule, there a hydrocarbon molecule. Slight differences in organization result in totally different substances.

HOW DOES PETROLEUM FORM?

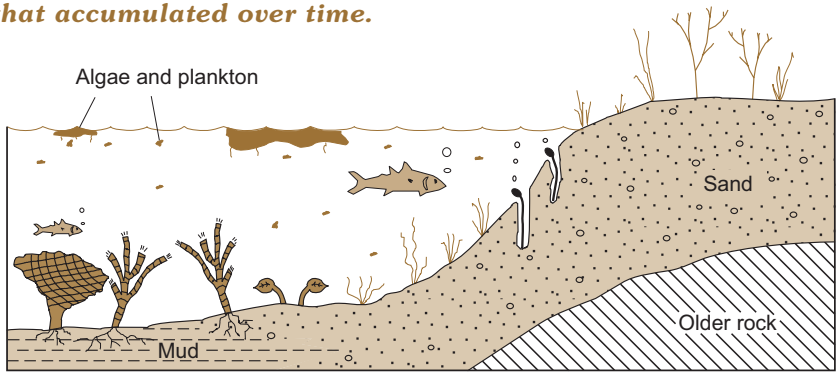
Variability in the composition of petroleum is related to how it was formed. Geologists believe that petroleum is produced from organic matter found in rocks.

Many sedimentary rocks contain organic matter formed from the remains of dead plants and animals. Most of the rocks under Pennsylvania are sedimentary rocks. The climate at the time these rocks were formed was very different than it is today. The air was warm, and a shallow sea covered much of the region in an elongated basin (the Appalachian basin) that stretched from Newfoundland to Alabama. Mountains bordered the east side of the basin (east of Pennsylvania). Plankton, fish, corals, marine plants, algae, and shellfish were abundant in the sea. At times, evaporation caused portions of the sea to dry up, leaving shallow, isolated ponds. Plants grew on the land surface between the ponds.

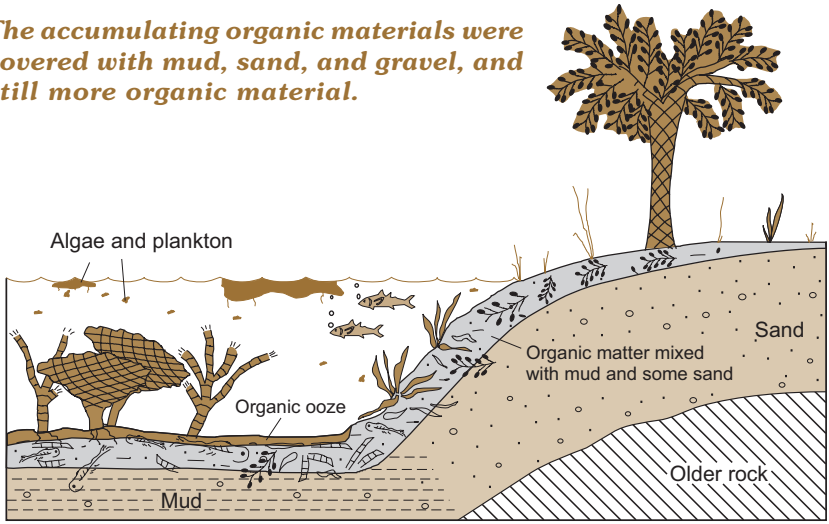
The mountains eroded very slowly. Streams flowing toward the sea carried grains, pebbles, and gravel broken away from the eroding mountains. These were deposited and became sandbars, beaches, and soil. They were then covered with more and more material eroding from the mountains.

Meanwhile, plants dropped leaves and branches onto the land and into the sea. They were covered with sand and gravel. Dead creatures and masses of dead algae and plankton sank to the muddy bottoms of the ponds and sea, and were slowly buried and pressed down by more layers of mud, sand, and gravel. The muddy bottoms of the ponds and sea hardened and became shale. Grains, gravel, and pebble layers hardened into sandstone and conglomerate.

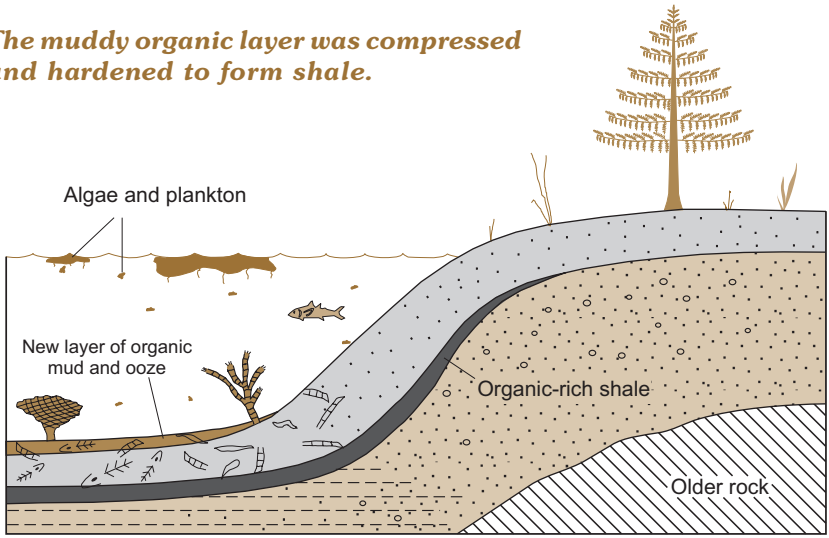
Living things became organic debris that accumulated over time.



The accumulating organic materials were covered with mud, sand, and gravel, and still more organic material.



The muddy organic layer was compressed and hardened to form shale.

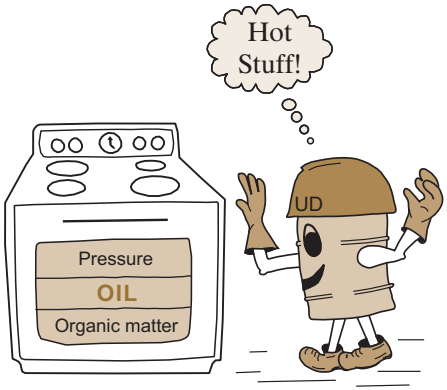


You see now that various processes form sedimentary rocks, including the deposition of sediments that have been moved from other places by wind or water. Chemistry plays a role in the decaying of plants and animals. Some sedimentary rocks, such as shale and limestone, may contain abundant organic material—the hydrogen and carbon that will become petroleum. Petroleum-rich rocks are called ***source rocks,*** and they occur at various depths below the earth's surface.

When a source rock is buried beneath the earth's surface, the organic material is subjected to heat and pressure. These forces trans-

form the organic material into hydrocarbon. The chemical composition of the hydrocarbon depends on several factors: the nature of the original organic material, the amount of pressure (deeper burial means higher pressure), the temperature (deeper burial means higher temperature), and the length of time the rock is buried (usually measured in millions of years).

Want to cook up some petroleum? The recipe is simple: just combine a few tons of organic matter, add a few thousand pounds per square inch of pressure, and set temperatures between 140°F and 320°F for a few million years to make oil. Natural gas requires a slightly higher temperature: 212°F to 392°F.



FINDING PETROLEUM

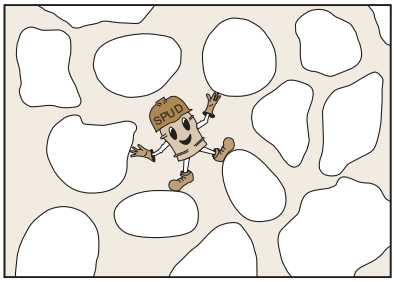
Where do you find oil and gas?

Petroleum (both oil and gas) may remain within the source rock in which it forms, or if there is a pathway, it may migrate upward and accumulate in places that have lower pressures and temperatures. Any rock that holds petroleum is referred to as a ***reservoir.*** Reservoirs include both source rocks and rocks that contain migrated petroleum. In the nineteenth and twentieth centuries, most production was from reservoir rocks, such as sandstones, that were not source rocks. Because of advances in drilling techniques and the rising cost of petroleum, drillers now produce a lot of petroleum from targeted zones within the source reservoir rocks themselves. Throughout the history of Pennsylvania's oil and gas industry, geologists have looked for certain physical characteristics that make some reservoirs or zones within reservoirs preferred targets for oil and gas production.

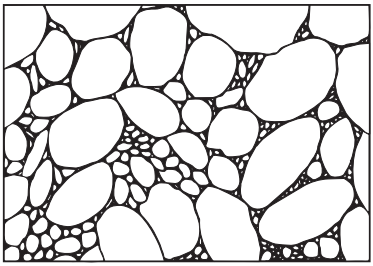
Open spaces in a rock are called ***pores.*** Rocks having lots of pore space are high in ***porosity***—an important characteristic of conventional oil and gas reservoirs. A reservoir having high porosity can hold a greater amount of petroleum. Porosity can be high if the rock grains do not fit together perfectly; it can also be high because of openings that are formed either when a rock is fractured or cracked, or when

minerals in the cement holding the grains together are dissolved. In Pennsylvania, the porosity of oil and gas reservoir rocks ranges from nearly none at all to more than 50 percent. Typical sandstone reservoirs average 12 percent porosity. This means that 12 percent of the rock is open pore space.

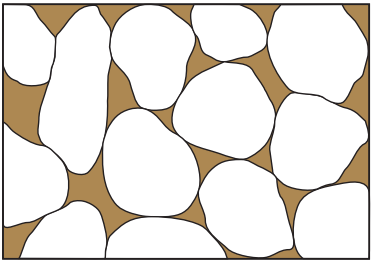
The ease with which petroleum moves from one pore space to another is called ***permeability*** and is determined by the size of the openings that connect the pores. If permeability is high, petroleum has the ability to move relatively easily. If permeability is low, petroleum may not be able to flow through the rock at all. As you will soon learn, drillers have a way to increase permeability in rocks, which many times can be used to overcome this problem. High permeability is desirable in a petroleum reservoir because petroleum that can move through a rock is easier to remove. ***Impermeable*** rocks, or those with little or no communication between pore spaces, serve as good ***cap rocks*** to seal the petroleum within the reservoir. Cap rocks function much like caps on bottles. Rocks with low permeability, such as some shale and limestone layers, make great cap rocks.



