BACKGROUND GEOLOGY OF THE SAN JUAN BASIN

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San Juan Basin

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Fundamental Geology of San Juan Basin Energy Resources

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Geology is a science that is inextricably linked to energy resources. Sub-disciplines of geology range from studies of the depths of the earth's interior to the interactions of the crust with the hydrosphere (water), biosphere (plants and animals), and atmosphere (air). Studying the geology of a region always reveals that there are many pieces to the complex geological puzzle of our planet.

Practically every energy resource imaginable is closely linked to geology. Obvious examples are those resources that we currently rely upon, such as oil and gas, coal, coalbed methane, and uranium. But geology plays a role in the development of renewable energy resources, as well. It influences the locations of dams that supply hydroelectric power. It has obvious connections to geothermal resources. It influences natural vegetation as well as crops, both of which can be used to produce biomass energy resources (firewood, ethanol, or bacteria-generated methane gas—all sources of energy derived from plants). Geology even plays a role in optimal placing of wind- and solar-driven power generators and heat collectors. Geology aids in providing the raw materials that make up the infrastructure of the energy industry, whether it's limestone and aggregate used to make concrete, silicon used to make semiconductors, or water used in cooling towers.

Natural resources are rarely exactly where we would like them to be. Therefore geologists spend many lifetimes ferreting out the clues, assembling the pieces of the puzzle, and building a logical and predictable geologic framework to give us an understanding of the location and extent of our energy resources.

FUNDAMENTAL GEOLOGIC CONCEPTS

Although there are many varied aspects of the geology of northwestern New Mexico, the key concepts related to energy resources are geologic structure and stratigraphy, and how these have changed over time. Their importance to the geology of natural resources in New Mexico was first demonstrated at Hogback dome, west of Farmington, where the first commercial oil well in New Mexico was drilled in 1922. There, sedimentary rocks (strata) that were deposited at the earth's surface as horizontal layers of sediment were folded into a dome-shaped geologic structure, which served as a trap for the accumulation of oil and gas. The Dakota Sandstone is the stratigraphic unit that hosts the oil, which migrated into the structure from source rocks nearby. Since the first successful oil well, activities associated with exploration and development in this part of the state have provided an extensive body of information on the subsurface. This information, combined with what we know of rocks on the surface (see map inside back cover), has given us a clear understanding of the geology of the region.

STRUCTURE OF THE SAN JUAN BASIN

The San Juan Basin is the dominant structural and physical feature in the northwestern part of the state, covering more than 26,000 square miles in northwestern New Mexico and southwestern Colorado (Fig. 1). The central part of the San Juan Basin (Fig. 1) is a nearly circular, bowl-shaped depression. This structural depression contains sedimentary rocks over two and a half miles thick (up to 14,400 feet), ranging in age from about 570 to 2 million years in age. Features that define the margins of the basin are the uplifted, folded, and faulted rocks in adjacent mountain ranges. Rocks that are deep in the subsurface in the center of the basin are exposed at various localities around the basin margin, where they are more easily studied. In addition, wells and mines provide further clues to what lies in the subsurface and allow us to correlate those strata with rocks at the surface.

The San Juan uplift, La Plata Mountains, and Sleeping Ute Mountain of southern Colorado form the northern boundary of the San Juan Basin (Fig. 1). The Carrizo and Chuska Mountains and the Defiance monocline (uplift) define the western edge of the basin. The southern edge of the San Juan Basin is bounded by the Zuni Mountains (uplift), the southeastern edge by the Lucero uplift and Ignacio monocline. The Nacimiento Mountains (uplift) and the Gallina-Archuleta arch form the eastern boundary of the basin. These highlands surrounding the basin receive most of the rainfall in the area and are more heavily vegetated than the semiarid San Juan Basin.

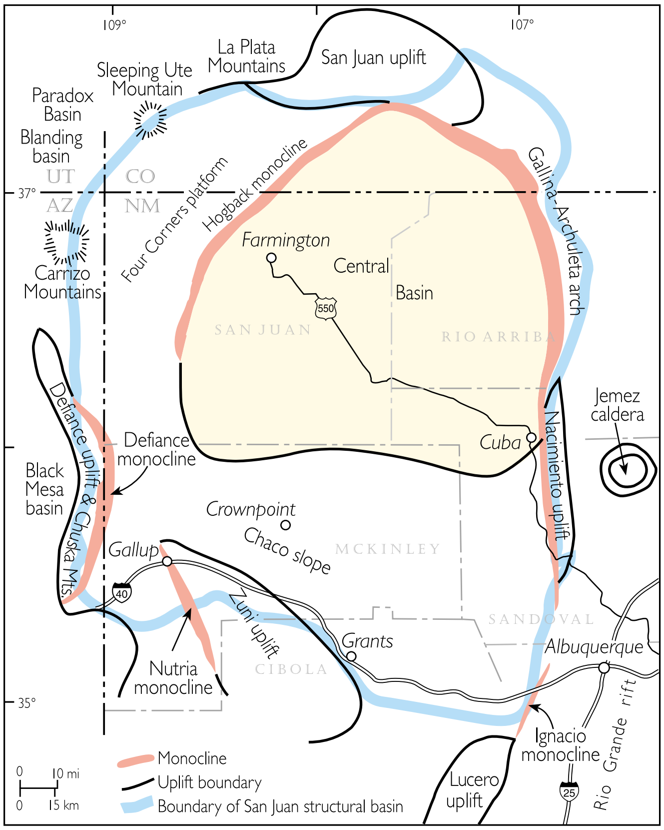

FIGURE 1 Structural features of the San Juan Basin and adjacent areas. From Craigg, 2001.

The central basin is defined on the west, north, and east sides by the Hogback monocline, whose rocks dip steeply into the basin. Hogback dome, where the first commercial oil well in New Mexico was drilled, is a small structure that's part of the western Hogback monocline. The southern edge is defined by the Chaco slope, a gently dipping platform with about 2,500 feet of structural relief above the central basin.

The terrain within the basin consists of mesas, canyons, and valleys eroded from nearly flat-lying sedimentary rock units deposited during the Upper Cretaceous and Tertiary (about 95 to 2 million years ago). The San Juan Basin, and many of the smaller structural details such as the mountains and hogbacks that define the basin boundary, began to form about 65 million years ago.

The close relationship between energy resources and geologic structure in northwestern New Mexico is evident throughout the region. Coal and uranium have been mined on the western and southern flanks of the San Juan Basin, where these deposits exist at or near the surface. Major reservoirs of natural gas and oil are found within the central part of the San Juan Basin. Oil and gas have also been produced in lesser quantities from the Chaco slope and Four Corners platform regions.

