NATURAL GAS IN WYOMING

by
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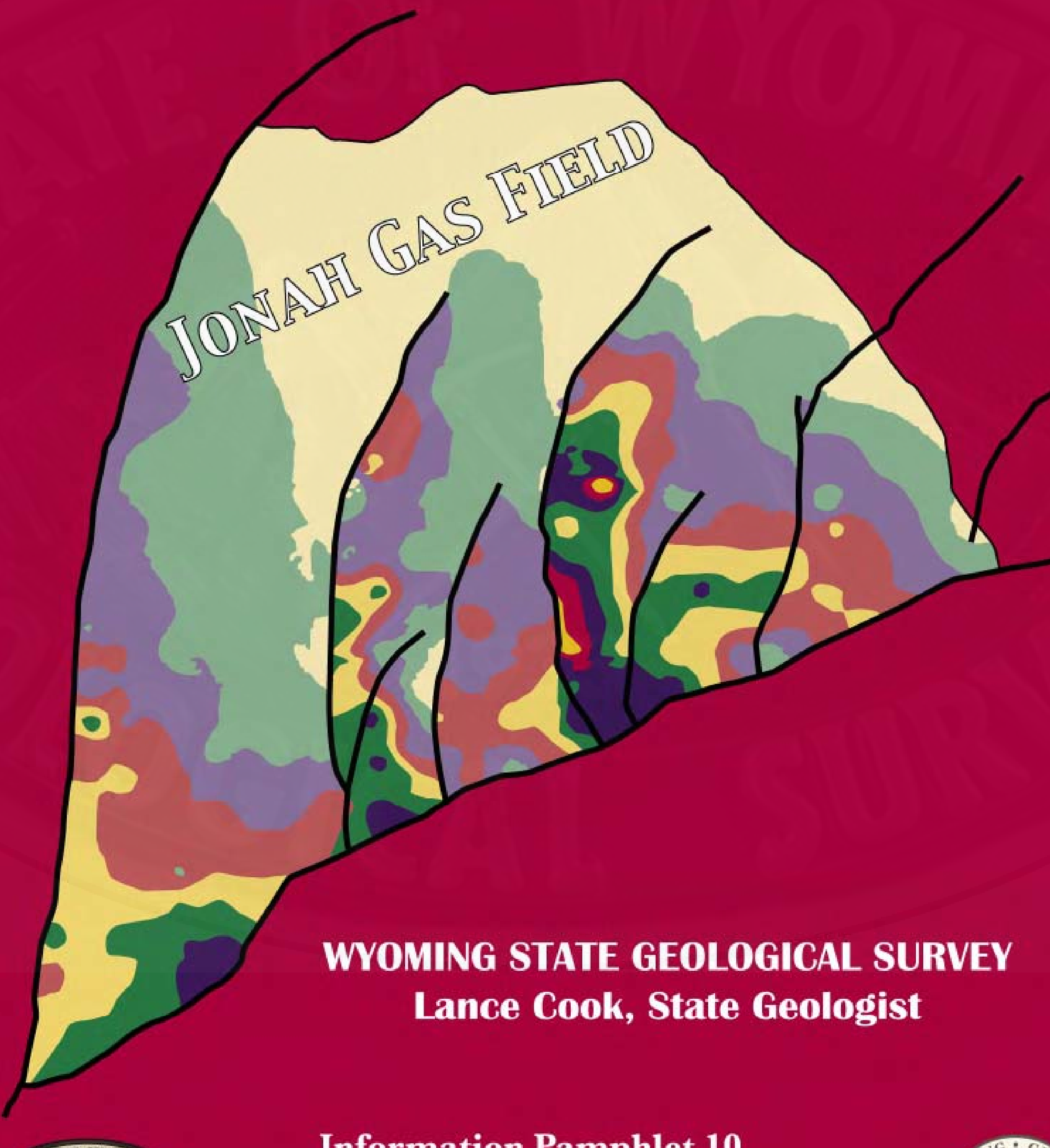

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What is natural gas?

Natural gas is defined as "hydrocarbons that exist as a gas or vapor at ordinary temperatures and pressures" (Bates and Jackson, 1987). It consists of varying proportions of gaseous *hydrocarbons* (compounds that contain only the elements hydrogen and carbon) such as *methane* (CH_4), *ethane* (C_2H_6), *propane* (C_3H_8), *n-butane* or *isobutane* (C_4H_{10}), and sometimes, liquid hydrocarbons such as *pentane* (C_5H_{12}) and *hexane* (C_6H_{14}) when the gas is under pressure. It may also contain non-hydrocarbon gases such as *carbon dioxide* (CO_2), *hydrogen sulfide* (H_2S), *nitrogen* (N_2), *hydrogen* (H_2), and *helium* (He_2). People are most familiar with the natural gas that they burn in their furnaces to heat their homes. Almost all of that natural gas is composed of methane, the simplest hydrocarbon molecule, which consists of one carbon atom surrounded by four hydrogen atoms (**Figure 1**). The natural gas burned for heat in homes may contain small amounts of other hydrocarbon gases such as ethane, propane, and butane; however, most of the hydrocarbons other than methane and most of the non-hydrocarbon gases are removed at natural gas processing plants (**Figure 2**). Methane exists in variable concentrations throughout the Earth's atmosphere, water, and rock layers.

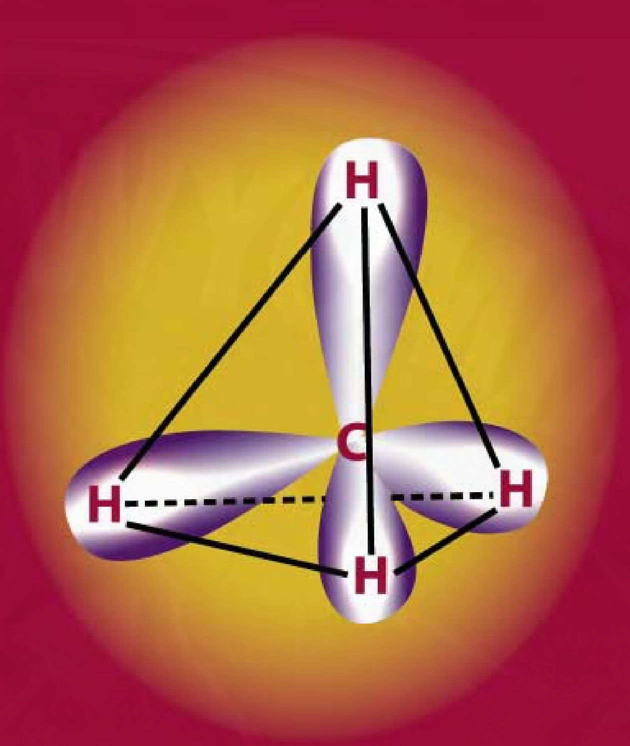


Figure 1. Schematic 3-D representation of the bonding orbitals in a methane (CH_4) molecule.

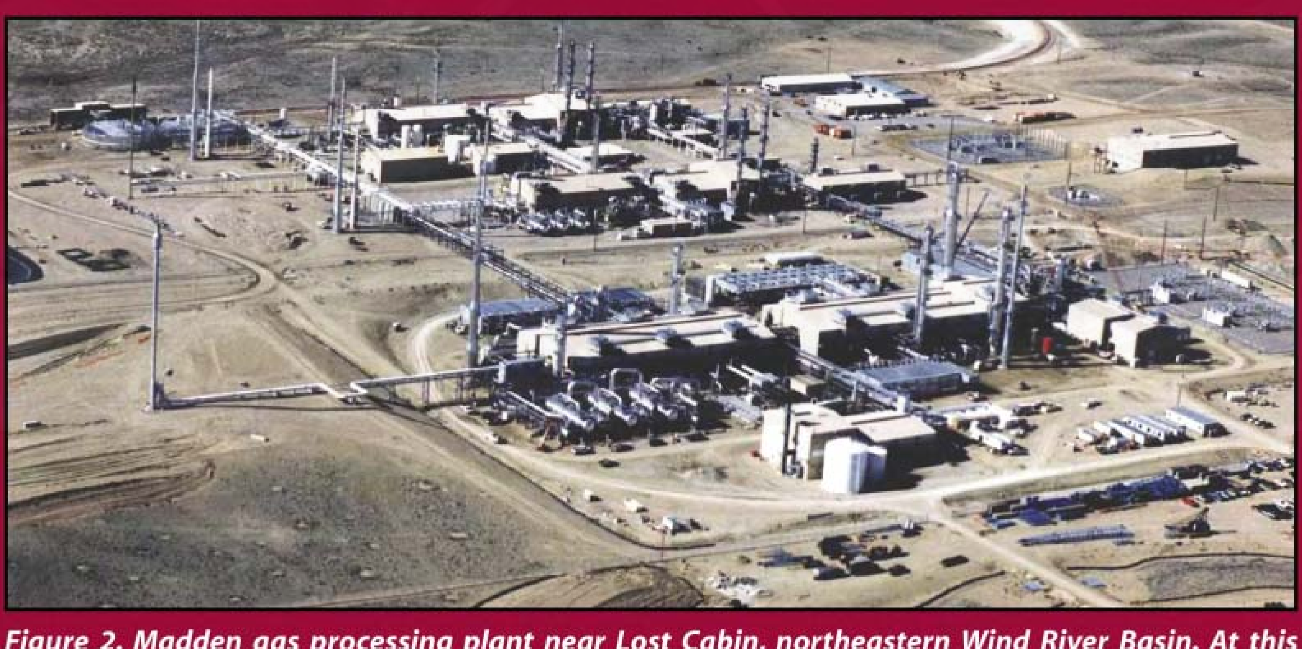


Figure 2. Madden gas processing plant near Lost Cabin, northeastern Wind River Basin. At this plant, carbon dioxide and hydrogen sulfide are removed from gas produced from the Madison Limestone. Photograph courtesy of Burlington Resources.

How is methane formed?

Three natural processes (**Figure 3**) can form methane: *biogenic* (gas expelled from microorganisms during their digestion of organic compounds), *thermogenic* (decomposition of organic matter by heat and pressure), and *abiogenic* (reactions of deep crustal gases with minerals or seepage of hydrogen-rich and carbon-rich primordial gases from the Earth's interior) (Howell and others, 1993). Most of the methane extracted from the large natural gas accumulations found in Wyoming is most likely formed by biogenic or thermogenic processes.