In this permeable rock, Spud has no difficulty moving between pore spaces.



In a rock having a mixture of grain sizes, smaller grains can clog the pores between larger grains. This is one of many ways a rock can have low porosity and low permeability.

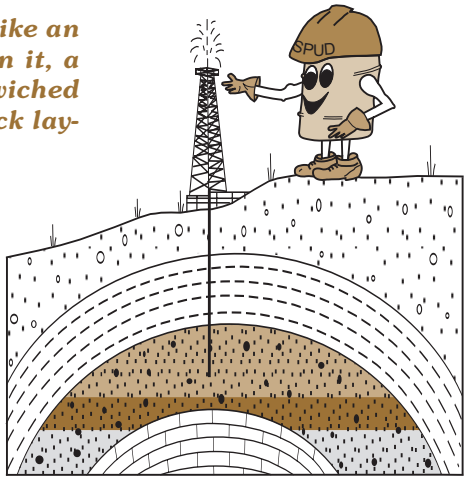


In a rock having similar-sized grains, the pores between the grains can be open but unconnected. This is one way a rock can have high porosity and low permeability.

There is nothing like a good trap!

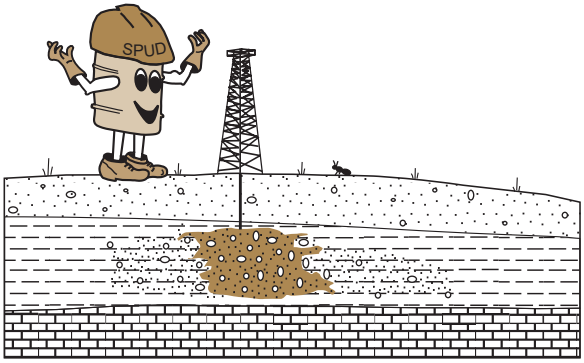
Oil and gas migrates until it becomes blocked by a cap rock. Because it cannot move any farther, it becomes trapped. Two common types of traps are ***structural traps*** and ***stratigraphic traps.*** In Pennsylvania, petroleum is found in both types of traps.

A geologic ***structure*** is formed when rock layers become folded (bent) or faulted (broken) by pressure from shifting landmasses. Structural traps occur where a rock holding oil or gas is isolated from other porous and permeable rocks by folds or faults that prevent the petroleum from escaping. Looking for oil and gas means looking for the kinds of structures that may trap it. Understanding how geological structures are formed and where they can be found is important to petroleum exploration.



This structural trap, shaped like an arch, is called an anticline. In it, a permeable sandstone is sandwiched between two impermeable rock layers, so that petroleum in the sandstone cannot escape. The hydrocarbons migrate upward through the sandstone and separate out: gas rises to the top, and oil (where it occurs) stays below the gas. Any water that was present in the sandstone is displaced below the oil and gas.

Stratigraphy is the study of strata, or layers of rock. Sediment, such as sand and small stones, and organic matter are deposited in layers, or beds. Variations in the type of materials, as well as processes such as cementation that hardens the sediment to rock, result in beds of rock that change character both laterally and vertically. Even slight changes in the characteristics of a rock can be enough of a barrier to cause it to behave like a trap to the migrating petroleum. A stratigraphic trap occurs where oil and gas collects in a more porous rock, like sandstone, and is sandwiched in place by less permeable rock layers. Of course, it is possible in nature to have a ***combination*** trap, which is a mixture of the features from both structural and stratigraphic traps.



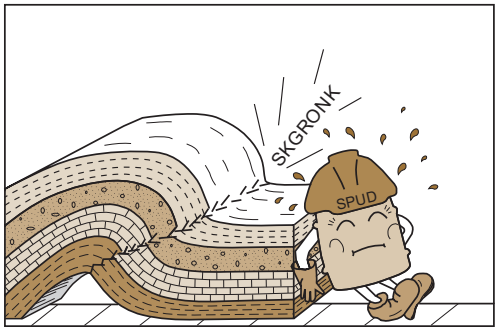
This stratigraphic trap holds petroleum within a porous rock that is surrounded by less porous and less permeable rocks.

Why is it important to know all of this? Petroleum occurs beneath the earth's surface at depths ranging from a few tens of feet to several miles. We obtain that petroleum by drilling a hole through the rocks until a reservoir is encountered. Therefore, it makes sense to have a good idea about where petroleum reservoir rocks may be found before starting to drill.

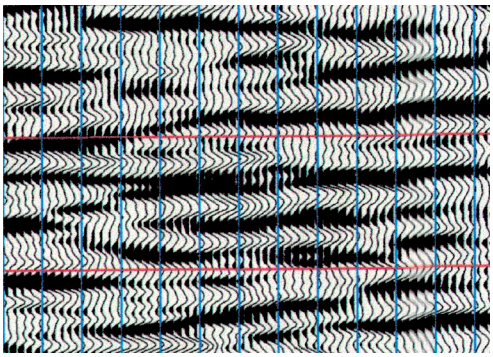
Let's go on a hunt!

We know that petroleum is trapped within a reservoir, and therefore the search for petroleum involves using ***subsurface*** information to find it. This process is known to geologists as ***prospecting.*** Much modern petroleum prospecting is done using digital data and computers. This usually means combining art with science. To be a good prospector, it is necessary to think in terms of three-dimensional space. The idea is to imagine and build a three-dimensional picture or model that shows the lateral and vertical dimensions of the target. Then the prospector can figure out where to begin drilling on the surface in order to intersect the reservoir rock.

Geologists construct models to help understand earth processes, such as the formation of this fold and fault. A simple three-dimensional sketch or computer model usually serves the purpose quite nicely.



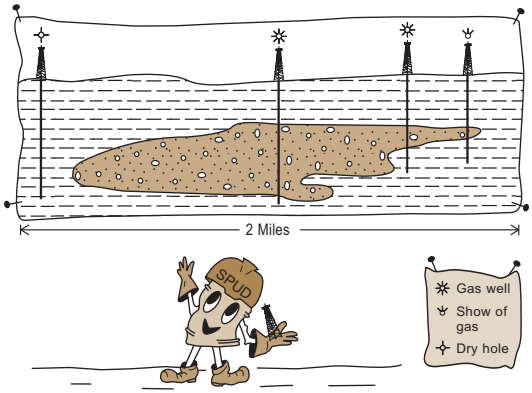
To create a three-dimensional image of a petroleum target, a geologist needs information. This information comes from many sources. First, the rocks on the earth's surface are studied. If there are existing holes drilled in the prospect area, rock cutting samples and other information from these holes are studied. In areas where no wells have been drilled, subsurface data can be obtained by a remote-sensing process such as ***seismic reflection.*** In seismic reflection, a large number of sensors are placed on the ground near a noise-making device. Sometimes the device is an in-ground explosive, and sometimes it is a large truck, called a "thumper truck," that has a vibrator attached. When all of the sensors are lined up or spread out in a gridlike network, workers generate the noise. Sound waves created by the noise travel downward and horizontally. As the sound waves travel, they encounter different types of rocks and are reflected back to the surface, where they are "heard" by the sensors. Different rock types reflect the waves differently. Some rocks, such as limestone, return a strong signal. The sensors record this information, and a sketch that represents the way the rocks are lying deep below the surface of the earth can be created. Interpretations of the recorded data enable geologists to learn more about the rocks that are too deep to be seen.



Seismic sound waves reflected off of subsurface rock layers are recorded by surface sensors. The recordings are plotted, as shown here, and used by scientists to help interpret rock types and structures occurring at depth.

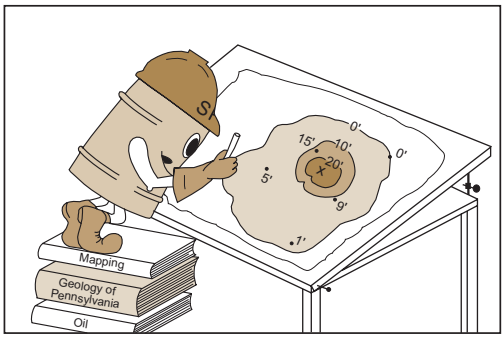
Geologists also use two-dimensional drawings to help visualize their targets. They might begin with a ***cross section,*** or side view, through the oil- and gas-bearing rocks. A cross section shows changes in rock type, orientation, and thickness in a given direction. Next, a geologist might draw an ***isopach map,*** which consists of contour lines showing the thickness of the source rock or reservoir. This may be important because the thicker the target rock, the more petroleum it may hold. Finally, a geologist might employ a ***structure map,*** which shows

contour lines on the surface of a rock layer, to illustrate how the rocks have been folded, faulted, or otherwise distorted underground. Geologists can use structure maps to target the higher portions of a fold or the side of a faulted sequence of rocks where oil and natural gas has accumulated. Just as importantly, structure maps may help geologists avoid excessively faulted or fractured rocks from which oil or gas has already escaped.



Spud uses a cross-section diagram to select a good spot in the thickest part of a petroleum reservoir to drill a new well.

By using tools such as isopach maps, cross sections, structure maps, and seismic or other remote-sensing data, a geologist constructs a complete view or model of the geometry and characteristics of the rocks before drilling. The model helps the geologist to determine where to drill a well. The goal is to find the most prospective oil and gas target, which may be where the reservoir rock is thickest, most porous and permeable, or influenced by a stratigraphic or structural trap.