SAN JUAN BASIN STRATIGRAPHY

Stratigraphy is the study of the layers of rock in the earth's crust, from the types of rocks and their thicknesses, to depositional environments and time of deposition (see inside back cover). The sedimentary strata of the San Juan Basin dip inward from the highlands toward the trough-like center of the basin. Older sedimentary rocks are exposed around the edge of the basin and are successively overlain by younger strata toward the center of the basin, similar to a set of nested bowls (Figs. 2, 3).

The Precambrian rocks are the oldest rocks (about 1,500 to 1,750 million years old). They are considered to be the basement rocks of the region because they underlie all of the sedimentary rocks within the basin. They are exposed at the surface in a few localities in uplifts along the basin margin, including the Nacimiento Mountains, the Zuni uplift, and the San Juan uplift in Colorado. Granite and quartzite are common Precambrian rock types in those regions.

Most of the sedimentary rocks in the San Juan Basin were deposited from the Pennsylvanian through Tertiary periods (from about 330 to 2 million years ago; Figs. 2,3). During this time the basin went through many cycles of marine (sea), coastal, and nonmarine (land or freshwater) types of deposition. These

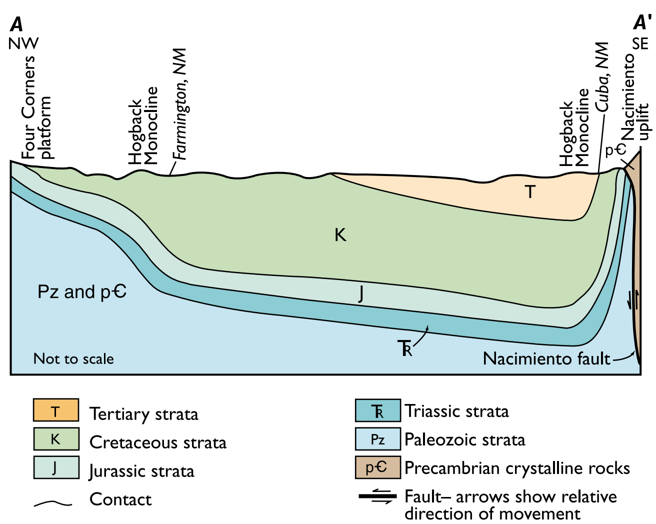

FIGURE 2 Diagrammatic east-west cross section of San Juan Basin, from Craigg, 2001 (p. 8, comb. of section A and B).

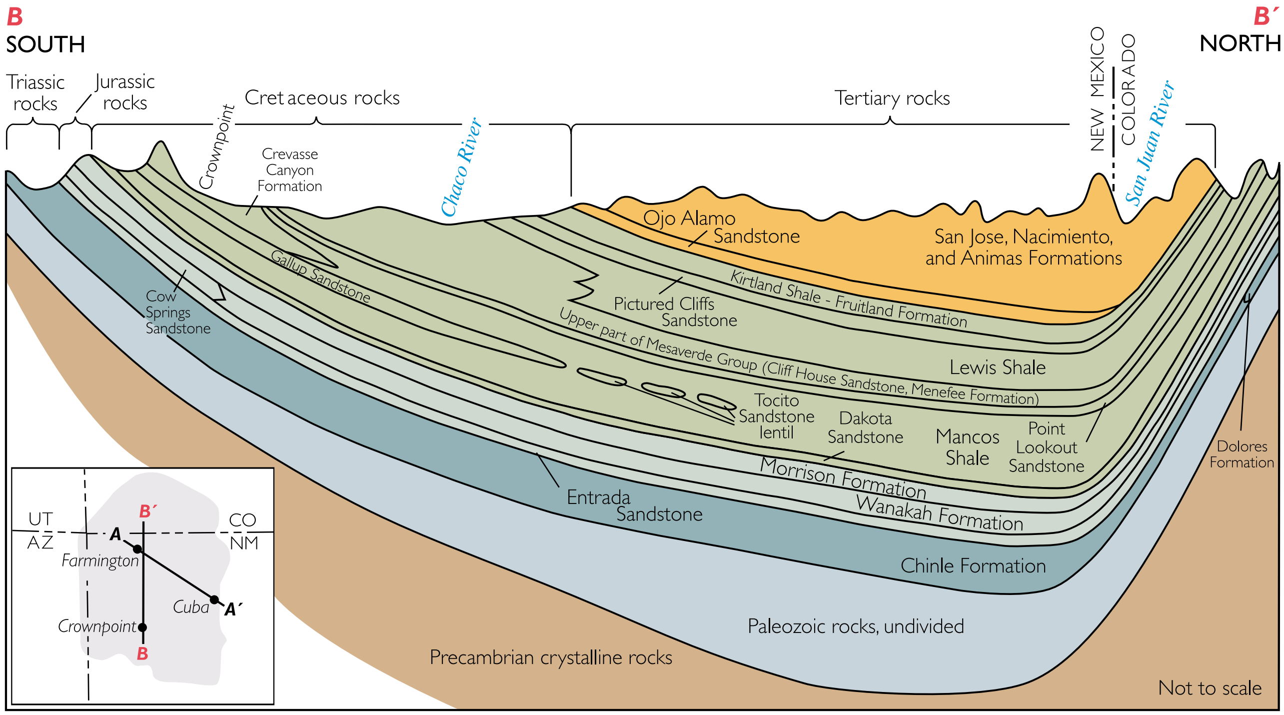

FIGURE 3 Diagrammatic southwest-northeast cross section of San Juan Basin, from Craigg, 2001 (p.12).

cycles are reflected in the characteristics of the rocks in the basin. Like the Precambrian basement, Pennsylvanian and Permian formations (about 330 to 240 million years in age) are exposed in those uplifts around the edge of the basin, most notably the Zuni uplift east of Gallup. These Paleozoic rocks are marine in origin, composed predominantly of limestone, shale, sandstone, and gypsum. Paleozoic rocks host several significant oil and gas fields west of the San Juan Basin and are fractured ground-water aquifers in the Zuni uplift region. Rarely are these rocks reached by drilling in the deeper part of the San Juan Basin, because they are found only at great depth.

Overlying these Paleozoic rocks are Triassic rocks (about 240 million years old). The Triassic was a time of nonmarine deposition, mainly by rivers and streams flowing into the region from the southeast. Triassic rocks include sandstone, siltstone, and mudstone of the Chinle Group and the Rock Point Formation. About 170 million years ago the area was covered by windblown sand dunes, preserved today in the Jurassic Entrada Sandstone. The Entrada is an excellent oil reservoir in several fields that line up in a northwestern trend along the Chaco slope. Stream-laid sandstones of the Jurassic Morrison Formation were deposited throughout the basin during the Jurassic (about 145 million years ago). The Morrison is one of several well-known uranium-bearing rock units in the mining districts along the southern flank of the basin. A period of non-deposition and erosion followed the Late Jurassic, and no sediments are preserved from the earliest Cretaceous in the San Juan Basin.