Biogenic methane

This methane is formed from the decomposition of organic matter as a by-product of bacterial respiration and is generated during *diagenesis* (all the chemical, physical, and biological changes undergone by sediment after initial deposition, during lithification, and after lithification), at tem-

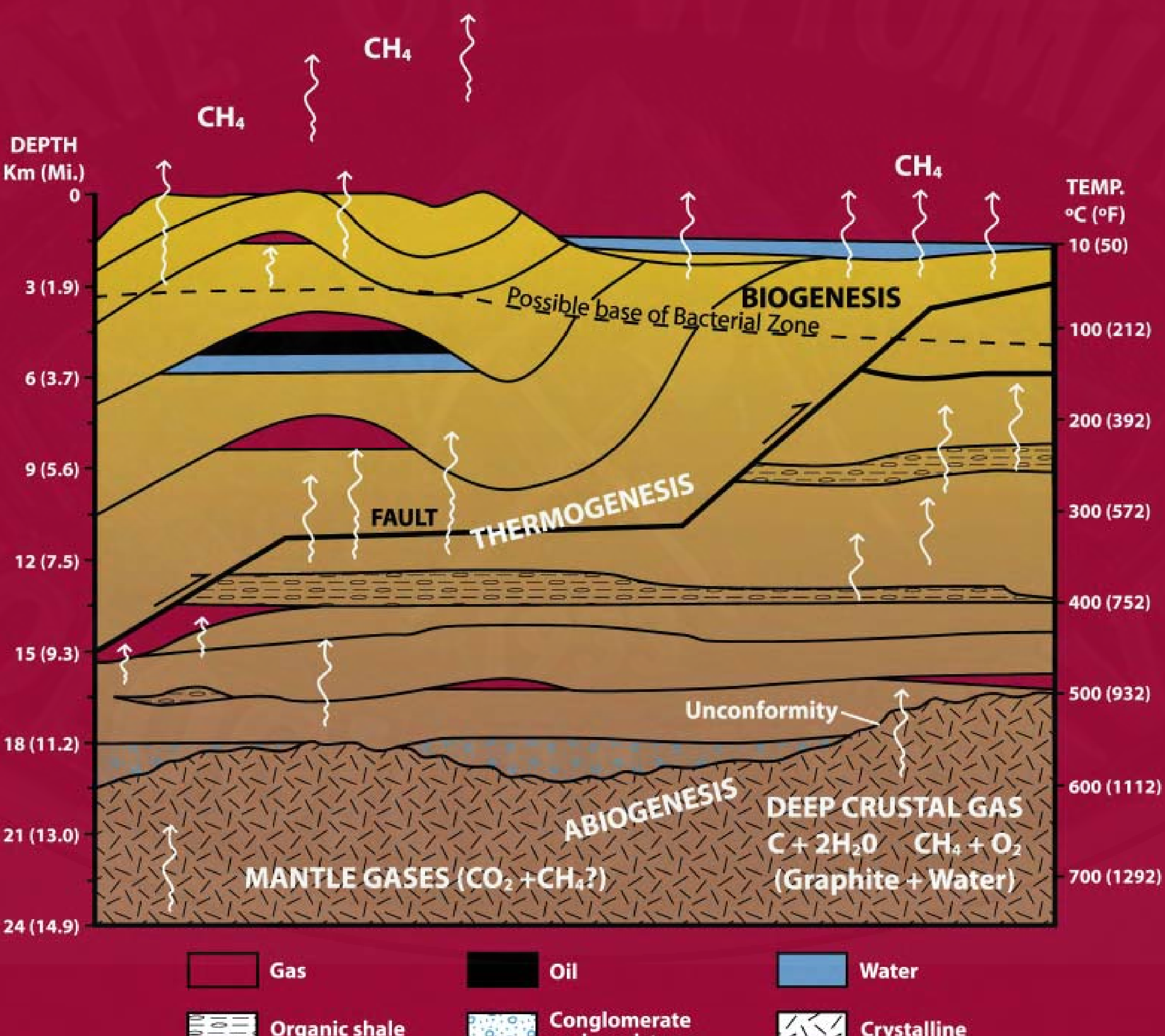


Figure 3. Schematic cross section of the Earth's crust, showing proposed origins, migration, and accumulation of methane (CH_4). Buoyant methane migrates upward through rock pores and fractures and either accumulates under impermeable layers or eventually reaches the surface and dissipates into the atmosphere. Modified from Howell and others, 1993.

peratures generally lower than those for oil generation. *Aerobic bacteria* (those that use oxygen in respiration) first metabolize any free oxygen left in organic remains and surrounding sediments. In fresh water environments, methane production begins immediately after the oxygen is depleted (Rice and Claypool, 1981). *Anaerobic bacteria* (those that don't use oxygen in respiration), which reside in the near surface in regions that lack oxygen and where temperatures generally do not exceed 122° F (but locally may approach 230° F), then reduce carbon dioxide and produce methane through anaerobic respiration (Rice and Claypool, 1981). Anaerobic bacteria also live inside the intestines of most animals and in the cud of ruminants such as cows and sheep, where they aid in the digestion of vegetable matter (and are prolific methane-producers).

Thermogenic methane

This methane is generated by temperature-induced reactions both at temperatures generally corresponding to oil generation (122° to 302° F) and at even higher temperatures (greater than 302° F). Temperatures over 122° F associated with increasing burial depths cause carbon bonds in organic compounds to break down and form oil with minor amounts of gas. At temperatures over 302° F (with increased burial depths) methane becomes the dominant product until it replaces oil altogether. In systems that contain *humic kerogen* (organic matter composed mainly of plant material), thermogenic methane is generated directly from kerogen at temperatures between 122° F and 302° F and through more complex processes at temperatures greater than 302° F (**Figure 4**). In systems that contain *sapropelic kerogen* (organic matter made up of fats, resins, and waxes derived from materials such as spores and algae), thermogenic methane is produced as a by-product of oil and/or *wet gas* (natural gas that contains significant amounts of liquefiable hydrocarbons, such as ethane, propane, butane, etc.) generation between temperatures of 122° F to 302° F. Methane is produced in even greater volumes at temperatures above 302° F as the result of cracking hydrocarbons that were generated at lower temperatures (Houseknecht and Spotl, 1993). *Cracking* is the thermal break down of larger, heavier, and more complex hydrocarbons into simpler and lighter hydrocarbons. Oil and natural gas are the predominant hydrocarbons found in the upper 10,000 feet of Earth's crust, while natural gas is the predominant hydrocarbon below this depth.

Abiogenic methane

This methane originates from inorganic sources, commonly as the result of deep crustal reactions involving graphite and water. Most experts believe that abiogenic methane does not occur in economically important concentrations.

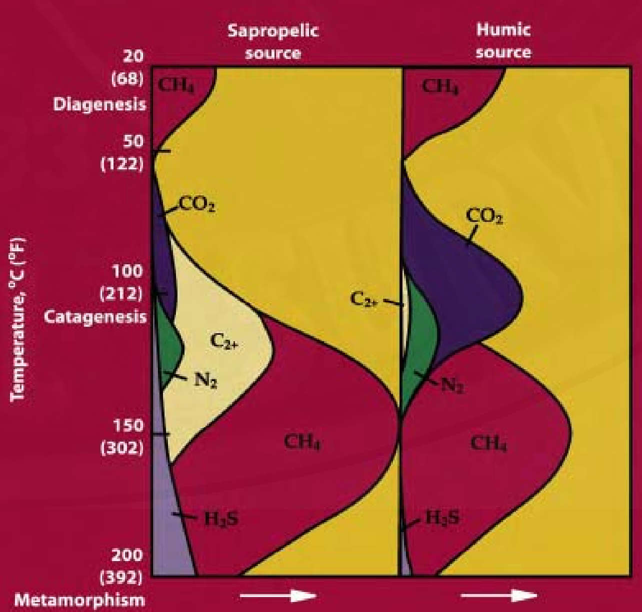


Figure 4. Generation of gas with depth from two major sources of organic matter. C_{2+} represents hydrocarbons heavier than CH_4 in gas phase. N_2 is generated initially as NH_3. Modified from Hunt, 1979.