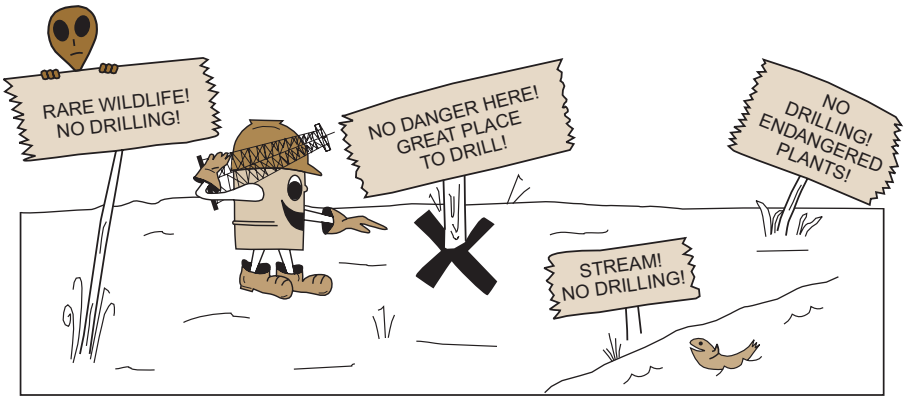


"X" marks the spot! An isopach map shows where a reservoir rock is thickest, and therefore where it may be the most productive.

DRILLING FOR OIL AND GAS

Let's drill here!

Once the geologist has determined the best location on the surface for a well, and after leasing the mineral rights, the next step is to plan for and obtain a permit to drill the well. In Pennsylvania, the Department of Environmental Protection, Bureau of Oil and Gas Manage-

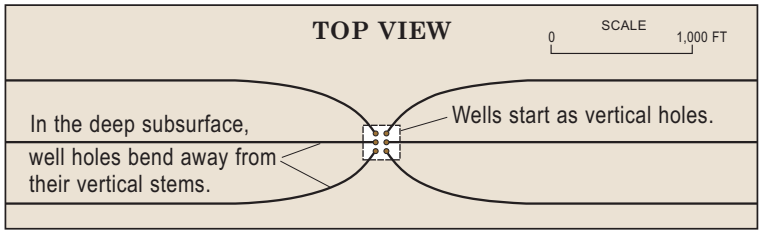


Sometimes it is a challenge to find an environmentally acceptable drill site in a geologically favorable area. It is the job of the well operator to conduct business in a responsible way with as little environmental disturbance as possible.

ment, issues such permits. To qualify for a permit, the well must be planned in an environmentally responsible manner. It may be necessary to shift the exact position of the proposed well in order to accommodate environmentally sensitive natural resources, such as streams and wetlands, or endangered and protected wildlife areas.

The distance from other producing wells can also be a consideration; a driller does not want to position a new well too close to an existing oil or gas well. Crowding might decrease the production of existing wells. The placement of the access road that leads from a paved highway to a proposed well location is another important factor. Care must be taken to minimize its impact on the general public and the surface landowner by avoiding government-owned lands, croplands, and pastures as much as possible. Because construction of the access road and well site usually involves moving considerable amounts of earth around with a bulldozer, all plans should be designed to minimize changes to an area's natural erosion and sedimentation processes.

Modern shale well sites are designed to minimize impact to the land. Many well operators plan their work in advance and build a well pad meant to accommodate several wells, rather than a separate pad site for each well. On a multi-well pad, the drilling rig can be moved in multiple directions, and the vertical portion of each well might be only 15 feet apart. A well is drilled vertically to about 1,000 feet above the shale. Then the driller kicks off, or starts to angle the hole, landing it horizontally in the shale zone of interest. From here, the well will be drilled several thousand more feet into the shale. The driller steers



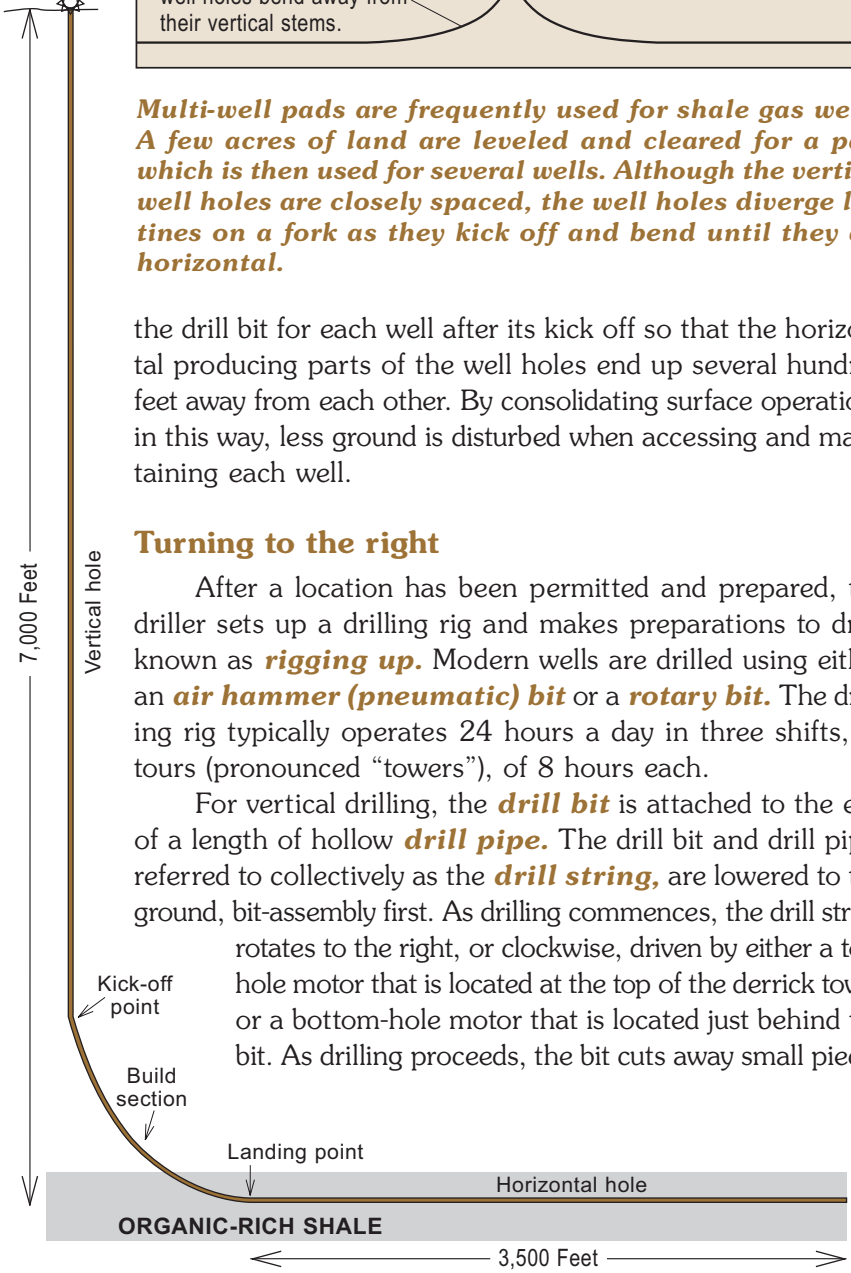
Multi-well pads are frequently used for shale gas wells. A few acres of land are leveled and cleared for a pad, which is then used for several wells. Although the vertical well holes are closely spaced, the well holes diverge like tines on a fork as they kick off and bend until they are horizontal.

the drill bit for each well after its kick off so that the horizontal producing parts of the well holes end up several hundred feet away from each other. By consolidating surface operations in this way, less ground is disturbed when accessing and maintaining each well.

Turning to the right

After a location has been permitted and prepared, the driller sets up a drilling rig and makes preparations to drill, known as ***rigging up.*** Modern wells are drilled using either an ***air hammer (pneumatic) bit*** or a ***rotary bit.*** The drilling rig typically operates 24 hours a day in three shifts, or tours (pronounced "towers"), of 8 hours each.

For vertical drilling, the ***drill bit*** is attached to the end of a length of hollow ***drill pipe.*** The drill bit and drill pipe, referred to collectively as the ***drill string,*** are lowered to the ground, bit-assembly first. As drilling commences, the drill string rotates to the right, or clockwise, driven by either a top-hole motor that is located at the top of the derrick tower or a bottom-hole motor that is located just behind the bit. As drilling proceeds, the bit cuts away small pieces

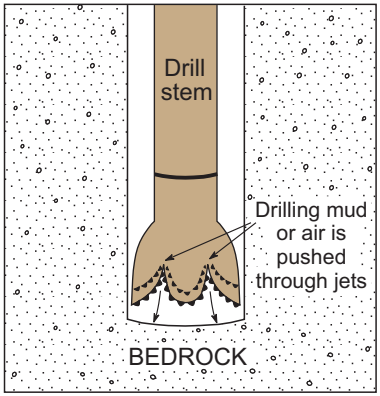


Photograph provided by Range Resources.

The rig and equipment for a conventional vertical gas well in Pennsylvania (left) uses approximately one acre of land. A multi-well pad targeting shale gas, such as the Range Resource site shown above, uses a few more acres at the drill site but has a much smaller footprint per well. When a well is completed, the drilling rig is removed, and a gas meter that has control valves and charts for recording the quantity of gas going into the pipeline is installed. A tank to collect water and oil produced with the gas also may be placed at the well location.

of rock. The churning action plus the weight of the drill string forces the drill bit deeper into the rock and causes a continuous borehole to form.

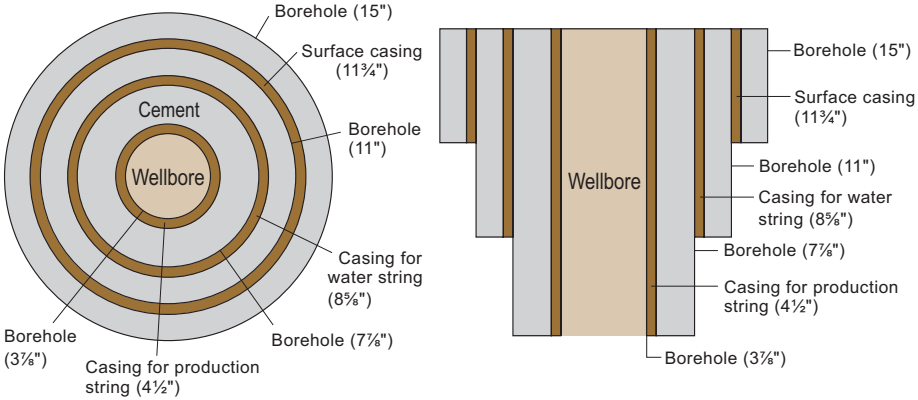
For horizontal wells, such as those drilled into shale reservoirs, operators detach the drill bit from the drill pipe and replace it with a bottom-hole motorized bit as the well approaches the kick-off point. From here to the landing point, only the bit is rotated. Once the well has been drilled to the landing point and is horizontal, the entire drill string is again rotated during the drilling process. Because it can be controlled accurately, drillers continue to use the steerable bottom-hole motor to drill the remainder of the borehole.