By the Late Cretaceous (about 95 to 65 million years ago) the western U.S. was dissected by a large interior seaway (Fig. 4). The northwest-to-southeast-trending shoreline of the sea in northwest New Mexico migrated back and forth (northeastward and southwestward) across the basin for some 30 million years, depositing about 6,500 ft of marine, coastal plain, and nonmarine sediments. The marine deposits consist of sandstone, shale, and a few thin limestone beds; the coastal plain deposits include sandstone, mudstone, and coal; and nonmarine deposits include mudstone, sandstone, and conglomerate.

The Late Cretaceous formations in the San Juan Basin, from the oldest unit (the Dakota Sandstone) to the youngest (the Kirtland Shale), are summarized in Figure 5. There is a recurring pattern in the type of

FIGURE 4 Paleogeographic map of North America during Cretaceous time. Map courtesy of Ron Blakey.

sediments that were deposited during the Late Cretaceous. The movement of the shoreline back and forth across the basin shifted the depositional environment from nonmarine to marine, and back to nonmarine, until the end of the Cretaceous, when the seaway retreated from the basin and nonmarine deposits dominated the area. Figure 6 is a snapshot in time of the Four Corners region when the swamps and coastal plain environments prevailed. These deposits today are preserved in the Crevasse Canyon Formation, an important coal-bearing unit.

The Cretaceous stratigraphy of the San Juan Basin makes it one of New Mexico's crown jewels, as far as energy resources are concerned. Many of the Late Cretaceous sandstones are oil and gas reservoirs (Figure 5, and page 152). Marine shales are source rocks for gas and oil. Coal beds are both source and reservoir for coalbed methane. The combination of thick Cretaceous source rocks and a large area of reservoir rocks makes the San Juan one of the most important gas-producing basins in the U.S. today. The coal deposits from the Cretaceous near-shore peat swamps are the source of coal and coalbed methane. The most notable is the Fruitland Formation, which is currently the world's most prolific coalbed-methane field. It is also the source of mined coal supplied to the Four Corners and San Juan power plants west of Farmington.

Youngest	Formation	Rock type (major rock listed first)	Depositional environment	Resources
↑	Kirtland Shale	Interbedded shale, sandstone	Coastal to alluvial plain	
	Fruitland Formation	Interbedded shale, sandstone and coal	Coastal plain	Coal, coalbed methane
	Pictured Cliffs Sandstone	Sandstone	Marine, beach	Oil, gas, water
	Lewis Shale	Shale, thin limestones	Offshore marine	Gas
	Cliff House Sandstone	Sandstone	Marine, beach	Oil, gas, water
	Menefee Formation	Interbedded shale, sandstone and coal	Coastal plain	Coal, coalbed methane, gas
	Point Lookout Sandstone	Sandstone	Marine, beach	Oil, gas, water
	Crevasse Canyon Formation	Interbedded shale, sandstone and coal	Coastal plain	Coal
	Gallup Sandstone	Sandstone, a few shales and coals	Marine to coastal deposit	Oil, gas, water
	Mancos Shale	Shale, thin sandstones	Offshore marine	Oil
Oldest	Dakota Sandstone	Sandstone, a few shales and coals	Coastal plain to a marine shoreline	Oil, gas, water

FIGURE 5 Late Cretaceous formations of the San Juan Basin.

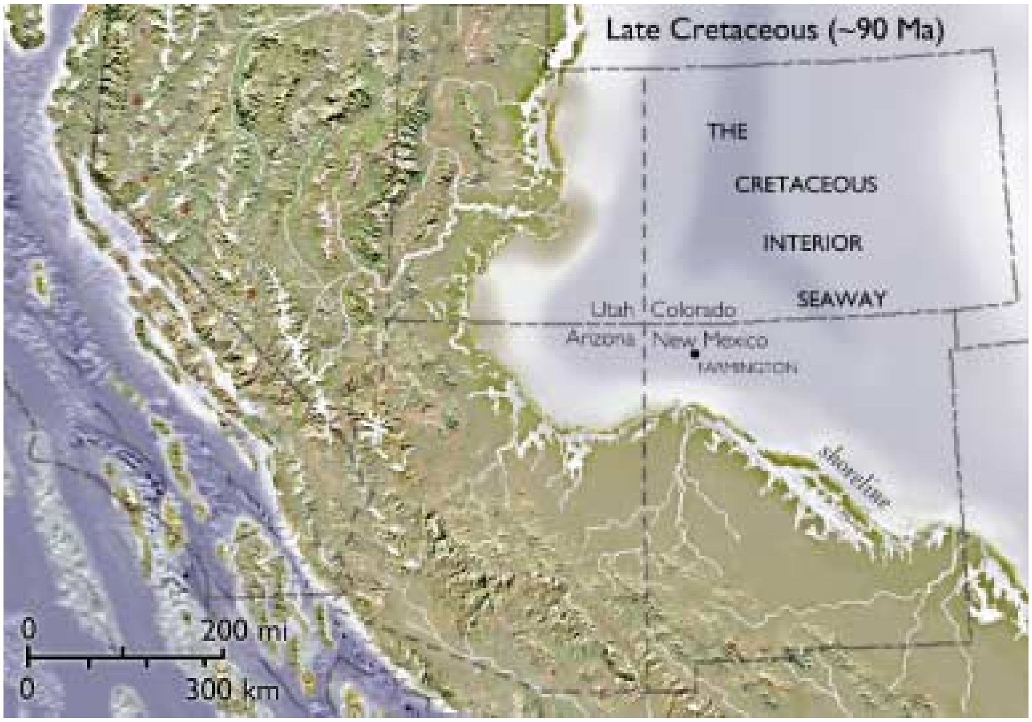

FIGURE 6 Snap shot of paleogeography of the Four Corners region during Late Cretaceous. Map courtesy of Ron Blakey.

From the end of the Cretaceous through the Tertiary (about 65 to 2 million years ago) the San Juan Basin was dominated by nonmarine deposition in stream channels, floodplains, lakes, and windblown sands. Volcanic activity to the north and southwest of the basin had some influence on the type of sediments being deposited within the basin. Tertiary rocks include sandstone, shale, and conglomerate. Tertiary rocks support the foundation of the dam at Navajo Lake on the San Juan River east of Bloomfield, where hydroelectric power is generated. Although Tertiary rocks have long been known to be aquifers in the northeast part of the San Juan Basin, only in the past decade has significant natural gas development in Tertiary rocks begun west of Dulce on the Jicarilla Apache Reservation.