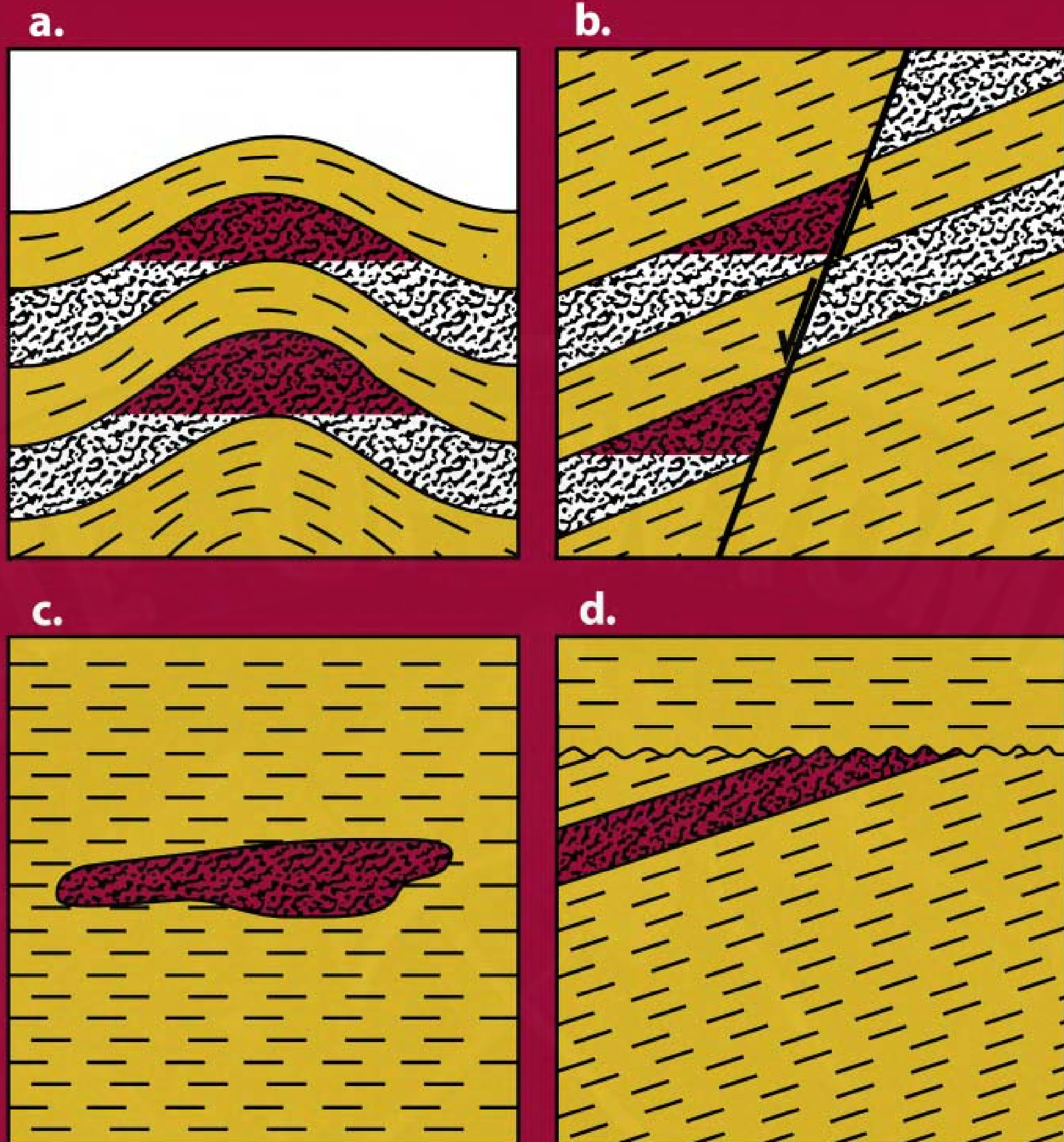
What elements form an economic resource of natural gas?

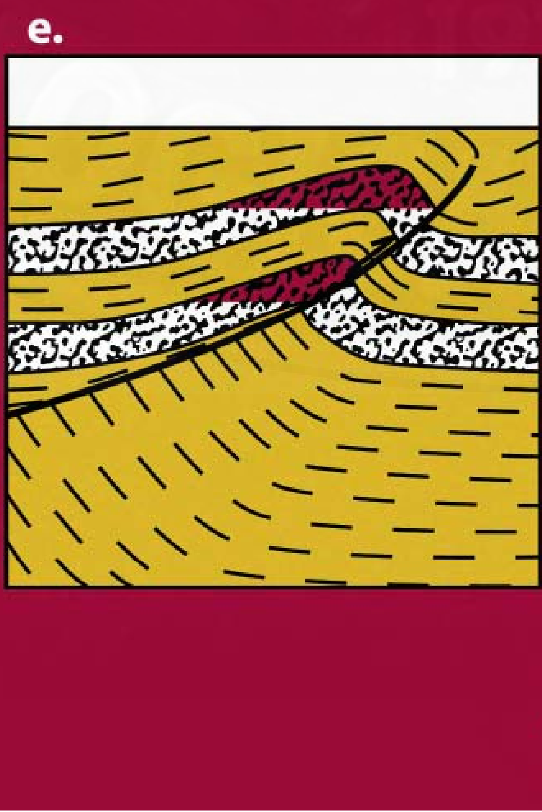
A source rock, a reservoir rock, and a seal rock must all be present. The *source rock* must be rich in organic material so natural gas can be generated through biogenic and/or thermogenic processes. Common source rocks are black marine shales and coal beds from continental or deltaic environments. The source rock must be buried to sufficient depths for thermogenic processes to generate natural gas. Biogenic processes generally occur at shallow depths and don't require deep burial of source rocks. *Reservoir rock* (normally sandstone or carbonate rock, but may be coal or shale) must be porous enough to hold sufficient quantities of natural gas and permeable enough to allow transmittal of natural gas to a well bore. *Porosity* is the measure of the volume of a rock occupied by interstices or pore spaces while *permeability* is a measure of the capacity of a porous rock to transmit or allow fluids to flow through it. Many reservoir rocks in Wyoming are nearly impermeable ("tight") for economic quantities of natural gas to flow naturally into well bores. These reservoirs need to be hydraulically fractured to create pathways for natural gas to flow. *Seal rock* (normally a fine-grained rock such as shale) is necessary to keep the natural gas from leaking out of the reservoir rock. Together, adequate reservoir rocks and seals must be in place to form a *trap* into which significant natural gas accumulates in the subsurface. There must also be a migration pathway from the organic-rich source rocks to the reservoir rocks in order for the generated natural gas to reach the trap. All these factors combine and interact in what is known as a *petroleum system*.

What are the conventional types of natural gas traps?

The main types of natural gas traps are structural, stratigraphic, and combination traps. *Structural* traps hold both oil and gas because the earth has been deformed in some way. The trap may be a simple *dome* (anticline) caused by compressive forces that have bent the rocks into a convex shape (**Figure 5a**), or it may be a more complex *fault* trap where there has been a break in the earth's crust caused by *compressional* (pushing together) or *tensional* (pulling apart) forces (**Figure 5b**). *Stratigraphic* traps are depositional in nature, which means they are formed in place, usually by sandstone being enclosed in shale, as often occurs in near-shore marine or deltaic environments. The impermeable shale keeps the oil and gas from escaping the trap (**Figure 5c**). Another type of trap is a *combination* (stratigraphic and structural) trap. This type of trap occurs where tilted layers are eroded and seal rocks are deposited horizontally over porous reservoir rocks to form a seal for natural gas (**Figure 5d**). The surface on which erosion has occurred is called an *unconformity*. Many of the traps in Wyoming are combination traps where deformational forces have interacted with depositional processes.

Most structural traps in Wyoming that contain natural gas are located around the faulted and folded edges of many basins and in the Overthrust Belt of western Wyoming. These traps are often complex, with the folds associated with faulting (**Figure 5e**) and with trapping mechanisms often associ-





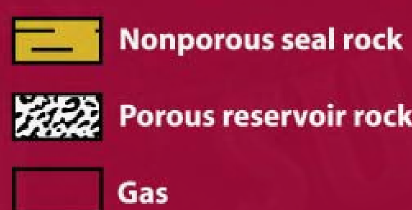


Figure 5. Examples of types of traps for natural gas. Structural traps include anticline or dome (a) or fault (b). A stratigraphic trap, such as a sandstone enclosed in shale, is shown in (c) and a combination structural and stratigraphic trap is shown in (d). A typical faulted anticlinal trap found in Wyoming is shown in (e).

ated with the faults. Examples of large structural traps containing major accumulations of natural gas include Madden, Whitney Canyon-Carter Creek, Painter Reservoir, Painter Reservoir East, and the La Barge anticline fields (Lake Ridge and Fogarty Creek) (**Figure 6**). Substantial accumulations of natural gas in stratigraphic traps are most common in the interiors of Wyoming basins and include Hilight, Wamsutter, and Echo Springs fields (**Figure 6**). Large combination traps containing significant natural gas accumulations include Pavillion, Table Rock, and Bruff fields (**Figure 6**).

What unconventional gas systems exist in Wyoming?

There are two classes of unconventional gas systems that contain tremendous amounts of natural gas in Wyoming, basin-centered gas and coalbed methane.

Basin-centered gas

These systems are regionally pervasive, gas saturated, abnormally pressured, low-permeability reservoirs that commonly lack

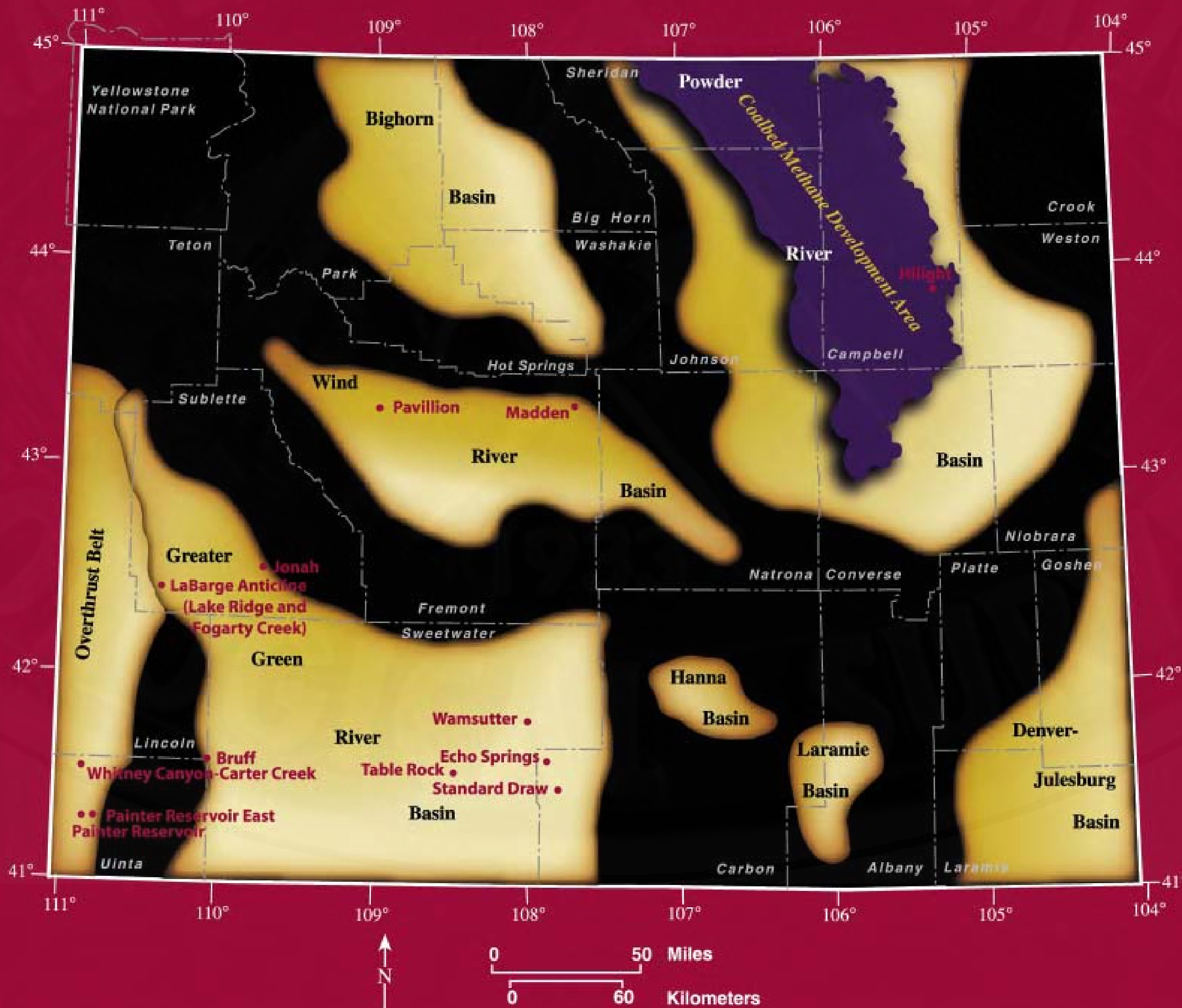


Figure 6. Wyoming sedimentary basins and selected natural gas fields. Areas of coalbed methane development are only shown for the Powder River Basin.