In a vertical hole, the drill bit and the entire length of drill pipe turn to the right. Teeth on the bit grind or pummel through the rock in the bottom of the hole. Air or drilling mud is pumped down the drill pipe and forced through jets in the drill bit. The air or mud pushes back to the surface along the outside of the pipe, carrying the pulverized rock with it.

As a well is drilled, a powerful flow of either air (with hammer or rotary bits) or synthetic- or water-based mud (with rotary bits) is pumped down the center of the hollow drill pipe and is pushed through openings in the drill bit. From there, the air or mud rushes back up the hole along the outside of the drill pipe to the surface; it carries the pulverized rock pieces, thereby keeping the borehole clean and enabling drilling to progress faster and easier. At the surface, air (if used) is vented, and the rock pieces and drilling mud (if used) are collected through a ***flow line*** into a ***drilling pit*** or a portable container. Geologists can intercept samples of the drill cuttings coming out of a well. They can examine these samples under a microscope to determine the type of rock and the presence of minerals or fossils. Because the cuttings come from increasing depths as drilling continues, geologists can use them to determine preliminary details about the depth of potential reservoir rocks. Cuttings and any drilling mud are disposed of in an environmentally proper manner after the well is completed. Many operators utilize zero-discharge, closed-loop processing systems to efficiently minimize, treat, and dispose of drilling waste with little or no environmental impact.

As a well is deepened, lengths of drill pipe must be added to continue the drilling. This is known in the petroleum industry as ***making a connection.*** This process continues until the well is a few hundred to, possibly, a few thousand feet deep, and a ***casing point*** is reached. A casing point is the depth at which the drill pipe is removed from the well and replaced with a steel pipe called casing. The casing is permanently cemented in place within the well to prevent cave-ins and to protect shallow groundwater or coal seams from contamination by petroleum. The cement is circulated in much the same manner as the air or drilling mud was circulated: down the center of the hollow casing



Horizontal (left) and vertical (right) cross-section views showing concentric rings of steel casing pipes (dark brown) and the cement (gray) between them. Typical diameter measurements for a vertical well are given, in inches, in parentheses; for casing, the measurement is to the outer edge. Wells that are completed in horizontal boreholes start with larger holes and casing sizes (e.g., 20 inches) and end with larger production casing (e.g., 5½ inches).

to the bottom of the well and back up the well alongside the outer surface of the casing. After the cement has hardened, drilling can be resumed by entering the cased drill hole with a drill bit and drill pipe of smaller diameter. This provides for a "telescoping effect" of successively smaller hole sizes and casing sizes. The well continues to be drilled until all target rocks have been penetrated. The well is now at ***total depth,*** and the drill string is removed from the well for the final time.

LOGGING THE WELL

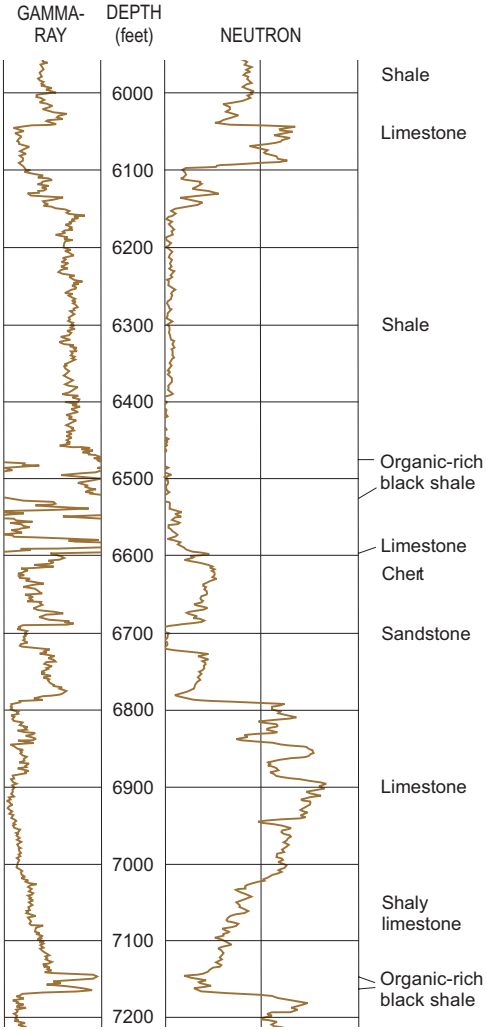
In the petroleum industry, ***logging*** is a technique used to record the characteristics and depths of the rocks penetrated by drilling. Logging a well is important because it provides geologists and engineers with an analytical tool upon which to base their evaluation of whether the well has the potential to produce oil or gas. Cylinder-shaped well-logging tools contain sensors that record important characteristics of the rocks through which the well was drilled, including porosity, rock type, hole diameter, downhole temperature, and electrical resistivity. The tools might be attached to the end of a long wire cable, which is slowly lowered down the well. As they move down to the bottom and then back up the hole, the sensors take continuous readings and transmit them

through the wire cable to recording devices. Sometimes the tools ride behind the bit; this is a necessity when logging horizontal wells.

Data from the logging devices are recorded as long vertical graphs, one for each of the rock characteristics being evaluated. Geologists and engineers study these graphs and interpret them in order to answer some key questions about new wells. Well logs can indicate whether a well was drilled deep enough to go through the target reservoir rock, whether oil and gas are contained in that rock in commercial quantities, and whether the porosity and permeability are high enough to recover the petroleum. This is the moment of truth for the geologist who

Sensitive gamma-ray logging tools record the small amount of natural radiation emitted from rocks. Each rock type has its own gamma-ray characteristics. Sandstone and limestone emit very little radiation, so the curve stays far to the left. Some organic-rich black shales contain concentrated amounts of radioactive elements and emit enough radiation that the graph goes off the scale to the right.

Neutron logging tools measure the porosity in a rock formation by responding to the amount of hydrogen present. Unlike the gamma-ray log, the neutron log shows higher values to the left. On the neutron log, the higher the reading, the more hydrogen there is in the rock. Water and petroleum are made partly of hydrogen and can be present in the pore spaces within a rock. Therefore, an increase in hydrogen indicates an increase in pore space.



planned the well and selected the well location based on a hypothesis of where the best geological conditions could occur.

If a well is not going to be productive, it will be filled with cement and ***plugged.*** A well that will produce oil or gas is prepared for completion.

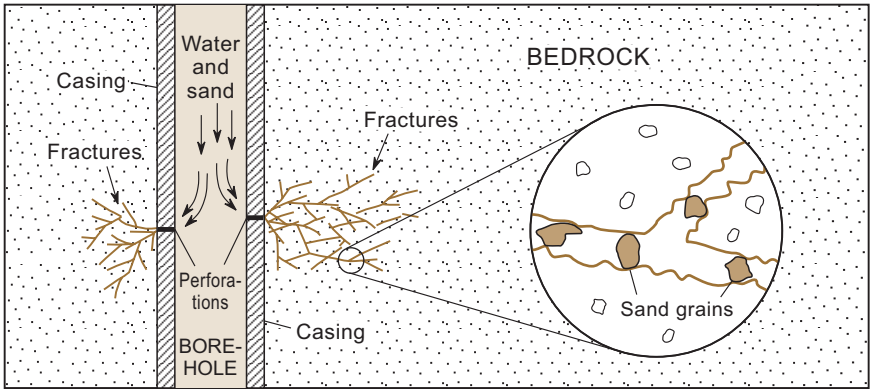
PRODUCING THE WELL

Fracturing the well

Using well logs as a guideline, geologists carefully note the precise depths where oil and gas occur—there may be more than one reservoir target in a well. However, the vast majority of new wells in Pennsylvania will not produce oil or gas by natural flow. The reservoir rocks usually do not have permeability high enough for the hydrocarbons to flow naturally. Therefore, the reservoirs must be stimulated to enhance their porosity and permeability so that the well can produce commercial quantities of oil and gas.

First, the final string of casing, ***the production string,*** which is extended below the deepest target reservoir, is put into the hole and cemented in place. This effectively seals off the entire portion of the well from which production is anticipated. Explosive charges known as shots are lowered down the hole to the precise depth of the deepest reservoir in the well from which production is desired. The shots are detonated, creating ***perforations,*** or holes, in the casing at the level of the deepest reservoir. These perforations provide openings for sand, water, and possibly weak acid and small amounts of other chemical additives that are pumped down the borehole and through the perforations at high pressures. The injection of sand and fluids causes the rock to fracture, or break down. The process is known as ***hydraulic fracturing,*** or more simply, ***fracing*** (pronounced "fracking") the well. The goal of fracing is to increase permeability by opening a pathway for easier flow of oil and gas into the well. The sand and fluids flow into the rock causing it to fracture, the fluids are then permitted to flow back into the well, and the sand remains behind, propping the fractures open.

For traditional vertical wells, the process of perforating, fracing, and flowing the well can be repeated for successively shallower reservoirs until all the potentially productive reservoirs have been fraced. Horizontal shale wells are treated a little differently. Many zones along the cased lateral are selected to perforate and fracture. Starting with



A reservoir is fractured through holes created by perforating the production string. Fractures extend out from the well, forming a network of small tunnels. Sand grains pumped down the hole with treated water become wedged in the tunnels, propping them open. Now, gas or oil has a way to flow out of the rock and into the well.

the farthest end of the lateral wellbore, each group of perforations, or ***stage,*** is fraced and then isolated from the rest of the untreated well with a plug. After all stages have been fraced, the well is often given a rest period of several weeks or even months. When the well is opened, the plugs are drilled out, and the well is allowed to flow back to rid the fractures of treated water and debris.