GEOLOGY AND ENERGY RESOURCES

Science is built upon a foundation of cumulative knowledge. Each successive geologic investigation contributes another piece of the puzzle of the how, where, and why of understanding natural resources. The fundamental concepts of geologic structure and stratigraphy are continually being refined. After 80 years of energy-related exploration, development, and geologic research in the San Juan Basin, there is still much to be gained from further research. Mined energy reserves such as fossil fuels and uranium are often short-lived and must be continually replaced as they are consumed. Replacement is not an easy task; the easy-to-find reserves are generally the ones we've already found and produced. Thus, we now search for the subtle, and often smaller, deposits and reservoirs. Our ability to find them, and to develop them, is closely tied to our willingness and ability to better understand the geology of this important part of New Mexico.

Badlands in the San Juan Basin

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Badlands are intricately dissected, water-carved topographic features characterized by a very fine drainage network with high numbers of small rills and channels, and rounded narrow ridges with short steep slopes between the drainages. Badlands develop on sloping surfaces with little or no vegetative cover, eroding poorly consolidated clays, silts, and minor amounts of sandstone, fossil soils (including coal), and less common soluble minerals such as gypsum or salts. The term was first applied to an area in South Dakota, which was called *mauvaises terres* by the early French fur traders. The French and English terms not only imply that badlands are bad ground, they also imply sparse vegetation—not good for agriculture. The Spanish term *malpais* may be translated as badland, but the term is applied to fresh, jagged lava, which not only are impossible for agriculture, they are difficult to cross on horseback. Badlands in the western United States are common and locally charming features of the natural landscape. Over time, badlands are cyclically exposed, eroded, and buried in response to environmental conditions including shifts in climate, changes in local vegetation, and changes in stream levels and sediment supply. Ironically, mankind has created some badlands that "live down" to their connotative names, in areas that did not have badlands before (Perth-Amboy, New Jersey, and Providence Canyon State Conservation Park, Georgia, to name two). Understanding how natural badlands are created, function, and heal has important applications to land management practices (including mine reclamation).

Badlands are abundant in northwestern New Mexico, forming 30–40% of the area. They are interspersed with more vegetated stream valleys, rolling uplands, mesas, sandstone canyons, covered sandy slopes, and windblown sand dunes. Their formation requires:

- extensive exposures of easily erodible mudstone
- abrupt elevational changes between stream valleys and valley margins
- sparse vegetation
- a semiarid climate with a large annual range in precipitation intensities, durations, and amounts.

The San Juan Basin has extensive exposures of gently sloping, poorly consolidated mudstones that protrude above the valleys of many streams. Most of the mudstones have clays that swell up and are very sticky and slippery when wet, shrink and curl when they dry, and are easily transported by water and wind. These mudstones yield very few nutrients when weathered to form soil and are rapidly eroded before most vegetation can eke out an existence. Some of the most extensive badlands are developed in coal-bearing rocks (the Menefee and Fruitland-Kirtland Formations), but mudstones dominate the geologic column at many levels throughout the San Juan Basin. These mudstones range in age from 285 million years to less than half a million years. Because average annual precipitation ranges from only 6 inches near Newcomb to 16 inches near the Continental Divide at Regina, vegetation tends to be sparse, ranging from grassland and sagebrush steppe to piñon-juniper woodland, depending upon elevation and soil type. The vegetation does not cover 100% of the ground in most places. Traditional land use, particularly intensive grazing, has reduced grass cover and increased pathways for concentrated runoff in local areas, initiating exhumation or extending badlands into previously covered areas.

Badlands form when runoff picks up and carries away overlying deposits and uncovers mudstone beneath. Mudstone is less permeable than overlying sandy deposits, and runoff increases as more mudstone is exposed. Strong winds may also remove overlying material. If the gradient for runoff is steep downslope, the sediments are carried to much lower elevations away from the incipient badland. The initial badland may be small, and may be buried again by local sheetwash processes or by windblown sand. Otherwise, the badland may expand upslope and along the sides of the drainage. The increased runoff may also connect to larger gullies downslope and help expand badland areas downhill.Over time, steep-sided badland exposures migrate up tributary valleys developed in mudrocks. Erosion progresses into upland areas that were formerly stabilized by a cap of alluvial deposits and windblown sand with good grass cover. As sediment is moved from the tops and slopes of individual features to the base of the slope and beyond, the features get progressively smaller while similar features evolve at ever-lower elevations. Regardless of size, common badland shapes are created and maintained by a series of natural processes:

- the dry crumbling, raveling, and blowing of weathered mud
- the flow of rain as sheetwash across the rounded hilltop

- the swell and downslope creep of saturated clays
- the accelerated flow and erosive force of rain and mudflows on steeper slopes
- the alluvial apron of particles shed from the hill as the flow of water loses velocity

Water that soaks into the weathered mudstone may dissolve chemical constituents, which then help disperse the clay and move it along a downward gradient and away from the hill. Removal of clay particles and dissolved constituents opens passageways or even small caves. These collapse into funnel-shaped areas known as "soil pipes." Water and sediment passing through the pipes come out of the pipes at the base of the slopes and form small alluvial fans. When dry, the alluvial fans may be reworked into windblown sand dunes or sand sheets. Such deposits are highly permeable and may reduce surface runoff.

Some human-disturbed lands resemble natural badlands. Human-disturbed lands range from obvious mine-spoil piles and road dugways to more subtle areal changes in vegetation and changes in the rates of natural processes. Those disturbances that resemble natural badlands may need human reclamation, a task that is overseen by environmental-protection legislation, regulation, and legal adjudication. The goals of reclamation commonly are:

- to return the land to be near its "original" condition both in terms of contours of the landscape and its previous vegetation
- to restore natural function of the landscape so that wildlife may benefit
- to increase production of vegetation, preferably for animal forage
- to reduce sediment production and transport of sediments offsite
- to improve the chemical quality of both surface water and ground water.

The Coal Surface Mining Law sets performance standards concerning topsoil, topdressing, hydrologic balance, stabilization of rills and gullies, alluvial valley floors, prime farm land, use of explosives, coal recovery, disposal of spoil, coal processing, dams and embankments, steep slopes, backfilling and grading, air resource protection, protection of fish, wildlife, and related environmental values, revegetation, subsidence control, roads and other transportation, how to cease operations, and post-mining land use. These performance standards are set nationally but applied locally, a worrisome task considering the low rainfall and nutrient-poor soils in northwestern New Mexico compared to other parts of the United States. Historically, low vegetation cover and high sediment yields across the local pre-mining landscape already fail to meet reclamation standards required nationwide.