a downdip water contact. The development of a basin-centered gas resource starts with a reservoir that usually has normal pressure and the fluid phase in the pore system is 100% water saturated. Compaction of grains in the reservoir rock is important to the process. With increasing burial depths and heating of the rocks, thermogenic gas generation begins from gas-prone source rocks in close proximity to the low-permeability reservoirs. With further burial and increasing temperatures, the source rocks generate even more natural gas, which is expulsed and migrates from the source rock into adjacent, water-wet sandstone reservoir rock. Because these sandstone reservoirs have low permeability, the rate at which gas is generated from source rocks and accumulated in reservoirs is greater than the rate at which gas is lost. Eventually, as newly generated gas accumulates in the pore system, the capillary pressure of the water-wet pores is exceeded, and free, mobile water is expelled. This results in the development of an overpressured, gas-saturated reservoir with little or no free water (Law, 2002). An *overpressured reservoir* is one in which its pressure is greater than normal *lithostatic pressure* (vertical pressure at a point in the Earth's crust equal to the pressure caused by a column of overlying rock).

Wyoming's basin-centered gas systems occur in the Greater Green River Basin (Law, 2002), Wind River and Bighorn basins (Johnson and others, 1996; 1999), Hanna Basin (Popov and others, 2001; Wilson and others, 2001), and Powder River Basin (Surdam and others, 1994; Maucione and others, 1994). Accumulations can range from single, isolated reservoirs a few feet thick to multiple, stacked reservoirs several thousand feet thick. For example, the Jonah Field in the Greater Green River Basin (**Figure 6**) contains basin-centered gas that is being developed from multiple stacked reservoirs in the Lance Formation that can be several thousand feet thick. Jonah Field has estimated recoverable gas resources of over 4 trillion cubic feet (TCF) and the accumulation has been enhanced by faulting. West and south bounding faults define the field boundaries and NE-SW-trending internal faults seal and segment the reservoir into pressure compartments (**Figure 7**).

Coalbed methane

These systems may differ from conventional gas systems in source rock and gas origin, migration paths, and storage and trapping mechanisms. Most coal beds are *self-sourcing reservoirs* (the source rock is also the reservoir rock); however, coalbed reservoirs may contain self-sourced or migrated thermogenic gas, self-sourced biogenic gas, or some combination of these. Some coalbed methane (CBM) is stored as free gas in natural fractures (cleats) within the coal beds and as solution gas dissolved in water that occupies the cleats and pores, but the majority of the CBM is adsorbed on the surfaces of organic matter particles that comprise the coal matrix. At the usual pressures encountered in producing CBM reservoirs (at depths less than 5000 feet), coal can store more adsorbed gas than a conventional sandstone reservoir can store in its pore space.

To start gas desorption and production from coals that are not gas saturated (which is usually the case), pressure in the coal must be lowered below the saturation point. Where coal cleats are saturated with water, it is necessary to dewater (depressurize) the coal bed to allow gas desorption and production. Coalbed reservoirs initially produce water and little or no gas.

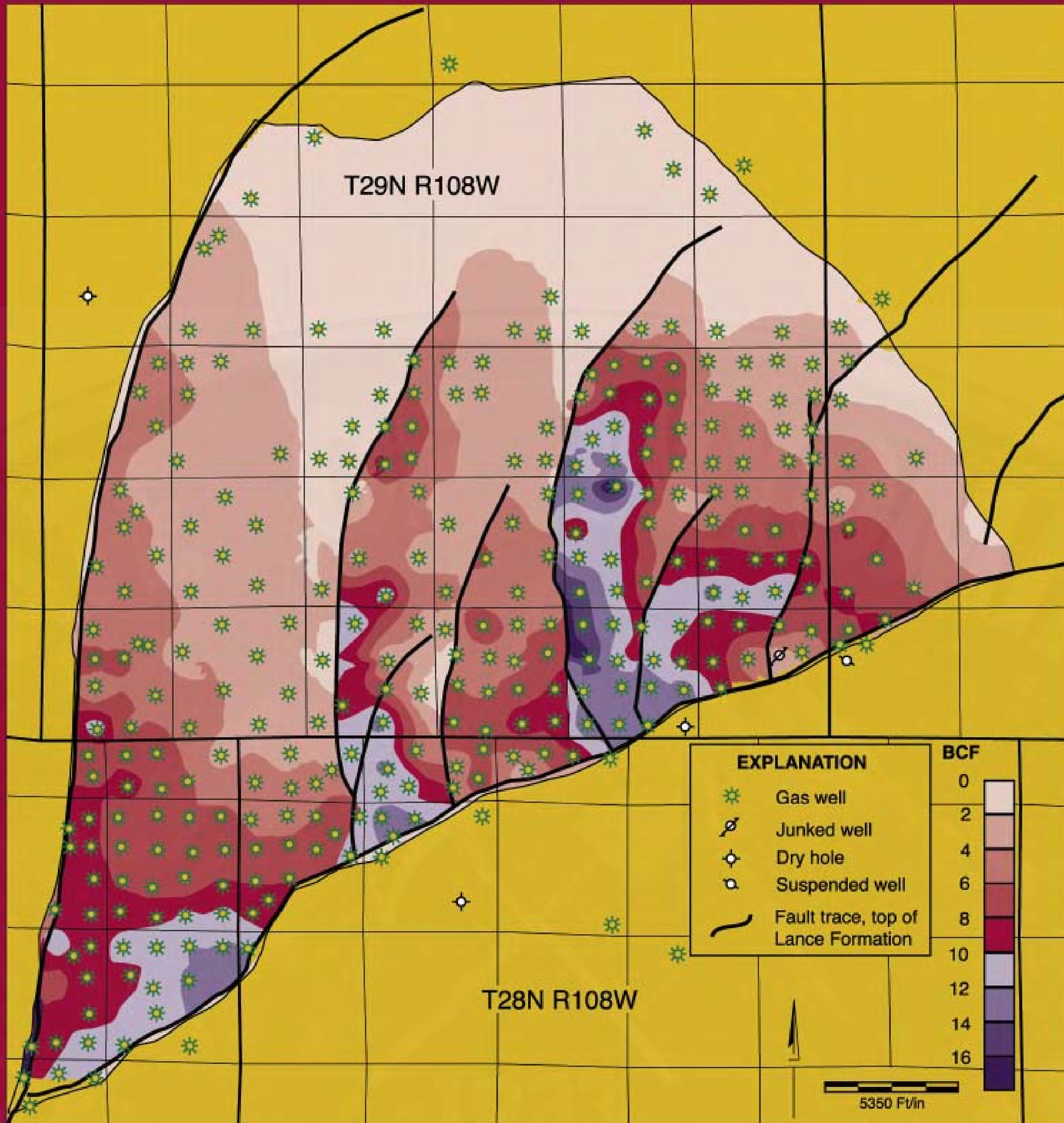


Figure 7. Contour map of estimated ultimate recovery (EUR), in two billion cubic feet (BCF) intervals, for the Jonah Gas Field, Sublette County, Wyoming. Modified from and used with permission of AEC Oil & Gas.

As depressurization occurs, gas desorbs (via a concentration gradient) from the coal matrix adjacent to the cleat and moves to the well bore (Ayers, 2002). Reservoir seals are necessary to maintain formation pressure and prevent gas escape. Conventional traps are not necessary in coalbed methane systems but their presence may enhance production. The most effective trap in CBM systems may be the water pressure that keeps gas from desorbing. Permeability is very important for production of CBM. Most of the flow of fluids from coal beds is through the cleats because the matrix permeability of coal is too low for commercial gas production.

An example of biogenic gas production from a CBM system is a large area in the Powder River Basin of Wyoming (**Figure 6**). Production from shallow coal beds in the Paleocene-age Fort Union Formation (**Figure 8**) is currently nearing 1.0 BCF per day and ultimate recovery may approach 25.2 TCF. Other areas in Wyoming have good potential for CBM production as well (De Bruin and others, 2001).

Where is natural gas found in Wyoming?

Natural gas occurs in all of Wyoming's basins (**Figure 6**) in sedimentary rocks as old as Cambrian and as young as Eocene (**Figure 9**). It may occur by itself where it is produced from a gas well or it may occur in association with produced water or oil, where it is in solution under pressure and becomes gaseous when it reaches the surface (or in the case of coalbed methane, in the well bore).

The five most productive reservoirs in Wyoming, in terms of cumulative production starting with the most productive, are listed in **Table 1**. These five reservoirs accounted for 19.5 TCF of production through 2002, which was 63.7% of Wyoming's cumulative production.

The Lance Formation (**Figure 9**) should break into the top five producing formations in the next several years because of extensive development at Jonah and Waltman fields as well as the Pinedale anticline. Much of the production from the Madison Limestone is low Btu gas, especially at Lake Ridge and Fogarty Creek fields (on the La Barge anticline). The

Figure 8. Typical coalbed methane well site in the Powder River Basin with water and gas lines installed. Control box (red) is about 3 1/2 feet above ground surface. A small well house will be installed to protect the equipment. Photograph from Wyoming Coalbed Methane Clearinghouse website, 2004.