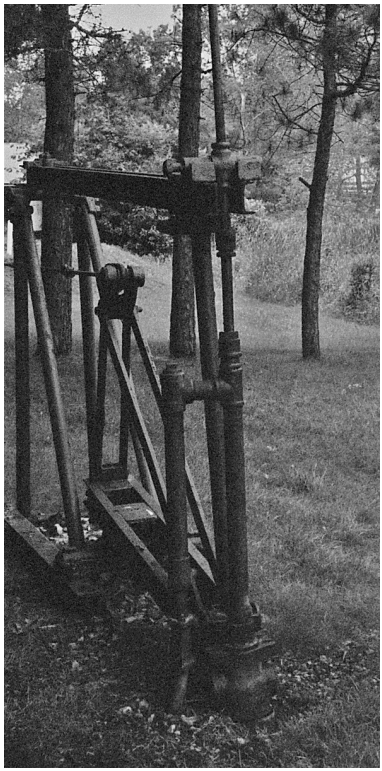
If the procedure is successful, the petroleum well responds by flowing with greater pressure and volume than were measured prior to fracing. Of course, higher volumes of oil and gas translate into greater economic benefit from the well.

Transporting oil and gas

Upon completion of hydraulic-fracturing activities, the well is ready to produce. Some wells produce commercial quantities of both oil and gas, but the more common situation is to have either an oil well or a gas well. Many modern shale wells produce wet gas, called ***condensate*** or ***natural gas liquids.*** This gas must be chilled and dehydrated through a separator unit to remove the liquids, such as propane and ethane, which are collected and sold separately.

A successful oil or gas well may produce for 30 years, and sometimes much longer. The world's oldest producing oil well, the McClintock No. 1 well, is located north of Oil City, Pa., and has been producing

a small amount of oil continuously since it was drilled in 1861. That historic well is now operated by the Friends of Drake Well as an educational site.



The McClintock No. 1 well is still pumped. It produces several barrels of oil per year.

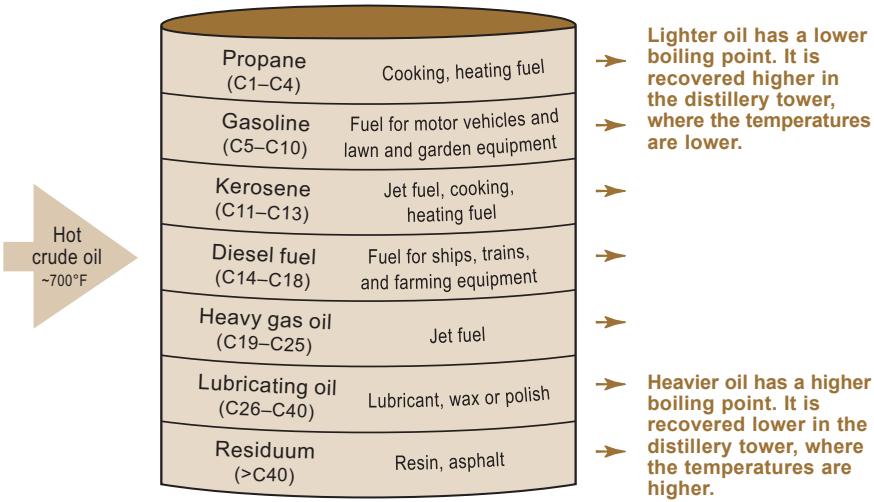
When the petroleum product is a natural gas that requires no treatment, all that is needed is to get the gas to customers. This is accomplished by moving the gas through pipelines. Wet gas, which may have some separation done at the wellhead, is transported through small "gathering" pipelines to centralized processing plants. Here, the fluids are removed, and the dry natural gas is routed to a transmission pipeline. Today, from the smallest gathering and distribution lines to the large-diameter, interstate gas-transmission lines, an impressive and efficient pipeline network crisscrosses Pennsylvania. Gas from these pipelines meets the energy needs of families, factories, and even cities, across the state and across the country. Compressor stations situated along the network of pipelines maintain pressure in the system and keep the gas moving. Gas storage pools (see page 26) located throughout the gas-producing region of Pennsylvania help to assure supplies during periods of high demand. Technological advances continue to increase the efficiency and the cost-effectiveness of the delivery of natural gas to customers who may be thousands of miles away from the wellhead. Some recent improvements include computer monitoring of gas meters, better separators and pipelines, and robotic inspections in remote areas.

The treatment of oil after production is not the same as it is for natural gas. Most oil that is produced from a well must be taken to an oil refinery to be prepared before use. It may be transported to the refinery by pipeline, or it may be stored in holding tanks near the well. If it is stored at the well site, an oil tanker truck must regularly collect the oil and transport it to an oil refinery.

REFINING OIL

Petroleum is ***refined*** to clean, break down, and rebuild the hydrocarbons that enter the refining process in the form of crude oil. As previously discussed, the primary elements that make up petroleum molecules are carbon and hydrogen. These hydrocarbon molecules vary in type, depending on how carbon and hydrogen atoms are combined. In addition, other elements, such as sulfur, nitrogen, oxygen, and some metals, can also be present. The organization of the molecules is affected by the composition of the original organic matter and by reactions to heat and pressure. Because the hydrogen molecules can be arranged in different ways and can include other elements, there are hundreds of different petroleum compounds. Refining is necessary to make usable products from this variety of complex hydrocarbons that is pumped out of the earth.

At the refinery, crude oil is separated into its components. The process is based on the fact that different compounds have different boiling temperatures. First, the crude oil is heated until it is partially



This is a simple sketch of a refining distillation tower. The temperature in the tower ranges from about 70°F at the top to more than 1,100°F at the bottom. For the various petroleum compounds, the number of carbon atoms per molecule is indicated by the number following the carbon symbol. Kerosene, for example, has between 11 and 13 atoms of carbon per molecule. Common uses are indicated beside each compound.

vaporized (between 650°F and 750°F). Then it is sent through a distillation tower, which has temperatures that increase from top to bottom, and which has many layers of condensers. The oil *vapor* rises toward the top of the tower, and as it rises and cools, it returns to a liquid state. Some vaporized hydrocarbons become liquid and settle in lower trays, whereas others move higher up before condensing. The *still-liquid* crude oils, which have higher boiling points, move to the bottom of the tower, where the temperature is higher. The result is a series of useful end products generated at each stage of the crude-oil refining process.

At this point, some of the separated components, such as propane, can be removed and packaged as end products. Some of the heavy gas oil and kerosene might be removed and subjected to ***cracking*** (breaking down) to turn them into gasoline. The cracking process involves the use of heat and pressure to crack the hydrocarbon molecules. This results in a chemically different substance. Frequently, other substances are introduced to make specialty fuels like high-octane gasoline and cleaner burning, reformulated mixtures. Sometimes oil contains other elements that have to be removed before the products can be used. Chemicals may be introduced to the distilled oils in order to react with the contaminants and make them easier to extract. Other substances, such as clay and acid, may be used to stabilize end products or break down tar components.

Not all oil requires this much treatment. The crude oil found in Pennsylvania is referred to as "Pennsylvania Grade Crude." Pennsylvania Grade Crude is prized as a high-quality lubricating oil that is especially good for light machinery, such as sewing machines. Because it has a very high boiling point, it can withstand the high temperatures reached by the operating machinery. Pennsylvania Grade Crude is also a light, sweet oil, which means it flows easily and has only minute quantities of sulfur and nitrogen. This makes it valuable for use in cosmetics and pharmaceuticals. Moreover, it contains wax. These waxy components are ideal for engine oil, gear lubricants, greases, candles, paper coatings, inks, fabrics, and food additives. Pennsylvania Grade Crude is sometimes used without refining it at all. When it needs to be refined, it requires much less processing than most crude oils found in other parts of the world.

Once refined, oil is shipped by pipelines, tank trucks, and ocean-going tankers to destinations where the refined product will be put to many uses. Petroleum helps the world go round in a very real sense.

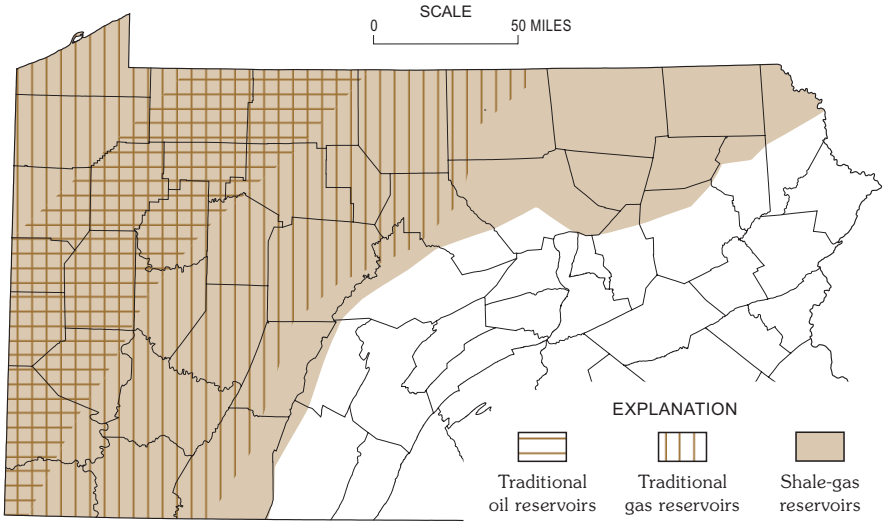
DEVELOPING AN OIL OR GAS FIELD

The search is on

Have all of the easy-to-find oil and gas reservoirs been discovered? The truth is that new oil and gas pools are being discovered all the time, even here in Pennsylvania, where drilling and production have been occurring for over 150 years. A pool is an accumulation of oil, gas, or both within one reservoir. A group of pools related to a single stratigraphic feature, structural feature, or geographic area are referred to as a field.