An understanding of the ways in which badlands evolve helps us understand the complex processes shaping all of the landscape. Land managers can improve local long- and short-term reclamation by studying the "performance" of the natural (or least-disturbed) landscape—uplands, badlands, alluvial bottomlands, and windblown sand dunes—with an eye on both existing standards and the natural processes involved. Armed with this understanding, they can solve specific problems of reclamation—optimizing long-term water retention and revegetation, for example, or minimizing sediment production and/or the release of soluble chemical compounds. The most valuable lessons we've learned from studies of naturally occurring badlands include the following:

- Badlands illustrate the fastest changing, least stable, most dynamic end of a range in natural rates and processes in the landscape, in contrast to the more stable parts of the same landscape (such as the sand-covered uplands)
- Internal and external environmental influences may alter the flux of materials and energy flow through the natural system
- Badlands demonstrate the importance of thresholds for change when the landscape is subjected to variable magnitudes and frequencies of environmental influences, such as rainfall or grazing pressure
- Badlands reflect the cyclic lowering of landscapes and landforms from higher, larger, and older levels to lower, smaller, and modern levels.
- Badlands and shapes of individual features in badlands may look the same, even though material is slowly being removed from the slopes and added to the valleys below
- Changes in one part of a system may have consequences in adjacent parts of the system
- In a regulatory environment one must consider the larger picture: How may human endeavors fit in with the natural processes that affect the development of landscape?

ADDITIONAL READING

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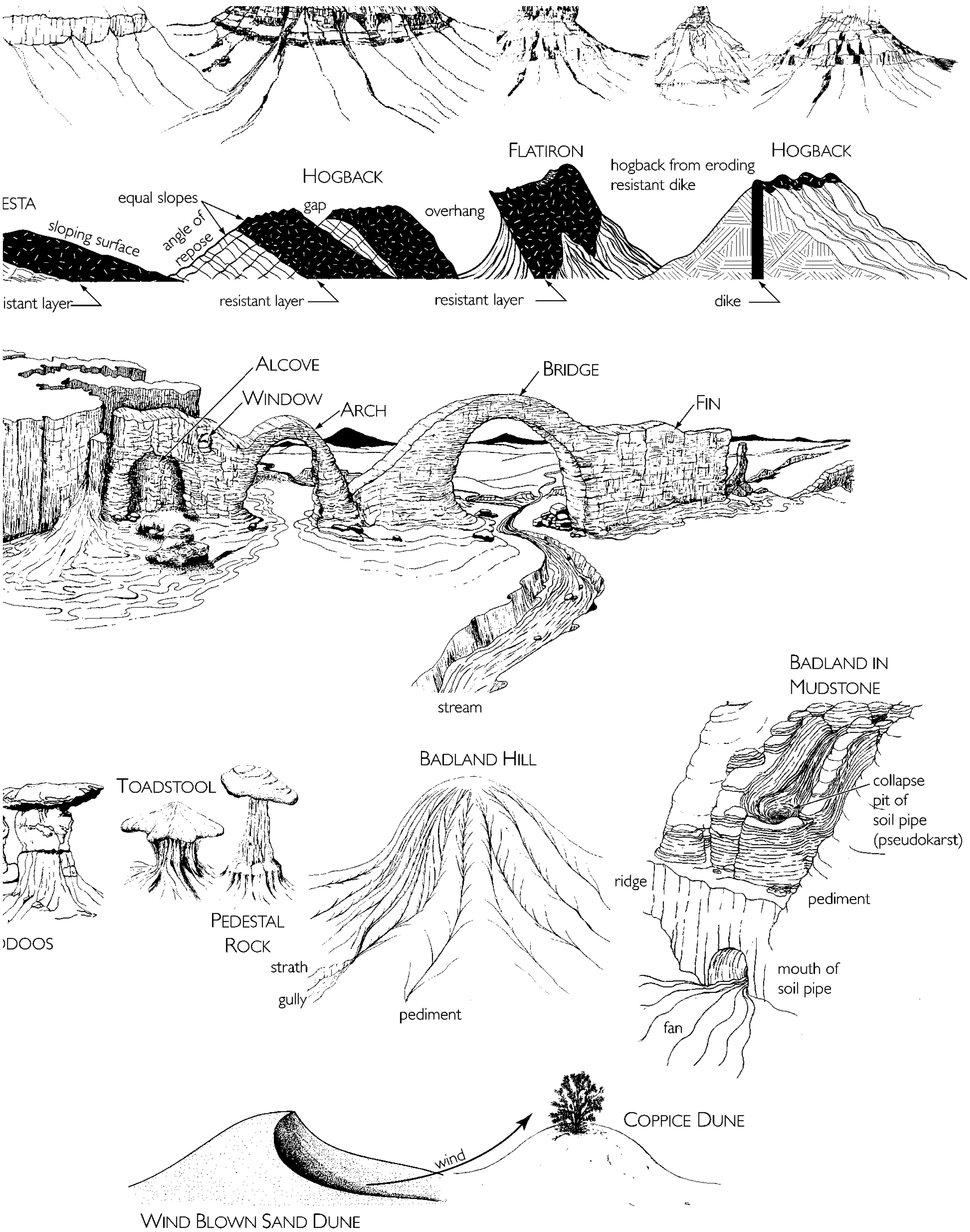
COMMON EROSIONAL FEATURES



Illustrations
by Leo O. Gabaldon

All Features Great and Small

Anthropologists use the phrase "name magic" to describe the tendency of people to think that they can understand or control something merely by naming it. It was a rage in geologic and geographic disciplines in the late nineteenth century. Early explorers, mappers, and geologists named hundreds of geographic features and rocks, using new or locally used exotic names, thereby bestowing some impression of enhanced understanding of the feature under scrutiny—and some enhanced status upon the namer.

But does naming a lumpy erosional feature a "hoodoo" or a "yardang" help our understanding of how it formed any more than if we had crawled around it and made careful observations? What if such terms bring with them negative connotations—such as "badlands" or "gully"? As we all know, terms are seldom neutral in their connotations. Today, in extreme cases, names are deliberately changed to conform to current standards of political correctness.