Era	Period	Formation
CENEZOIC	Quaternary	
	Tertiary	Wind River Fm. Almy Fm. Fort Union Fm. (317 BCF) (includes coalbed mehtane from PRB)
MESOZOIC	Upper Cretaceous	Lance Fm. (208 BCF) Lewis Shale (30 BCF) Baxter Shale Blair Fm. Almond+Mesaverde Fms. (179 BCF) Cody Shale Frontier Fm. (194 BCF) Shannon Ss. Teapot Ss. Turner Ss. Wall Creek Ss.
	Lower Cretaceous	Muddy Ss. (43 BCF) Dakota Ss. (50 BCF) Lakota Fm. Bear River Fm.
	Jurassic	
	Jurassic-Triassic	Nugget Ss. (97 BCF)
	Triassic	Chugwater Fm.
PALEOZOIC	Permian	Phosphoria Fm.
	Pennsylvanian	Weber Fm. Tensleep Ss. (38 BCF)
	Mississippian	Madison Ls. (353 BCF) (includes Mission Canyon Ls.)
	Devonian	
	Ordovician	Bighorn Dolomite
	Cambrian	
Precambrian		

Figure 9. (Right) Stratigraphic units in Wyoming that produced at least 30 BCF of natural gas in 2002. Actual production shown in parentheses. Other stratigraphic units not shown produced natural gas in lesser quantities (see De Bruin, 2002, for a list of all units). Photograph of Devils Tower is from Richard W. Jones.

Madison, mainly because of production at Whitney Canyon-Carter Creek, Lake Ridge, Fogarty Creek, and Madden fields, will pass the Frontier Formation in several years and will remain the most productive until CBM from the Powder River Basin (Fort Union Formation on **Figure 9**) becomes the top supplier of methane over the next 20 to 30 years. The CBM play is developing rapidly, and there are about 21.6 TCF of remaining recoverable gas resources in coal beds of the Powder River Coal Field, Wyoming (Finley and Goolsby, 2000). The top ten producing stratigraphic units produced about 1.5 BCF or 94% of Wyoming's total natural gas in 2001.

Table 1. Cumulative natural gas production through 2002 from the top five reservoirs in Wyoming. Production is in fields with reservoirs that have produced at least 5 BCF.

Rank	Reservoir	Production (TCF)
1	Frontier Formation	6.872
2	Madison Limestone	5.267
3	Muddy Sandstone	2.643
4	Almond Formation	2.391
5	Nugget Sandstone	2.291
	Total	19.464

When was natural gas first discovered in Wyoming?

The first written account of the occurrence of petroleum within the area that would later become Wyoming was in Washington Irving's book *Adventures of Captain Bonneville* (Irving, 1849). Irving described Captain Bonneville's 1833 discovery of a "great tar spring" on the Popo Agie River, approximately 8 miles southeast of present-day Lander. The "tar" from that spring was used by hunters and trappers for medicinal purposes (Knight, 1897) and later was used by the military and early travelers as lubrication for their wagon wheels (Roundtree, 1984).

In 1884, 25 years after E.L. Drake's discovery of oil in western Pennsylvania, Mike Murphy completed the first well drilled for commercial oil production in Wyoming and opened the Dallas Oil Field. This well was drilled to a depth of 300 feet adjacent to the "great tar spring" that Captain Bonneville discovered. The first discovery of natural gas in Wyoming was also in the Dallas Field, although the gas was not recovered. Knight (1897) reported that

> *... the Murphy No. 1 and Murphy No. 2 wells when opened, roar so that one can hear them a quarter of a mile away. As soon as the greatest gas pressure has died away the oil shoots into the air thirty or forty feet if the escape is directed upwards.*

What is the history of Wyoming's natural gas industry?

Biggs and Espach (1960) made one of the first references to the exploitation of natural gas for commercial purposes. They reported that the Casper Creek South Field, discovered in 1918, had 14 wells completed in the Sundance Formation. These wells had initial daily open-flow volumes that ranged from 1 to 30 million cubic feet (MMCF) of gas. The gas was piped to Casper until the field was depleted in 1925.

Mackey (1997) reported that the first natural gas pipeline in Wyoming was built in the early 1920s by the Ohio Oil

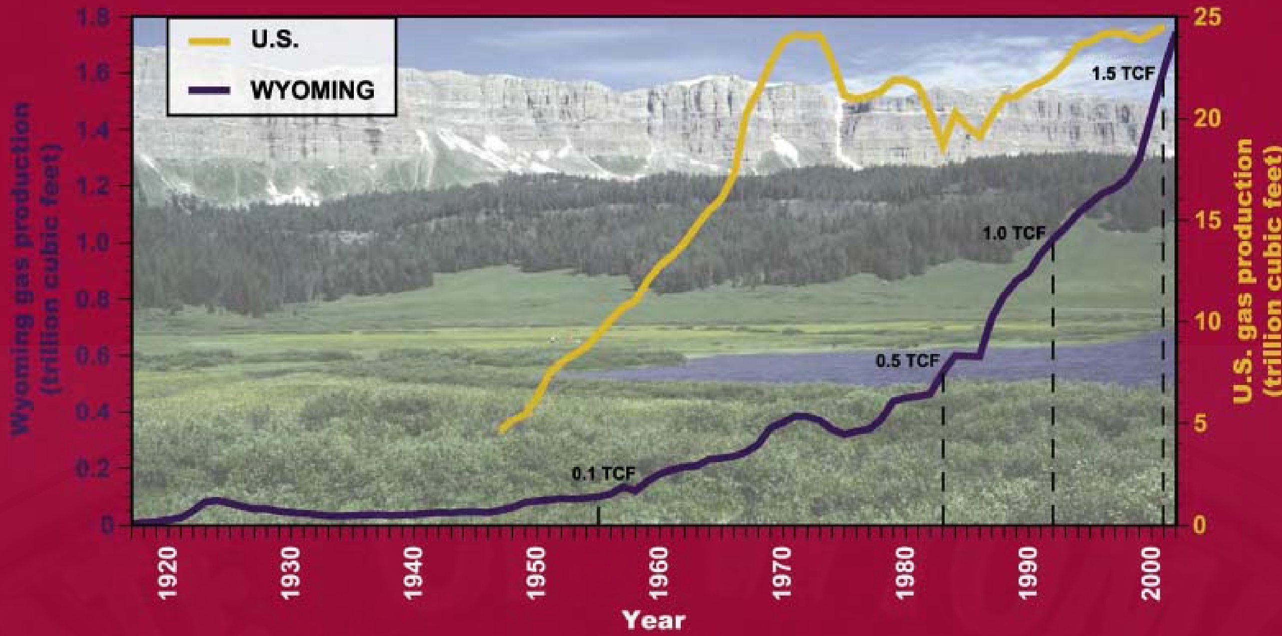


Figure 10. Natural gas production (trillions of cubic feet) in Wyoming from 1917 to 2002 and in the U.S. from 1947 to 2001. Wyoming production from Biggs and Espach (1960), U.S. Bureau of Mines Natural Gas Annals (1958 to 1966) for marketed production only, U.S. Energy Information Administration (1967 to 1969), and Wyoming Oil and Gas Conservation Commission (1970 to 2002). U.S. production from U.S. Bureau of Mines Natural Gas Annals (1947 to 1966) for marketed production only and U.S. Energy Information Administration (1967 to 2001). Photograph of the Absaroka Mountains is from Richard W. Jones.

Company. The 67-mile line supplied gas to Billings, Montana from Elk Basin Field in the Bighorn Basin. Another early natural gas pipeline was built from Oregon Basin Field in the Bighorn Basin to Cody in 1927 (Mackey, 1997). Many wells in Oregon Basin were capped off when high-pressure gas was discovered; the wells were only reopened after the construction of the pipeline to Cody. As with oil, transportation (or the lack thereof) was critical in the rate of development of Wyoming's natural gas resources.

Wyoming's natural gas industry developed slowly, even after the commercial success of using the gas from Casper Creek South, Elk Basin, and Oregon Basin fields. It was not until 1955 (**Figure 10**) that yearly natural gas production in Wyoming topped 100 BCF. The 500 BCF production milestone was not reached until 1983, while the 1 TCF mark reached in 1992 happened rather quickly, due in large part to major discoveries in the Overthrust Belt. The Overthrust Belt discoveries required very large investments in development drilling, gas processing plants, and pipelines to transport the gas to markets in other states. In 2001, statewide production topped 1.5 TCF.

Most of the recent production increase is due to development of gas fields throughout southwestern Wyoming, Jonah and Pinedale anticline fields in the northern Green River Basin, Madden and Waltman (Cave Gulch) fields in the Wind River Basin, and CBM in the Powder River Basin. Production of CBM in the Powder River Basin was nearly 350 BCF in 2003 and accounted for over 19.4% of Wyoming's total production for that year. Wyoming's natural gas production for 2003 was over 1.8 TCF and cumulative natural gas production was 32.4 TCF through the year 2003.

How much natural gas does Wyoming have left?

The Potential Gas Committee (2001) estimated that Wyoming's most likely resources of recoverable natural gas (not including coalbed methane) are almost 54.8 TCF; the U.S. consumed around 23 TCF of natural gas in 2002. These 54.8 TCF of resources are categorized for Wyoming's five gas provinces by probable, possible, and speculative resources (**Figure 11**) for reservoirs from 0 to 15,000 feet in depth and for reservoirs from 15,000 to 30,000 feet in depth (**Table 2**). The Greater Green River Basin has the most resources with almost 26.0 TCF and the Wind River Basin is second with 13.2 TCF.

Proved reserves are the estimated quantities of natural gas that current analysis of geologic and engineering data demonstrate with reasonable certainty to be recoverable in the future from known reservoirs under existing economic and operating conditions. Petroleum engineering and geological judgment are required to estimate proved reserves; therefore, the results are not precise measurements. Proved reserves are the class of recoverable resources that are the most certain yet to be produced and are in addition to the Potential Gas Committee's estimates.