There are two types of oil and gas drilling, ***exploratory*** and ***development.*** Exploratory drilling, also known as ***wildcatting,*** is conducted where there are few, if any, existing wells nearby. Because exploratory wells are drilled in areas where there are little or no subsurface well data, they are risky endeavors. Although the potential rewards are high, commercial quantities of petroleum are identified in only 10 percent of wildcat wells. ***Rank wildcats,*** or wells drilled in more remote, totally unproven frontier areas, have a success ratio of only 1 in 40 (2.5 percent).

Development drilling, or infill drilling, involves drilling that takes place in areas where petroleum has already been discovered by explor-



The map above shows the general areal extents of traditional oil reservoirs, traditional gas reservoirs, and shale-gas reservoirs in Pennsylvania.

atory wells. The geographic extent of the production area may have already been defined by the initial exploratory wells. Therefore, development wells that build upon the successes of the exploratory drilling program are more likely to be successful. These lower risk wells serve to further define the extent of the target reservoirs, making it even more probable that additional development wells will be productive.

Pennsylvania lies in the heart of the Appalachian basin, which is referred to as a "mature basin" because there has been more than 150 years of active drilling. So far, drilling activity has occurred primarily within the top 3,000 to 5,000 feet of the up to 30,000-foot interval of sediments contained in the basin. Some gas fields are producing from depths of 8,000 to 9,000 feet. Exploration is ongoing for natural gas at depths greater than 10,000 feet. New technology and ideas have led to a significant increase in drilling horizontally from vertical boreholes in Pennsylvania. Horizontal drilling exposes a wellbore to thousands of feet of additional reservoir rock and increases the potential of the well to produce more oil and gas than a vertical well could ever produce.

As stated above, more oil and gas pools are being discovered each year, and additional supplies are waiting to be discovered in the future. The key to success is to become better scientists. Geologists must exercise the scientific method and their technological skill, and use their tools effectively, in order to extend existing fields, identify deeper horizons, and plan viable exploratory prospects in new geographic areas.

Enhancing oil production

A second try

Primary production from an oil reservoir consists of oil recovered by ordinary means, such as natural oil flow or oil being pumped to the surface. However, only one tenth of the oil available in a reservoir can be produced during primary production. Ninety percent of the oil remains tightly held within the reservoir. To produce as much of the oil as possible after primary production has tapered off, ***secondary recovery*** methods are employed. In Pennsylvania, the main secondary recovery techniques are vacuum, waterflooding, and gas drive.

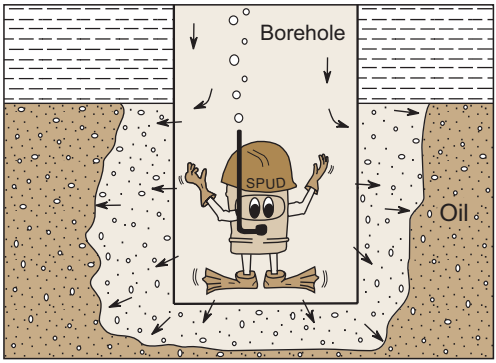
Secondary recovery by vacuum. Reservoirs were "vacuumed" in Pennsylvania as early as 1869, but vacuum techniques were used mostly in the early 1900s. Vacuuming involves pumping wells so thoroughly that the pressure in the wellbore is less than natural air pressure. In some of those early days, when a well was drilled in a Pennsylvania

oil field near another well that was being suctioned, air could be heard whistling down the new wellbore. The new well was affected by the draw of air going through the vacuumed reservoir! Even with this amount of suction applied to a reservoir, the quantity of additional oil recovered by vacuum is relatively small. Moreover, the vacuum process removes the thinner, less viscous oil components. The heavier oil remains in the reservoir and is more difficult to produce.

Secondary recovery by waterflooding. The initial secondary recovery by waterflooding was unintentional. In the 1870s, oil producers in Venango County, Pa., noticed that wells that had been abandoned and left open accumulated water from intersected groundwater reservoirs and from rainwater runoff. The pressure created from tall columns of water in the bores of the abandoned wells forced water into the petroleum reservoirs, and this water pushed the oil toward wells that were still producing.

Oil companies realized that if they were to selectively plug some wells and flood others with water, the results would become more predictable. The field would no longer be subjected to haphazard production. Eventually, the ***circle flood*** method was used. In a circle flood, water is injected into one well (the injection well) in the center of a cluster of producing oil wells. The water fans out from the injection well in a circle and pushes the oil toward the producing wells.

In 1922, companies started drilling one row of water-injection wells between two rows of oil wells. In this type of recovery, called ***line flood,*** water injected into the wells pushes the oil in the direction of the oil wells. As the oil is depleted, the producing wells are converted to water-injection wells, and the oil is pushed out toward a new line of pro-

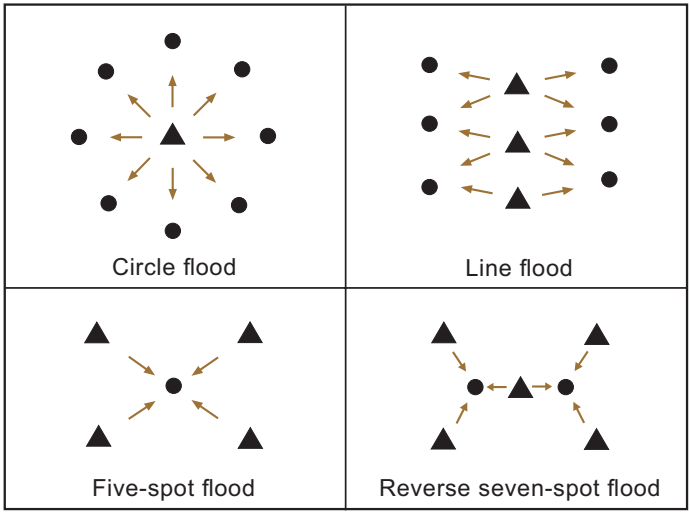


In waterflooding, water from the borehole invades the reservoir under hydrostatic or applied pressure. Oil left after primary production is forced away from this injection well and toward other nearby producing wells.

ducing wells. The first time line flooding was used, it took 2 to 3 years for the water from the injection wells to reach the oil wells! This style of secondary recovery was used with some success in the famous Bradford oil field in McKean County, Pa.

The ***five-spot*** method was introduced in 1928. One producing oil well was centered among four water-injection wells. Five-spot, which proved to be very effective, was later combined with ***pressure flooding*** techniques. In pressure flooding, hydraulic pressure is added to the column of water in the injection well, making injection of the water into the reservoir formation more forceful. In Pennsylvania, a pressure flood of a typical five-spot arrangement uses 10 to 25 barrels of water at pressures of 1,800 to 2,000 pounds per square inch to produce one barrel of oil. The distances between the water-injection and producing oil wells range from 200 to 300 feet.

The combination of five-spot and pressure flooding proved so successful that it is still commonly used today. The success of any pressure flooding project, however, depends greatly on the characteristics of the local reservoir rocks. While pressure flooding is not effective in many Pennsylvania oil fields, it has produced more than 10,000 barrels per acre in some parts of the Bradford field.



Four of the many arrangements of injection and production wells that have been tried in Pennsylvania. Dots represent oil wells; triangles represent injection wells (water or gas).

Secondary recovery by gas drive. High-pressure gas was first used in an oil reservoir in 1890 in Venango County, Pa. A well was intentionally drilled deeper than the oil reservoir to reach a natural gas reservoir under high pressure. The operator shut the well in (closed the well), and the pressurized gas was naturally driven into the oil reservoir. All the surrounding oil wells realized an increase in production. Since that time, gas and/or air injection has become a popular method to repressurize oil reservoirs to produce additional oil. This method requires approximately 1,000 cubic feet of air or gas per day per vertical foot of reservoir to be injected at pressures ranging from 50 to 400 pounds per square inch. The arrangement of wells can vary as it does for waterflooding. The distance between the injection wells and the producing wells should be 150 to 250 feet in a ***reverse seven-spot*** arrangement. In a typical Pennsylvania oil field, this will give an expected production of 10 to 100 barrels of oil per acre for each foot of reservoir thickness.

A third try

Sometimes the reservoir is subjected to yet another round of petroleum recovery enhancement called ***tertiary recovery.*** Tertiary recovery techniques used in petroleum-producing areas include injecting steam, chemical solvents, foams, biochemicals, or carbon dioxide, and heating the reservoir. These have been tried in Pennsylvania with limited success.

UNDERGROUND NATURAL GAS STORAGE

An important activity undertaken by natural gas companies in Pennsylvania is the underground storage of natural gas. Underground storage involves pumping natural gas into the ground where rock reservoirs have porosity, permeability, and a trap so that the gas cannot escape. Frequently, gas reservoirs are used for storage after much of the original natural gas has been produced. One benefit of having underground gas storage is that extra supplies are ready and available during the cold winter months when gas is in great demand for heating.

Perhaps the most important requirement for suitability for gas storage is that the underground container or reservoir is well defined and has known limits to ensure that gas pumped underground will not escape. Therefore, geologists look for a seal, or trap, around the reservoir. This

At this storage facility near Pittsburgh, Pa., natural gas is stored in an Upper Devonian sandstone, between 1,900 feet and 2,200 feet underground. Well pressure and the flow of gas into and out of the rock formation are controlled from this station.

might be indicated by a "dry hole perimeter," a series of wells encircling the reservoir that were drilled but had no production. The lack of production signals the presence of a natural barrier that caused the original gas to be contained within the reservoir and that makes the reservoir suitable for storage.

Natural gas is usually pumped into a storage reservoir during the late spring and summer months, when gas supplies are abundant because demand is low. Storage reservoirs are generally filled to capacity by the fall, and gas is available to be withdrawn as needed during the winter months.