Names tell us something about our past and ourselves. Names applied to features in northwestern New Mexico serve several purposes. Some are descriptive and serve as place names: Standing Rock, The Hogback, Waterflow, Angel Peak. Some are for fun: Beechatuda Draw, Santa Lulu. Some generic terms have both popular and technical definitions: mesa, butte, badland, pedestal rock. The landscape of northwestern New Mexico is described using names for features of various sizes. Erosional features rooted in bedrock range from large to small (see illustrations on facing page). These features are a result of "differential erosion." Some rock units resist erosion better than others. Well-cemented sandstone, limestone, and/or lava resist weathering and erosion better than mudstones. Mudstones interbedded with these more resistant rocks are more easily eroded and transported away downstream, leaving the more resistant rocks high on the landscape. The volcanic neck of Ship Rock, the plumbing system for a 25-million-year-old volcano, sticks up 1,700 feet above the surrounding countryside because the surrounding mudrocks have been removed by differential erosion. Surficial deposits may also resist erosion—soils developed with calcium carbonate horizons (caliche) may be difficult to erode. Windblown sand may be so permeable that the small amounts of precipitation that do fall soak in before they have a chance to run off. Gravel deposits may be more difficult to erode than sand or mud and therefore are left behind as terraces along streams. Uncommonly, some deposits are protected from erosion by their proximity to resistant rocks ("bedrock defended").

Erosional products The fragmental products of weathering and erosion are moved away from the underlying bedrock, travel downslope, and ultimately come to rest in new deposits. The most common erosional products seen in badlands and in stream channels in northwestern New Mexico are:

- loose grains of sand, silt, and clay
- textures that range from velvety smooth surfaces to popcorn-like crusts to flat mudcracked plates on weathered, clay-rich slopes
- slabs or blocks of cemented sandstones, siltstones, or limestones
- concretions and fragments of concretions (rounded or oblong objects formed by concentrated chemical precipitation of cements in preexisting rocks)
- red dog and clinker (red or brown baked, partially melted, and/or silicified mudstones adjacent to burned-out coal seams)
- fossil fragments such as silicified wood, bones, teeth, shells, fish scales, and other fossils
- reworked older clasts (such as pebbles from bedrock formations).

Features of sediment accumulation Oddly enough, fewer specific terms have been coined for features or forms that are built up by sediment accumulation. Perhaps ambitious namers are unimpressed with the subtle features developed on areas of lesser topographic relief ("feature challenged"). Instead, the features commonly are tagged with descriptive phrases:

- modern low-gradient washes with adjacent floodplain alluvium
- upland surfaces covered with old alluvium, sand sheets, and eolian dunes
- intermediate slopes with alluvial aprons
- alluvial fans; bajadas
- terraces
- sand sheets, sand dunes, climbing and falling dunes, rim dunes, barchan dunes, parabolic dunes, distended parabolic arms of dunes; longitudinal dunes, star dunes, coppice dunes
- landslides, slumps, debris flow lobes, debris runout fans.

Uranium in New Mexico

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Uranium is a hard, dense, metallic silver-gray element with an atomic number of 92 and an atomic weight of 238.02891. It is ductile, malleable, and a poor conductor of electricity. Uranium was discovered in 1789 by Martin Klaproth in Germany and was named after the planet Uranus. There are three naturally occurring radioactive isotopes (U-234, U-235, and U-238); U-238 is the most abundant.

Most of the uranium produced in the world is used in nuclear power plants to generate electricity. A minor amount of uranium is used in a variety of additional applications, including components in nuclear weapons, as X-ray targets for production of high-energy X-rays, photographic toner, and in analytical chemistry applications. Depleted uranium is used in metal form in yacht keels, as counterweights, armor piercing ammunition, and as radiation shielding, as it is 1.7 times denser than lead. Uranium also provides pleasing yellow and green colors in glassware and ceramics, a use that dates back to the early 1900s.

Nuclear power is important to New Mexico and the United States. Nuclear power plants operate the same way that fossil fuel-fired plants do, with one major difference: nuclear energy supplies the heat required to make steam that generates the power plant. Nuclear power plants account for 19.8% of all electricity generated in the United States (Fig. 1). This generated electricity comes from 66 nuclear power plants composed of 104 commercial nuclear reactors licensed to operate in the U.S. in 2001.

Although New Mexico does not generate electricity from nuclear power in the state, the Public Service Company of New Mexico (PNM) owns 10.2% of the Palo Verde nuclear power plant in Maricopa County, Arizona. PNM sells the generated electricity from Palo Verde to its customers in New Mexico. In 1999 the average cost of electricity generated by nuclear power plants was 0.52 cents/kilowatt hour, compared to 1.56 cents/kilowatt hour for electricity generated by fossil fuel-fired steam plants. Most of the electricity generated from plants in New Mexico comes from coal-fired plants (Fig. 2), and New Mexico sells surplus electricity to other states.

NUCLEAR FUEL CYCLE

The first step in understanding the importance of uranium and nuclear power to New Mexico is to understand the nuclear fuel cycle. The nuclear fuel cycle consists of ten steps (Fig. 3):

1 Exploration—using geologic data to discover an economic deposit of uranium.

2 Mining—extracting uranium ore from the ground.

3 Milling—removing and concentrating the uranium into a more concentrated product ("yellow cake" or uranium oxide, U_3O_8).

4 Uranium conversion— uranium oxide concentrate is converted into the gas uranium hexafluoride (UF6).

5 Enrichment—most nuclear power reactors require enriched uranium fuel in which the con-

Electricity fuel source	Net generation by fuel source (billion kilowatt hours)	Net generation by fuel source (%)	Industry capability by fuel source (megawatts)	Industry capability by fuel source (%)	Fuel Costs (dollars per million Btu)
Coal	1,968	51.8	315,249	38.9	1.2
Petroleum	109	2.9	39,253	4.8	4.45
Gas	612	16.1	97,632	12.1	4.3
Nuclear	754	19.8	97,557	12.0	
Hydroelectric	273	7.2	99,068	12.2	
Other (geothermal, wind, multifuel, biomass, ect.)	84	2.2	162,866	20.0	
Total industry	3,800	100	811,625	100	

FIGURE 1 Net generation and industry capability of electricity generated by fuel in the United States in 2000 (from Energy Information Administration, 2001).

Electricity fuel source	Net generation by energy source (%)
Coal	85.5
Petroleum	0.1
Gas	13.7
Duel	—
Nuclear	—
Hydroelectric	0.7
Other (geothermal, wind, multifuel, biomass, etc.)	—
Total industry	100

FIGURE 2 Net generation of electricity generated at electric power plants in New Mexico in 2000 from Energy Information Administration, 2001.

tent of the U-235 isotope has been raised from the natural level of 0.7% to approximately 3.5%. The enrichment process removes 85% of the U-238 isotope. Some reactors, especially in Canada, do not require uranium to be enriched.

6 Fuel fabrication—enriched UF^6 is converted to uranium dioxide (UO^2) powder and pressed into small pellets. The pellets are encased into thin tubes, usually of a zirconium alloy (zircalloy) or stainless steel, to form fuel rods. The rods are then sealed and assembled in clusters to form fuel elements or assemblies for use in the core of the nuclear reactor.