Wyoming's proved reserves of natural gas are about 20.5 TCF, which includes 2.4 TCF of CBM reserves. Proved reserves increased from 9.1 TCF at the end of 1980 to 20.5 TCF at the end of 2002 (**Table 3**) despite continued reductions from production that totaled 21.1 TCF over that time span. Wyoming currently ranks second in the nation in proved reserves of natural gas (**Table 4**). Only Texas has more proved reserves of natural gas than Wyoming.

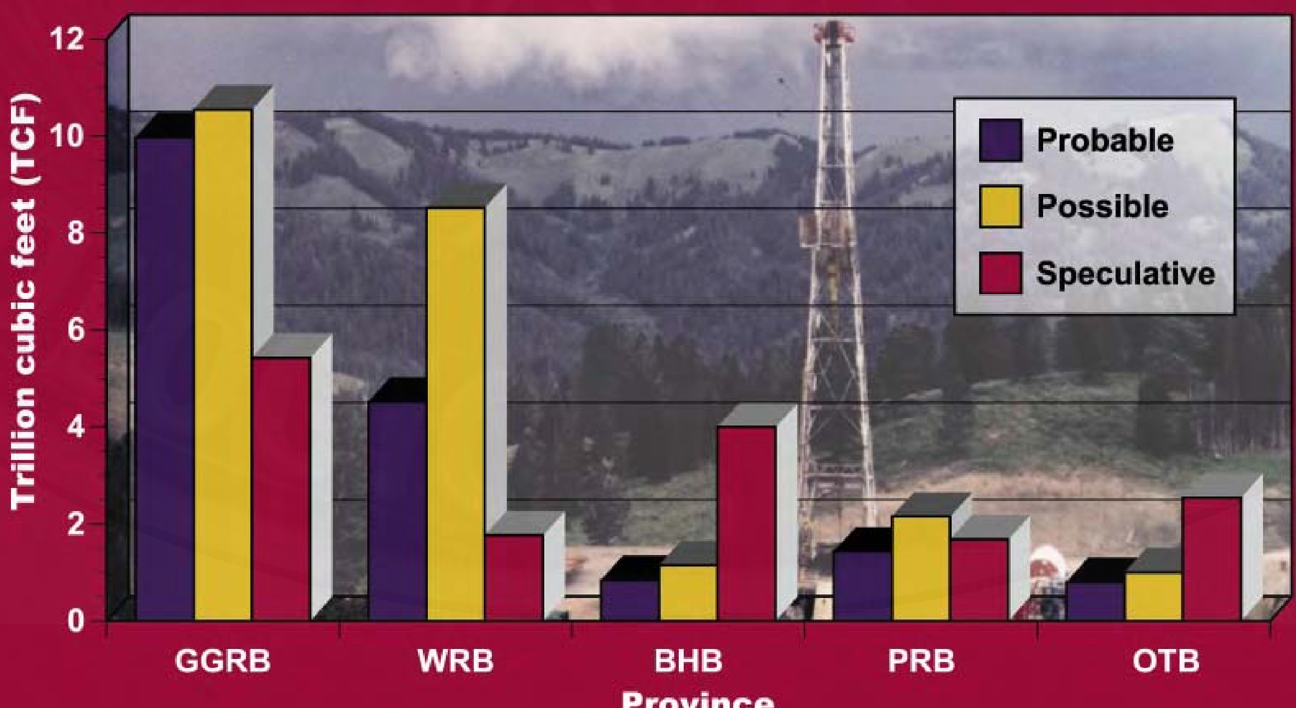


Figure 11. Wyoming's most likely resources of recoverable, traditional natural gas, by gas province, for all reservoirs. GGRB = Greater Green River Basin, WRB = Wind River Basin, BHB = Bighorn Basin, PRB = Powder River Basin, and OTB = Overthrust Belt. Estimates as of year-end, 2000. Modified from Potential Gas Committee (2001). Photograph of drilling rig in Bridger Teton National Forest in the 1980s is from Lance Cook.

Table 2. Most likely resources of traditional natural gas (in TCF) for Wyoming gas provinces at the end of 2000. Modified from Potential Gas Committee, 2001.

Province	0-15,000'	15,000-30,000'	Subtotal
Greater Green River Basin	17.595	8.358	25.953
Wind River Basin	8.195	5.019	13.214
Bighorn Basin	3.172	2.810	5.982
Powder River Basin	4.276	1.00	5.276
Overthrust Belt	3.700	0.650	4.350
Grand Total	36.938	17.837	54.775

In addition to the above resources and reserves, remaining recoverable coalbed methane resources in Wyoming through 2003 are about 28.1 TCF. These resources are equal to original recoverable resources of 31.7 TCF (De Bruin and others, 2001) minus CBM production of 1.2 TCF and proved reserves of CBM of 2.4 TCF. Over 77% of these remaining recoverable resources are in the Powder River Basin. Cumulative production of coalbed methane exceeded 1.2 TCF by the end of 2003 with daily production of almost 1.0 BCF. Almost all of the cumulative production is from the Powder River Basin and over 98% of it has been produced since 1997.

How are the major components of natural gas used?

Methane

Most components of the natural gas produced in Wyoming are separated at gas plants. Methane, the main component of natural gas, is used to heat homes and businesses, to provide fuel for factories, to fuel a variety of vehicles that burn compressed or liquefied natural gas, and to an increasing degree, to generate electricity (by fueling boilers that produce steam to turn turbines). The methane is put into pipelines that carry it to markets in the Midwest, the West Coast, the Front Range of Colorado, other western states, and to a storage facility for later use if supply exceeds demand.

Condensate

Condensate is often produced with natural gas in Wyoming. *Condensate* consists of light liquid hydrocarbons (including natural gasoline) that are in a gaseous state under pressure (underground) and separate from the natural gas when they condense to a liquid at the surface. Condensate generally is water-white, straw, or bluish in color. In some reservoirs, condensate may form in place if the reservoir pressure is reduced too much during gas production. Condensate and other hydrocarbon components of natural gas such as propane, butane, pentane, and ethane are used for fuel and for feedstock in chemical plants to make a variety of synthetic fibers, plastics, and solvents.

Helium

Several of the non-hydrocarbon components of natural gas such as helium, carbon dioxide, and hydrogen sulfide are valuable for various uses and are produced in Wyoming. Helium is the second lightest element, is chemically inert, and liquefies at approximately –452° F. These properties make helium useful for a variety of applications. Helium controls atmospheric conditions in chambers where silicon crystals are grown, it is a heat transfer medium in gas-cooled nuclear power reactors, it is used to detect leaks during the manufacture of sealed fluid systems in refrigerators and

Table 3. Comparison of Wyoming's proved reserves of dry natural gas (TCF) for the years 1980 through 2002. Source: U.S. Department of Energy, 2003.

Date	Dry natural gas
1980	9.100
1981	9.307
1982	9.758
1983	10.227
1984	10.482
1985	10.617
1986	9.756
1987	10.023
1988	10.308
1989	10.744
1990	9.944
1991	9.941
1992	10.826
1993	10.933
1994	10.789
1995	12.166
1996	12.320
1997	13.562
1998	13.650
1999	14.226
2000	16.158
2001	18.398
2002	20.527

vacuums, it shields reactive metals from contamination during welding, and it is used in breathing mixtures for divers and operating room patients. Because it is lighter than air, it is used in weather (and other) balloons and in blimps. The fuel tanks of spacecraft are pressurized with helium so that they do not collapse when empty. Liquid helium cools materials so that they become superconductors. Powerful magnets, composed of superconductors, are used in high-energy physics experiments and medical research.

Wyoming has a world-class helium resource associated with the natural gas produced from Lake Ridge and Fogarty Creek fields (**Figure 6**). The gas produced at these fields contains approximately 0.5% helium and accounts for about 1.0 BCF of helium per year. This amount

Table 4. Wyoming's ranking in proved reserves of dry natural gas (TCF) at the beginning of 2003. Source: U.S. Department of Energy, 2003.

State	Dry natural gas
Texas	44.297
Wyoming	*20.527*
New Mexico	17.320
Oklahoma	14.886
Colorado	13.888
Louisiana	8.960
Alaska	8.468
Kansas	4.983
Utah	4.135
Alabama	3.884

of helium equals nearly one-third of all helium extracted from natural gas in the U.S. in 2002 and slightly over one-third of the helium consumed in the U.S. that year. Wyoming has helium resources estimated at over 600 BCF, mainly in the natural gas produced at fields on the La Barge anticline (De Bruin, 1995). At the present production rate of 1.0 BCF per year, Wyoming will be one of the most important helium producers in the U.S. for years to come.

Carbon dioxide

Another non-hydrocarbon component of natural gas produced in Wyoming is carbon dioxide. Solid CO_2 *sublimes* (changes directly from solid to gaseous state, without going through an intermediate liquid state) at –173° F under 1 atmosphere of pressure. This form of CO_2 is a convenient, clean refrigerant called dry ice. Water saturated with carbon dioxide at 3 to 4 atmospheres of pressure is called carbonated water, and is the foundation for the huge soda-water beverage industry. Carbon dioxide does not support combustion; gaseous or liquid CO_2 under about 60 atmospheres of pressure in cylinders is used to extinguish fires. Gaseous CO_2 is also used to prepare food, purge tanks and pipelines, manufacture aspirin, weld, propel aerosols, stimulate respiration, manufacture carbonates, and produce inert atmospheres.

One of the most important uses of liquified carbon dioxide in Wyoming is to flood old oil fields for enhanced oil recovery. Although only two oil fields in Wyoming (Wertz and Lost Soldier) and the Rangely Field in Colorado have been flooded so far, there is potential to produce an additional 400 million to 1.2 billion barrels of oil that would otherwise be left in the ground. For more information on Wyoming carbon dioxide, refer to Wyoming State Geological Survey Information Pamphlet 8 (De Bruin, 2001).