Most people are unaware of the several dozen natural gas storage pools in Pennsylvania because the large areas used for storing the gas are located underground at depths of 2,000 to 8,000 feet. The only indications on the surface of the earth are the compressors, flow meters, valves, and pipelines that are found at the wellheads associated with these areas. Gas storage pools vary in size from those requiring single wells to those having more than 150 storage wells. Oil and gas law in Pennsylvania allows for the storage of natural gas in any rock type except underground coal seams.

WHAT HAPPENS WHEN THE WELL RUNS DRY?

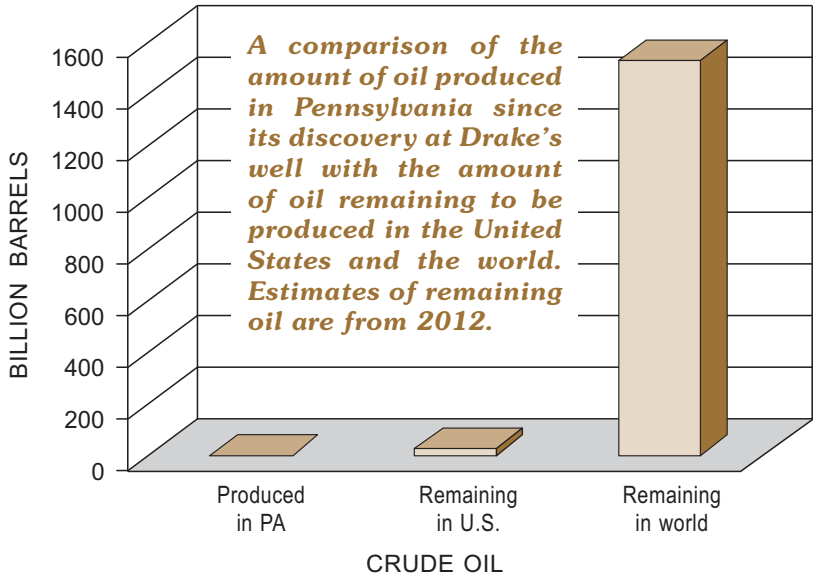
When a well no longer produces economic quantities of oil or gas, the well operator is required to ***plug*** the well. First, the well is disconnected from the gas or oil pipeline, and any production casing inside the well is removed for scrap value. Then, cement is pumped down the hole to seal off the oil- and gas-bearing rocks. At the surface, a 6-foot-tall vent pipe must be installed to prevent pressure build-up from any gas that may still work its way to the borehole. The vent pipe also serves as a marker so that old wells can be located if the land is going to be developed by builders.

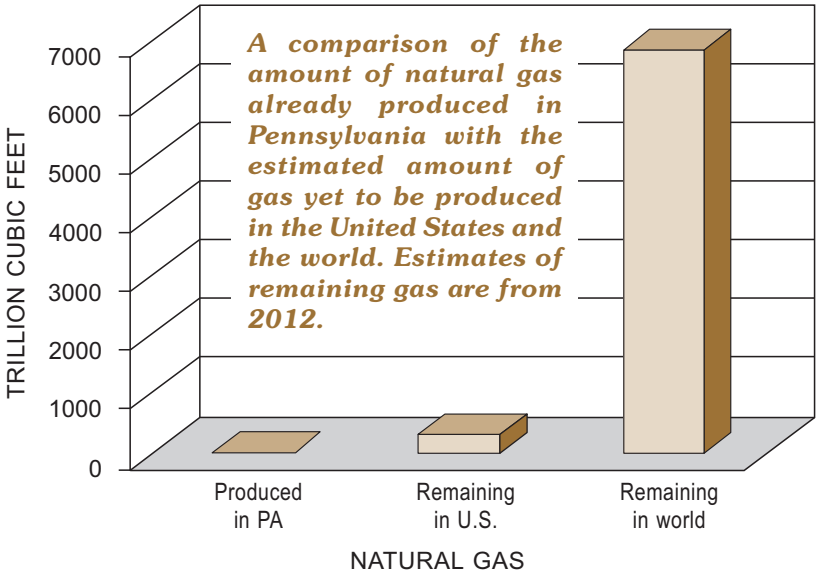
THE FUTURE OF OIL AND GAS

Since Drake's discovery of oil in 1859, Pennsylvania oil fields have produced about 1.4 billion barrels of crude oil. That's more than enough oil to fill 6.5 million swimming pools 20 feet in diameter and 4 feet deep. Our natural gas production has exceeded 16 trillion cubic feet since 1906, when gas production was first measured. In 2012 alone, Pennsylvania gas wells produced over 2 trillion cubic feet of gas, enough to meet the fuel needs of all of the homes in Pennsylvania for 2.5 years. All of this oil and gas came from the more than 350,000 wells that have been drilled in Pennsylvania to date.

The amount of petroleum that remains to be discovered and retrieved has concerned the energy industry, governments, and many other people since petroleum was discovered. Teams of scientists meet regularly to discuss the petroleum supplies that remain in the ground and the technology necessary to find, drill, and produce them. Of all the oil and gas known in the world today (total resource), only some of it is available to be collected (recoverable) because of economic, environmental, or technological limitations.

Estimates from the U.S. Department of Energy in 2012 put known oil reserves in the United States (reasonably certain to be in place and retrievable) at nearly 26.54 billion barrels of crude oil. That's enough oil to fill the 15-gallon gas tank in one car three times a day every day for more than 65 million years. Worldwide, oil reserves were estimated at 1,526 billion barrels. The Department of Energy also estimated that the United States has 334 trillion cubic feet of natural gas reserves, enough to heat every home in Pennsylvania for hundreds of years. Natural gas reserves worldwide were estimated at 6,845 trillion cubic feet.





For many years, the United States was dependent on imported petroleum for more than half of our daily needs. The technical advances in horizontal drilling and completions that the petroleum industry has achieved during recent decades have helped us to begin to realize more energy independence. Tapping our shale gas resources has encouraged economic growth in Pennsylvania and the entire Appalachian region.

Residents and business consumers have a reliable supply of affordable, abundant, clean-burning natural gas. Many new jobs have been created that are directly related to or are in support of the new gas well activity (drilling, completion, pipeline, and production). Domestic production of natural gas in the United States is approaching 90 percent of our needs, discontinuing much of our reliance on imports. Crude oil imports to the United States have declined to the levels they were 20 years ago, and they continue to fall. Efficiency and conservation efforts, together with technical improvements in our search, discovery, and production of oil and natural gas, will continue to help Pennsylvania and the United States maintain a strong economy.

The national interest in improving air quality and continuing to decrease our dependence on imported fuels has a positive impact on research and development of viable alternative fuel sources. Two very promising products are ***liquefied natural gas*** and ***compressed natural gas.***

Liquefied natural gas (LNG) is a nearly pure, very cold methane (−260°F). It takes up less space and weighs considerably less than the equivalent amount of water. LNG is considered to be environmentally friendly; it burns with little waste, it is economical, and it is an efficient fuel. Difficulty in maintaining the very low temperatures needed to keep this gas from evaporating makes it impractical to use in passenger vehicles at present, although it is used to power long-distance delivery trucks.

Compressed natural gas (CNG) is primarily methane compressed to 200 to 3,600 pounds per square inch. It is stored in tanks designed especially to maintain that pressure. CNG is becoming more common and available for daily commuter use. It is cheaper than gasoline, environmentally friendly, and efficient. This fuel is being used in local delivery trucks and car fleets.

LOOKING BACK: HOW IT ALL BEGAN

Petroleum has been used since at least 4,000 B.C. Ancient Egyptians used oil when preparing mummies for burial. The asphalt mortar used to construct the Tower of Babel in ancient Mesopotamia and the Hanging Gardens and city walls of Babylon rendered those structures virtually indestructible. Hardened asphalt was used for carved ornaments in Jerusalem. Hindu people used oil to treat diseases, treat timber, and cremate corpses. The ancient Chinese drilled for, produced,

and marketed natural gas, and transported it to their homes through bamboo pipelines to use for lighting and heat.

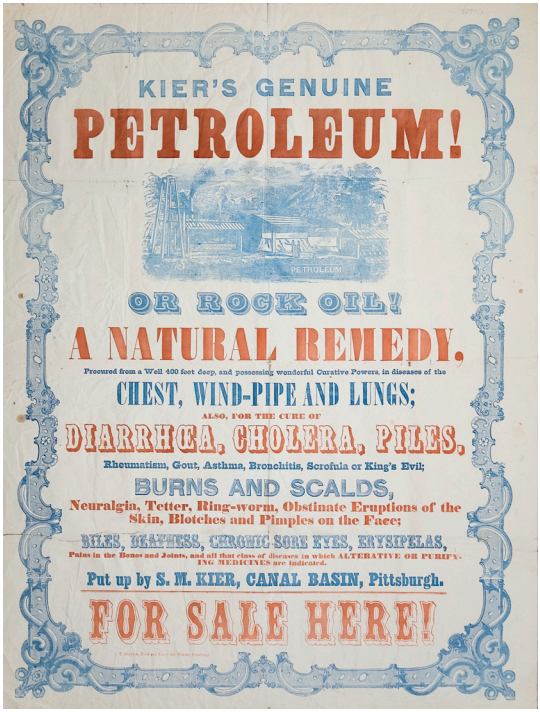
The properties and usefulness of other oils was familiar to many cultures. As early as 800 A.D., Basques hunted whales and used whale oil for light and heat. Through time, many other products, including paint, varnish, soap, candles, medicines, lubricating oil, and leather tanning oils were made from whale oil. The more people used oil, the more they needed oil. During the 1600s, shortages of whales and whale oil led to skirmishes between the Dutch and English. Whales were becoming harder to find, and whalers ventured farther from Europe. Eventually, even the whalers realized that future supplies were to be found in "rock" oil.

The Seneca Indians told early explorers about the oil seeps they found. These Native Americans were the first oil producers in North America. Hundreds of years before Columbus sailed to North American shores, the Seneca were collecting oil by trapping it behind dams and in timber-lined pits near the seeps on the banks of Oil Creek in northwestern Pennsylvania. The Seneca also skimmed oil off the surface of oily water with blankets. The collected oil would eventually be used for trading, ceremonial acts, and medicinal purposes, including treatment of stomach ailments, aching muscles, and dry skin.