7 Power generation—generate electricity from nuclear fuel.

8 Interim storage—spent fuel assemblies taken from the reactor core are highly radioactive and give off heat. They are stored in special ponds, located at the reactor site, to allow the heat and radioactivity to decrease. Spent fuel can be stored safely in these ponds for decades.

9 Reprocessing—chemical reprocessing of spent fuel is technically feasible and used elsewhere in the world. However, reprocessing of spent fuel is currently not allowed in the United States as a result of legislation enacted during the Carter administration.

10 Waste disposal—the most widely accepted plans of final disposal involve sealing the radioactive materials in stainless steel or copper containers and burying the containers underground in stable rock, such as granite, volcanic tuff, salt, or shale.

Historically, New Mexico has played a role in three of these steps: exploration, mining, and milling. For nearly three decades (1951–1980), the Grants uranium district in northwestern New Mexico produced more uranium than any other district in the world (Figs. 4, 5). However, as of spring 2002, all of the conventional underground and open-pit mines are closed because of a decline in demand and price. The only uranium production in New Mexico today is by mine-water recovery at Ambrosia Lake (Grants district). Two companies are currently exploring for uranium in sandstone in the Grants uranium district for possible in situ leaching.

There are six conventional uranium mills licensed to operate in the U.S.; only one is operating (Cotter in Canon City, Colorado), and it will probably close in 2002. The Quivera Mining Company's Ambrosia Lake mill near Grants, New Mexico, is currently inactive and is producing uranium only from mine water.

TYPES OF URANIUM DEPOSITS IN NEW MEXICO

The Grants and Shiprock uranium districts in the San Juan Basin are well known for large resources of sandstone-hosted uranium deposits in the Morrison Formation (Jurassic). More than 340 million lbs of uranium oxide (U_3O_8) were produced from these uranium deposits from 1948 through 2001 (Fig. 5), accounting for 97% of the total uranium production

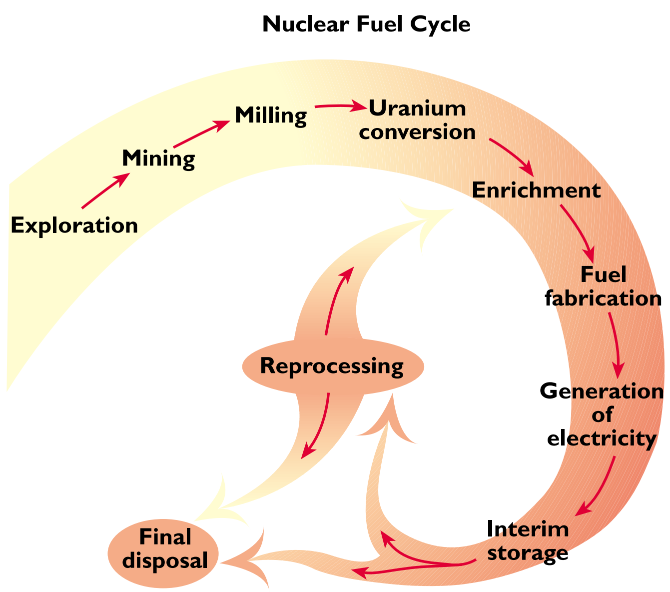

FIGURE 3 The nuclear fuel cycle (Uranium Information Centre Ltd., 2000; Energy Information Administration, 2001).

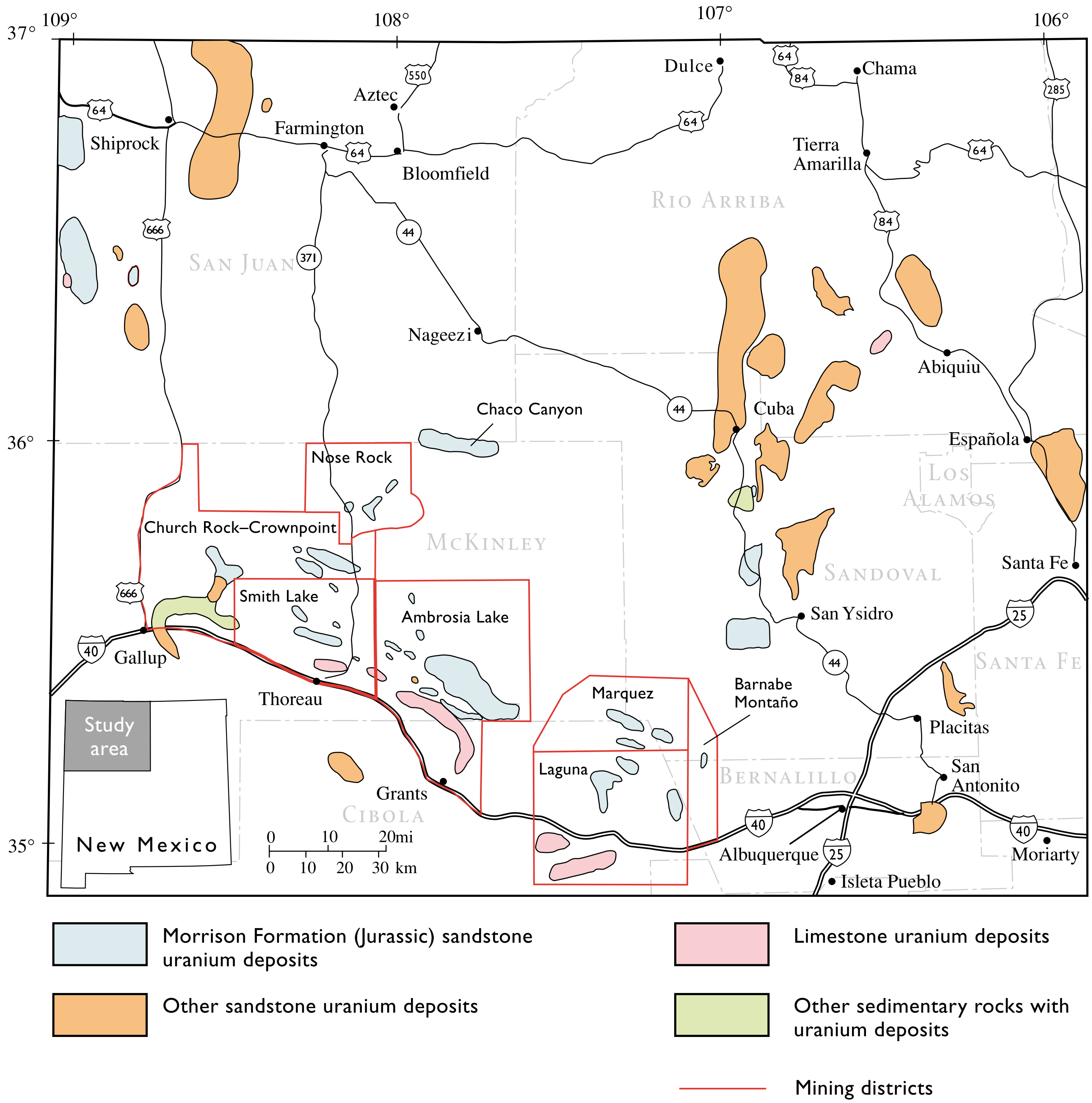

FIGURE 4 Uranium potential in the San Juan Basin, New Mexico (from McLemore and Chenoweth, 1989).