Carbon dioxide is produced with natural gas in Wyoming from the Madison Limestone at fields on the La Barge anticline and at Madden Field (**Figures 12** and **13**). There is an estimated 55 TCF of recoverable CO_2 at the La Barge fields and an additional 0.5 TCF at Madden (De Bruin, 2001). Production of CO_2 from these fields was about 174 BCF per year; unfortunately, most of this carbon dioxide was vented to the atmosphere because there were few markets for it. The enhanced oil recovery projects instituted by Anadarko Petroleum at Salt Creek and Patrick Draw fields in late 2003 will use large volumes of CO_2 from La Barge. For comparison, the Naughton Power Plant in western Wyoming produces about 273 MMCF per day or 99 BCF per year (De Bruin and others, 2004) of carbon dioxide byproducts as flue gas from the burning of coal.

Hydrogen sulfide

The third important non-hydrocarbon component of natural gas produced in Wyoming is hydrogen sulfide. H_2S is poisonous even in low concentrations and must be removed before the natural gas is sold. Sulfur is manufactured (extracted) from hydrogen sulfide at gas plants (**Figure 2**)

Figure 12. A typical wellhead and production "Christmas tree" at a deep well completed in the Madden Field. This is the deepest producing gas field in the Rocky Mountains. Rod De Bruin, author of this pamphlet, for scale. Photograph by Robert M. Lyman.

Figure 13. Wellhead and surface production facilities at the Bighorn No. 2-3 gas well in the Madden Field. The well reached a total depth of 24,250 feet in the Gros Ventre Formation (Cambrian) and was completed in the Madison Limestone (Mississippian), establishing the deepest commercial gas production in the Rocky Mountains. Initial gas composition was 68% methane, 20% carbon dioxide, and 12% hydrogen sulfide (Brown and Shannon, 1989).

serving Whitney Canyon-Carter Creek, La Barge (H_2S will be reinjected here in the future), and Madden fields. In 2002, about 1.2 million short tons of sulfur were produced from the H_2S in natural gas from Wyoming fields. A large portion of the sulfur produced in the U.S. is used to produce sulfuric acid. Sulfur is also used to vulcanize rubber, as a fuel in gunpowder and matches, for insecticides and soil conditioners, for the manufacture of fertilizer, and for the manufacture of carbon disulfide (a solvent).

Does natural gas go directly from producers to consumers?

No, in Wyoming, almost all of the natural gas is processed to remove natural gas liquids for later sale and other gases if they occur in economic concentrations. The remaining methane is shipped via pipeline to consumers to an underground storage facility.

Natural gas storage is the process of injecting natural gas into porous underground rock formations so that it can be withdrawn later to meet customer demand. Before injection can take place, the natural gas must be compressed. Underground storage is a very common, safe practice that has been in use since 1916, when a commercial operation (that is still operable) was started near Buffalo, New York. There are approximately 400 active natural gas storage projects in the U.S. and Wyoming has five of them. The most important characteristics of an underground storage reservoir are its capability to hold natural gas for future use and the rate at which gas inventory can be withdrawn (delivery rate). There are three types of underground natural gas storage used in the U.S.: depleted oil and gas reservoirs, natural aquifers, and salt caverns, as described below.

Most underground storage in the U.S. is in depleted natural gas or oil fields close to consumption centers. These depleted reservoirs are the most common sites because of their wide availability. Conversion of a field from production to storage takes advantage of existing wells, gathering systems, and pipeline connections.

In some areas, especially in the Midwest, *natural aquifers* (underground layers of porous rocks that contain water) have been converted to gas storage reservoirs. An aquifer is suitable for gas storage if the water-bearing sedimentary rock formation is covered by an impermeable cap rock. The use of aquifers for gas storage usually requires a more permanent gas inventory than depleted oil and gas reservoirs so that adequate pressures and deliverability rates throughout the withdrawal season can be maintained. The withdrawal and injection performance of aquifers used for gas storage also requires greater monitoring than depleted oil and gas reservoirs. Deliverability rates of natural gas from aquifers may be enhanced by an active water drive.

Salt caverns are most common in salt domes located in the Gulf Coast states. The caverns provide very high natural gas withdrawal and injection rates. Salt caverns have also been leached from bedded salt formations in Northeastern, Midwestern, and Southwestern states to take advantage of the high injection and withdrawal rates. Cavern construction is more costly than depleted reservoir conversions when measured on the basis of dollars per MCF of *working gas capacity* (total gas storage capacity minus permanent gas in storage necessary to maintain adequate pressure and delivery rates). However, caverns can have several withdrawal and injection cycles each year, thereby reducing the cost of each MCF of gas injected and withdrawn.

How is natural gas transported?

Nearly all natural gas is transported by pipeline in the U.S., and Wyoming is no exception. There are over 300,000 miles of natural gas pipelines in operation in the U.S. and most of this pipeline network transports natural gas 24 hours a day, 365 days a year. Wyoming has several thousand miles of major natural gas pipelines (De Bruin, 2002) and another several thousand miles of smaller gathering lines that bring natural gas from individual wells or groups of wells to the larger pipelines. Pipelines normally operate at high pressures to increase their capacity, requiring compressor stations to pressurize the transported gas (**Figure 14**). Wyoming is a net exporter of natural gas and presently uses less than 5% of the gas that it produces. It is very important for the state to have enough pipeline capacity and other infrastructure to carry over 95% of the natural gas that it produces to markets outside of Wyoming.

Figure 14. Colorado Interstate Gas Company's Laramie Compressor Station west of Laramie. This is one of a number of similar facilities along the pipeline corridor that traverses southern Wyoming.

How safe are natural gas pipelines?

Statistics gathered by the National Transportation Safety Board, a federal agency, show that natural gas pipelines are the safest mode of transportation for meeting the nation's energy needs. Less than .01% of all transportation accidents in the U.S. are related to interstate natural gas pipelines. The U.S. Department of Transportation (DOT) imposes a broad range of requirements for pipeline design, materials, construction, testing, maintenance, and inspection.

To ensure safe operations, natural gas companies: 1) use high-strength steel for the pipelines; 2) coat the steel with special protective compounds to prevent corrosion; 3) inspect all welds joining each section of pipe with x-rays; 4) bury the pipeline with a minimum of 36 inches of ground cover; 5) use a low-voltage electric system called cathodic protection to further prevent corrosion; 6) use water to pressure test the pipeline far in excess of its normal operating pressure; 7) install automatic shutoff valves that shut off the flow of gas if a sharp decrease in pressure is detected; 8) install pipeline markers to alert the public of the pipeline's location; 9) patrol the pipeline right of way regularly by foot, vehicle, and by aircraft; 10) perform periodic maintenance inspections, including leak surveys, valve inspections, and internal electronic inspections inside the pipeline with a device known as a "smart pig;" 11) meet with local emergency response personnel to coordinate procedures in the event of an emergency; 12) participate in the local One-Call program for excavators to call before they dig; and 13) monitor pipelines 24 hours a day with a computer network from a gas control center, in addition to local station offices (Williams Pipeline Company, 2002) (see http://www.williams.com/community/pipelinesafety/index.asp).

Why does natural gas smell so bad?

As produced at the well head, natural gas may have an odor depending on the other components present, but processed methane gas is odorless. However, anyone who has been near a natural gas leak (or an unlit pilot light) has smelled a rotten egg odor. Since it is desirable to detect leaks of natural gas before the gas reaches concentrations that are explosive, utility companies add mercaptans to the natural gas before it is distributed. *Mercaptans* are chemical compounds that contain sulfur and have an objectionable odor that can be readily detected (smelled) when natural gas is leaking.

How is natural gas sold?

Producers of natural gas generally sell their product by a unit known as an MCF, which equals 1000 cubic feet of gas at standard conditions, i.e., a temperature of 60° F and a pressure of 14.65 pounds per square inch (psi), which is atmospheric pressure at sea level. An MCF of natural gas contains approximately 1,000,000 Btus. A *Btu* stands for a British thermal unit and is a precise measure of energy: the amount of energy required to raise the temperature of one pound of water one degree Fahrenheit when the water is near 39.2° F. It is approximately the amount of heat generated by one blue-tip kitchen match. Producers receive different prices for their gas depending on Btu content, temperature, and pressure. Utility companies used to sell natural gas by the MCF, but recently most utility companies have changed to a unit called the *therm*, which approximately equals the number of Btus in 100 cubic feet (0.1 MCF) of natural gas (**Table 5**). Since 1 MCF of natural gas contains about 1,000,000 Btus, 0.1 MCF (or 1 therm) of natural gas contains 100,000 Btus. A therm is used instead of cubic feet of gas because the amount of energy in natural gas varies, and a therm reflects the actual energy content of the gas. When utility companies figure consumer gas bills, they must make allowances for conditions other than standard temperature and pressure and for gas that may contain greater than or less than one million Btus per MCF. To see how natural gas compares in Btu content to other forms of energy, see **Table 5**.

Who regulates natural gas wells in Wyoming?

The Wyoming Oil and Gas Conservation Commission (WOGCC), an agency of the State of Wyoming, is the primary regulator of the natural gas industry in the state. WOGCC issues permits for seismic exploration and all oil and gas drilling (**Figure 15**). It also requires a bond to ensure that each well is operated and maintained so that it does not cause waste or damage the environment, and upon permanent abandonment the well is plugged in accordance with WOGCC's rules and regulations. The Commission also enforces rules and regulations that pertain to well spacing, safe drilling practices, flaring or venting of natural gas, injection of produced water, comple-

Table 5. Units of measurement for natural gas, metric units, and caloric equivalents for fuels.