In the foreground of this photograph is a pit. The area shown is on the grounds of the Drake Well Museum, and the pit may have been one of the seeps from which the Seneca Indians skimmed oil. The museum property is situated along Oil Creek.

The next big step in the history of petroleum is credited to a clever entrepreneur and inventor named Samuel M. Kier. In the early 1800s, Kier was operating a salt well near Tarentum, Pa. Salt wells, which were common in northwestern Pennsylvania at the time, were used to pump salty water out of the ground. The salt would then be evaporated out of the water and sold. In the 1840s, salt-well operators along the Allegheny River were discouraged when their wells began to produce nasty, greasy crude oil along with the sought-after salt water. Kier, however, saw opportunity. He came up with uses for the "nuisance" oil that was ruining his salt wells, and even got people to pay for this waste product!

Kier began by selling crude oil as medicine. This business became so successful that Kier started buying crude oil from other salt-well operators. He also experimented with refining crude oil into kerosene, and he adapted burners from whale-oil lamps to burn the kerosene "rock oil" that he refined from crude oil. Because of his pioneering work, Kier is credited as the founder of the American oil refining industry. Refining decreased the amount of smoke emitted from the burning oil. Improvements in Kier's distillation (refining) process led to increased demands for the oil that he collected. It burned brightly, provided good heat for warmth or cooking, was considerably cheaper than whale oil and lards, and was safer to burn than other fluid fuels available at that time.



An old poster advertises the curative properties of Kier's genuine petroleum or rock oil. Image courtesy of the Pennsylvania Historical and Museum Commission (PHMC), Drake Well Museum.

Kier's enterprising distillation and uses of oil caught the attention of East Coast investors. Sensing a business opportunity, they contracted the services of "Colonel" Edwin L. Drake for the purpose of supervising oil gathering. Because skimming the oil springs did not collect large amounts of oil, Drake was instructed to bore a hole into the earth specifically to find and retrieve crude oil. With the cooperation of William "Uncle Billy" Smith, a blacksmith and an experienced salt-well driller, the tools to drill a well were constructed and brought to Titusville, Pa., near the site of the oil seeps. The first drilled well was a success. Oil was found at 69.5 feet below the surface of the earth in August 1859, and the modern oil industry began.

INFLUENCE OF THE PETROLEUM INDUSTRY ON OTHER INDUSTRIES

Much excitement and opportunity resulted from the discovery and development of the petroleum industry in western Pennsylvania. Many different kinds of people traveled to the oil regions in Pennsylvania soon after news began to spread about Drake's successful oil well. Scientists, naturalists, explorers, adventure-seekers, capitalists, and suppliers of goods and services needed by the rapidly increasing population made their way to the new boomtowns.

Railroads were built and expanded to accommodate the influx of activity in the petroleum-producing region and to transport the oil out of the area to the refineries. When several important railroad bridges were completed in the mid-1860s, trains connected the oil region to the large cities of the eastern seaboard, to other cities such as Buffalo, Rochester, and Pittsburgh, and to the Great Lakes area.

The growing petroleum industry required large quantities of new iron and steel products. Each new well required between one and three tons of steel drive pipe as well as boring tools, valves, fittings, derricks, cables, and a myriad of other specialty parts. Iron and steel manufacturers in the western region of Pennsylvania met the challenge of providing the equipment—not just for the local petroleum industry, but for other oil fields in the United States, Europe, Russia, Peru, India, Japan, and China. The coal industry in western Pennsylvania also benefited from the increased demand for iron and steel products, because coal fueled the iron- and steel-making furnaces of the day.

This replica of Drake's well house and derrick on the grounds of the Drake Well Museum in Titusville, Pa., was built in 1945. It shows a "board-for-board" reconstruction of the original structures, which burned down in October 1859. Visitors can enter the wooden building and see the simulated pumping process, which uses a steam engine and a boiler. Drake's drilling tools are on display inside the main museum building.

Manufacturers of pumps, engines, rope, tubing, glass, chemicals, and wooden barrels also realized positive benefits from the activities in the oil fields. By 1866, five glass factories in Pittsburgh were shipping 48,000 oil-lamp chimneys per week. Services such as machine shops, blacksmithing, freight, and hauling were in high demand.

Oil-field-related employment kept workers in Pennsylvania and surrounding states busy and had positive, lasting impacts on the reputation of the industrious, hardworking population of the region.

The importance of petroleum to the economy and history of Pennsylvania is represented in Edwin Austin Abbey's painting, *The Spirit of Light,* one of four lunettes in the rotunda of the Pennsylvania State Capitol Building in Harrisburg. The 1911 painting features a background of derrick towers and a foreground suggesting both light and lightness of spirit. Petroleum has long been recognized as a treasure in the Commonwealth of Pennsylvania.

ADDITIONAL READING

If we have oiled your enthusiasm, you may want to check the internet or local library for some of the many websites and books that include information on petroleum resources and the oil and gas industry. Among them, the authors recommend the following:

Websites

Pennsylvania Geological Survey
dcnr.state.pa.us/topogeo/econresource/oilandgas/marcellus
dcnr.state.pa.us/cs/groups/public/documents/document/dcnr_006821.pdf

Pennsylvania Department of Environmental Protection
depweb.state.pa.us/portal/server.pt/community/oil_and_gas/6003

Penn State Extension
extension.psu.edu/natural-resources/natural-gas

PHMC—Drake Well Museum
www.portal.state.pa.us/portal/server.pt/community/industrial_heritage_trail/20265/drake_well_museum

Books

Bommer, P. M., 2008, **A primer of oilwell drilling** (7th ed.): Austin, Tex., University of Texas, 264 p.

Devereux, Steve, 1999, **Drilling for oil and gas—a nontechnical guide:** Tulsa, Okla., PennWell, 337 p.

Giddens, P. H., 1948, **Early days of oil:** Princeton University Press, 149 p.

Hyne, N. J., 2012, **Nontechnical guide to petroleum geology, exploration, drilling, and production** (3rd ed.): Tulsa, Okla., PennWell Corp., 698 p.

Selley, R. C., 1998, **Elements of petroleum geology** (2nd ed.): San Diego, Academic Press, 470 p.

Stoneley, Robert, 1995, **Introduction to petroleum exploration for non-geologists:** Oxford University Press, 119 p.

PLACES TO VISIT

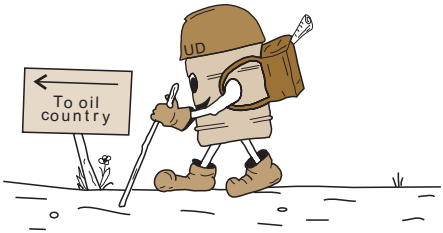
Coolspring Power Museum
179 Coolspring Road
Coolspring, PA 15730
Telephone: 814–849–6883
coolspringpowermuseum.org

Drake Well Museum
202 Museum Lane
Titusville, PA 16354
Telephone: 814–827–2797
drakewell.org

Oil Creek State Park
305 State Park Road
Oil City, PA 16301
Telephone: 814–676–5915
dcnr.state.pa.us/stateparks/findapark/oilcreek

Penn Brad Oil Museum
901 South Avenue
Bradford, PA 16701
Telephone: 814–362–1955
pennbradoilmuseum.org

Pithole Visitors Center
14118 Pithole Road
Pleasantville, PA 16341
Telephone: 814–827–2797
visitpa.com/pa-museums/pithole-visitors-center



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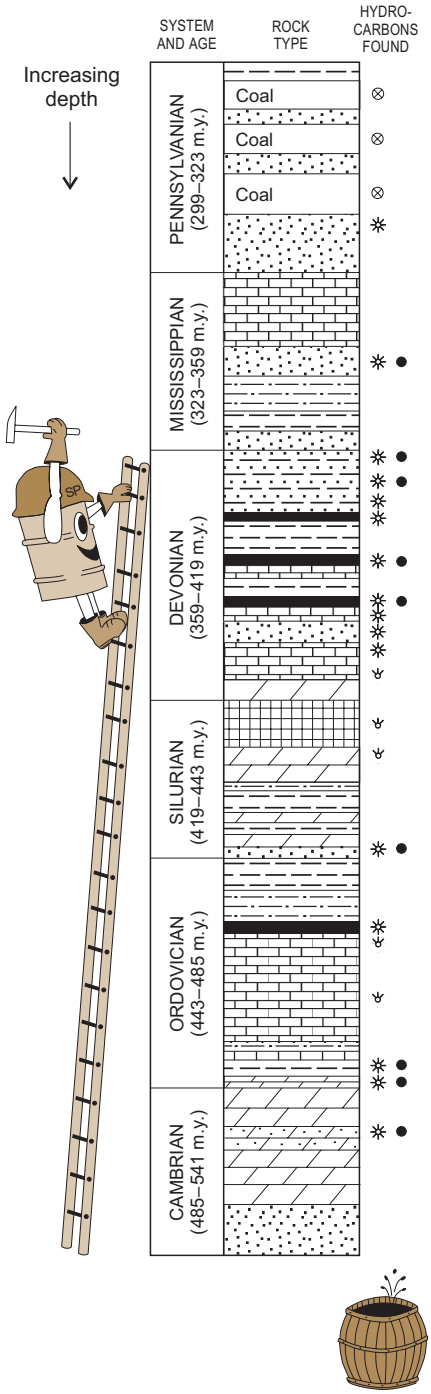

Generalized stratigraphic column for the rocks found beneath the western part of Pennsylvania. The numbers in the left column show the ages represented by each time period (m.y., millions of years ago). Rock types are shown in the middle column. The symbols in the column on the right indicate if oil, gas, or coalbed methane has been found in that part of the stratigraphic column.

EXPLANATION

- Sandstone
- Siltstone
- Shale
- Black shale
- Coal
- Limestone
- Dolomite
- Sandy dolomite
- Salt

- ⊗ Coalbed methane
- Show of gas
- Gas
- ● Oil