Units of measurement for natural gas

MCF=1000 cubic feet of natural gas
MMCF=1,000,000 (one million) cubic feet of natural gas=1000 MCF
BCF=1 billion cubic feet of natural gas=1000 MMCF= 1 million MCF
TCF=1 trillion cubic feet of natural gas=1000 BCF=1 million MMCF=1 billion MCF
1 MCF=1,031,000 Btus or approximately 1 million Btus
1 therm=100,000 Btus=approximately the heat contained in 100 cubic feet or 0.1 MCF of natural gas

Metric units

Value	Metric prefix	American	English
10^3	kilo(k)	thousand (M)	thousand
10^6	mega(M)	million (MM)	million
10^9	giga(G)	billion (B)	thousand million
10^{12}	tera(T)	trillion (T)	billion
10^{15}	peca(P)	quadrillion (Q)	thousand billion
10^{18}	exa(E)	quintillion	trillion

Approximate caloric equivalents (based on average densities for various fuels)

	MCF gas	barrels crude oil	short tons bit. coal	short tons anth. coal	barrels gasoline	barrels res. fuel oil	short tons wood	Btu
1000 cubic feet (MCF) natural gas=	1	0.178	0.0431	0.0406	0.196	0.164	0.0617	1.031×10^6
1 barrel crude oil=	5.618	1	0.243	0.228	1.105	0.923	0.347	5.8×10^6
1 short ton bituminous coal and lignite=	23.20	4.115	1	0.941	4.554	3.802	1.43	23.9×10^6
1 short ton anthracite=	24.631	4.386	1.0627	1	4.840	4.04	1.52	25.4×10^6
1 barrel of gasoline=	5.102	0.905	0.220	0.207	1	0.835	0.314	5.248×10^6
1 barrel residual fuel oil=	6.098	1.083	0.263	0.2475	1.198	1	0.376	6.287×10^6
1 short ton wood=	16.21	2.88	0.699	0.658	3.18	2.66	1	1.67×10^7

tion practices, and reporting of production. The WOGCC collects a conservation tax which is paid by the industry on oil and gas production. This tax pays for the operation and activities of the WOGCC.

If natural gas exploration and production activities take place on federal lands, the U. S. Bureau of Land Management (BLM) also has regulatory requirements. The BLM requires a seismic exploration permit and a drilling permit for activities on federal land. The BLM's requirements for these permits may include an onsite inspection by BLM personnel or the preparation of planning documents such as an Environmental Assessment (EA) or an Environmental Impact Statement (EIS), depending on the perceived impacts on the environment that these activities may have. These documents, depending on the complexity of the analysis and the scope of the proposed development, may delay industry activities for several years and may even eliminate some lands from exploration and development. Since the federal government owns over 50% of the land in Wyoming, their requirements often times significantly impact (or even exclude) oil and gas industry activity in the state.

How important is the natural gas industry to Wyoming?

The State of Wyoming receives revenue from several taxes and sources, depending on the individual oil and gas lease. Revenues are based on the value of the gas produced, which is related to its selling price, and in turn related to whether the gas was produced from private, state, or federal leases. Revenues are received from: 1) severance taxes (6% of the value of produced gas), which go to the State of Wyoming's General Fund, Highway Fund, and Permanent Mineral Trust Fund; 2) royalties from gas produced on state leases (about 16.67% of the value) and lease bonuses and rentals which mainly go to support schools in the state; 3) half of the lease bonuses and rentals when federal lands are leased; 4) half (6.25%) of the 12.5% royalty from gas produced on federal lands; and 5) sales and use taxes from purchase of equipment associated with development.

The State of Wyoming receives an average of about 10% of the gross revenue stream from all natural gas produced in the state. County governments collect an ad valorem tax on produced gas (at a rate usually between 6% and 7%, depending on the county), sales and use taxes from other development activities, and property taxes on the value of production facilities and pipelines. Mineral owners are entitled to receive lease bonus payments and production royalties. Surface owners on mineral leases are entitled to receive payments for any damage caused to their land during exploration and production activities. Local economies are boosted through sales of equipment, supplies, and services, as well as by non-industry-related purchases of such things as vehicles, food, insurance, and lodging.

Minerals are the only class or kind of property in Wyoming that are valued and taxed at 100% of their actual value. Minerals are also the only class or kind of property which pay two direct taxes, property and severance. Based on 2001 production values, Wyoming's natural gas industry accounted for over 57.5% of the property taxes levied in Wyoming on all mineral production. Property taxes paid on natural gas production were $243.4 million, over $172.5 million more than those paid on crude oil production, and over $152.2 million more than those paid on coal production. The industry also paid $209.4 million in state severance taxes in 2001 (Petroleum Association of Wyoming, 2003). That total accounted for over 54.8% of all severance taxes paid on minerals, which was $151.9 million more than severance taxes paid by oil producers and $104.1 million more than severance taxes paid by coal producers. In addition, income from state and federal royalties and leasing for oil and gas in 2001 was over $285.4 million. Wyoming's petroleum industry directly employed nearly 21,000 people with an annual payroll of over $804 million in 2001.

Figure 15. Grey Wolf Drilling Company's Rig No. 558 drilling a 24,000-foot deep well to the Madison Limestone at the Madden Field, northeastern Wind River Basin. This rig is one of the largest land-based drilling rigs in the world, capable of drilling to 30,000 feet.

What is the future of natural gas in Wyoming?

Because natural gas is the largest revenue generator for the State of Wyoming, the prices and volumes produced each year are very important to the state's economy. For every one-cent increase in the yearly average price of natural gas, revenues to the State of Wyoming increase by about $1.6 million. An in-depth analysis of the natural gas markets and prices is beyond the scope of this publication, but a quarterly publication of the Wyoming State Geological Survey, *Wyoming Geo-notes*, does provide timely estimates of future price and production trends for natural gas.

In general, the differential between national and regional gas prices and Wyoming gas prices experienced since 1987 (**Figure 16**) has nearly disappeared as pipeline capacity out of Wyoming has increased the last few years. This has a positive impact on future Wyoming gas prices, which are expected to remain strong the next few years as more Wyoming gas reaches the national markets. Our latest forecast (2003) estimates that prices will remain around $3.25 per MCF in the near future. The future production trends for Wyoming natural gas are also positive, as many other gas-producing states are experiencing stagnant or declining production and imports from Canada may be on the decline. State production in 2003 exceeded 1.8 TCF, and predictions are for natural gas production to almost reach 2.0 TCF by 2007. Wyoming has a resource base of natural gas that can support this production rate for many years.

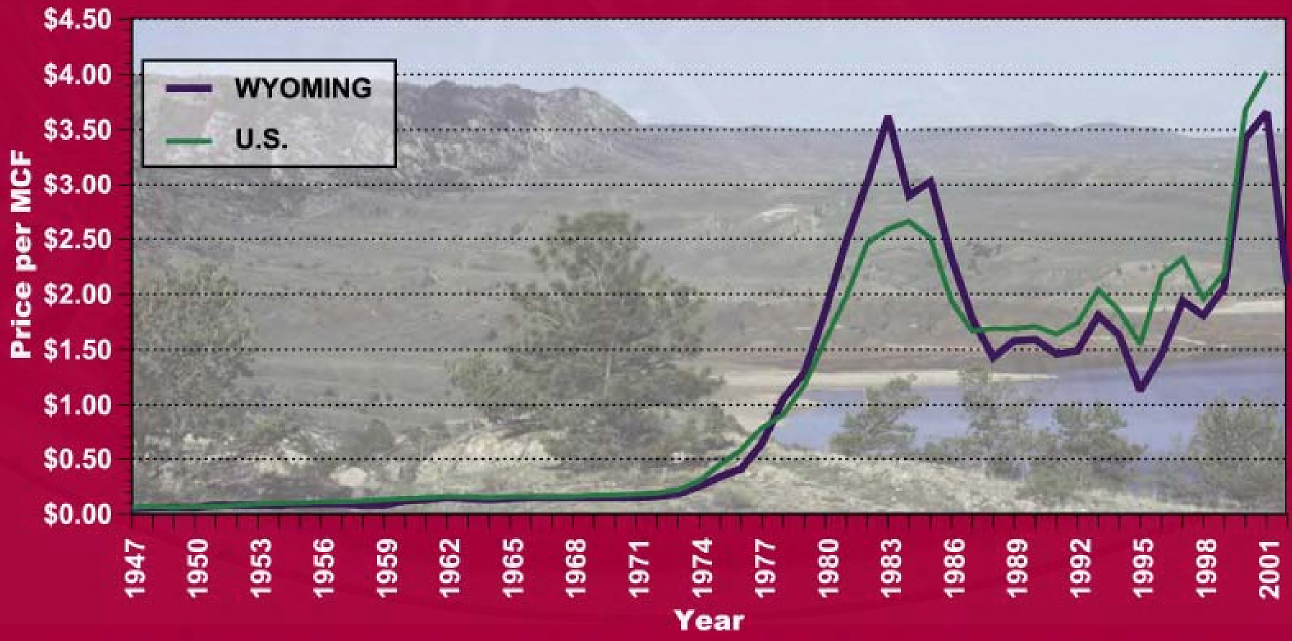


Figure 16. Natural gas prices (dollars per MCF) for Wyoming from 1947 to 2002 and for the U.S. from 1947 to 2001. Wyoming prices from U.S. Bureau of Mines Natural Gas Annals (1947 to 1972), U.S. Energy Information Administration (1973 to 1977), U.S. Minerals Management Service, Federal Royalty Payments (1978 to 1988), Wyoming Department of State Lands and Investments, State Royalty Payments (1989 to 1997), and Wyoming State Geological Survey average Opal prices (1998 to 2002). U.S. prices from U.S. Bureau of Mines Natural Gas Annals (1947 to 1972) and U.S. Energy Information Administration (1973 to 2001). Photograph of Seminoe Mountains and Reservoir is from Richard W. Jones.

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State of Wyoming agencies to contact about natural gas:

Oil and Gas Conservation Commission

P.O. Box 2640, 2211 King Blvd.
Casper, Wyoming 82602-2640
Phone: (307) 234-7147
Fax: (307) 234-5306
Web site: http://wogcc.state.wy.us

Wyoming State Geological Survey

P.O. Box 1347
Laramie, Wyoming 82073-1347
Phone: (307) 766-2286
Fax: (307) 766-2605
Web site: http://wsgsweb.uwyo.edu

Others to contact about natural gas:

Petroleum Association of Wyoming

951 Werner Court, Suite 100
Casper, Wyoming 82601
Phone: (307) 234-5333
Fax: (307) 266-2189
Web site: http://www.pawyo.org

U.S. Bureau of Land Management

Wyoming State Office
5353 Yellowstone Road
Cheyenne, Wyoming 82009
Phone: (307) 775-6256
Fax: (307) 775-6129
Web site: http://www.wy.blm.gov

Cover: Abstract map of estimated ultimate recovery of natural gas from the Jonah Gas Field, a giant field in the Green River Basin, Wyoming. For a more detailed map, refer to Figure 7 of this publication. Modifed and used with permission of AEC Oil & Gas.