in New Mexico and 37.8% of the total uranium production in the United States. New Mexico ranks second in uranium reserves in the U.S., with reserves of 15 million short tons of ore at 0.277% U_3O_8 (84 million lbs U_3O_8) at $30/lb (Fig. 6). The Department of Energy classifies uranium reserves into forward cost categories of $30 and $50 per lb. Forward costs are operating and capital costs (in current dollars) that are still to be incurred to produce uranium from estimated reserves. All of New Mexico's uranium reserves in 2002 are in the Morrison Formation in the San Juan Basin,

Uranium ore bodies are found mostly in the Westwater Canyon, Brushy Basin, and Jackpile Sandstone Members of the Morrison Formation. Typically, the ore bodies are lenticular, tabular masses of complex uranium and organic compounds that form roughly parallel trends; fine- to medium-grained barren sandstone lie between the ore bodies.

Nearly 6.7 million lbs of uranium oxide (U_3O_8) have been produced from uranium deposits in limestone beds of the Todilto Member of the Wanakah Formation (Jurassic). Uranium deposits in the Todilto limestone are similar to primary sandstone-hosted uranium deposits; they are tabular, irregular in shape, and occur in trends. Most deposits contain less than 20,000 tons of ore averaging 0.2-0.5% U_3O_8, although a few deposits were larger. Uranium is found only in a few limestones in the world, but, of these, the deposits in the Todilto limestone are the largest and most productive. However, uranium has not been produced from the Todilto Member since 1981, and it is unlikely that any additional production will occur in the near future.

Other uranium deposits in New Mexico are hosted by other sedimentary rocks or are in fractured-controlled veins or in igneous or metamorphic rocks. Production from these deposits has been insignificant (Fig. 5) and it is unlikely that any production will occur from them in the near future.

FUTURE POTENTIAL

The potential for uranium production from New Mexico in the near future is dependent upon international demand for uranium, primarily for fuel for nuclear power plants. Currently, nuclear weapons from the former U.S.S.R. and the U.S. are being converted into nuclear fuel for nuclear power plants, reducing the demand for raw uranium. In addition, higher-grade, lower-cost uranium deposits in Canada and Australia are sufficient to meet current international demands. Thus, it is unlikely that conventional underground mining of uranium in New Mexico will be profitable in the near future. However, mine-water recovery and in situ leaching of the sandstone-hosted uranium deposits in the Grants uranium district are

Type of deposit	Production (lbs U_3O_8)	Period of production (yrs)	Production per total in New Mexico (%)
Primary, redistributed, remnant sandstone uranium deposits (Morrison Formation, Grants district)	332,107,000[1]	1951–1989	95.4
Mine-water recovery	8,317,788	1963–2000	2.4
Tabular sandstone uranium deposits (Morrison Formation, Shiprock district)	493,510	1948–1982	0.1
Other Morrison sandstone uranium deposits	991	1955–1959	—
Other sandstone uranium deposits	468,680	1952–1970	0.1
Limestone uranium deposits (Todilto Formation)	6,671,798	1950–1985	1.9
Other sedimentary rocks with uranium deposits	34,889	1952–1970	—
Vein-type uranium deposits	226,162	1953–1966	—
Igneous and metamorphic rocks with uranium deposits	69	1954–1956	—
Total in New Mexico	348,321,000[1]	1948–2000	100
Total in United States	922,870,000[1]	1947–2000	37.8 of total U.S.

FIGURE 5 Uranium production in New Mexico (McLemore and Chenoweth, 1989; production from 1988-2000 estimated by the author). [1]Approximate numbers rounded to the nearest 1,000 lbs. Total U.S. production from McLemore and Chenoweth (1989) and Energy Information Administration (2001).

State	$30 per lb ore (million tons)	$30 per lb grade (% U_3O_8)	$30 per lb U_3O_8 (million lbs)	$50 per lb ore (million tons)	$50 per lb grade (% U_3O_8)	$50 per lb U_3O_8 (million lbs)
New Mexico	15	0.277	84	102	0.166	341
Wyoming	42	0.129	110	240	0.077	370
Arizona, Colorado, Utah	7	0.288	41	42	0.138	115
Texas	4	0.079	7	19	0.064	24
Other	7	0.202	29	25	0.107	54
Total	76	0.178	271	428	0.106	904

FIGURE 6 Uranium reserves by forward-cost category by state, 2000 (Energy Information Administration, 2001). The DOE classifies uranium reserves into forward cost categories of $30 and $50 per lb. Forward costs are operating and capital costs (in current dollars) that are still to be incurred to produce uranium from estimated reserves.

likely to continue as the demand and price of uranium increase in the next decade.

Only one company in New Mexico, Quivira Mining Co. owned by Rio Algom Ltd. (successor to Kerr McGee Corporation), produced uranium in 1989-2001, from waters recovered from inactive underground operations at Ambrosia Lake (mine-water recovery). Hydro Resources Inc. has put its plans on hold to mine uranium by in situ leaching at Churchrock until the uranium price increases. Reserves at Churchrock are estimated as 15 million lbs of U_3O_8. NZU Inc. also is planning to mine at Crownpoint by in situ leaching. Rio Grande Resources Co. is maintaining the closed facilities at the flooded Mt. Taylor underground mine, in Cibola County, where primary sandstone-hosted uranium deposits were mined as late as 1989. In late 1997 Anaconda Uranium acquired the La Jara Mesa uranium deposit in Cibola County from Homestake Mining Co. This primary sandstone-hosted uranium deposit, discovered in the late 1980s in the Morrison Formation, contains approximately 8 million lbs of 0.25% U_3O_8. Future development of these reserves and resources will depend upon an increase in price for uranium and the lowering of production costs.

ACKNOWLEDGMENTS

This work is part of ongoing research of mineral resources in New Mexico and adjacent areas currently underway at the New Mexico Bureau of Geology and Mineral Resources.

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Ground Water and Energy Development in the San Juan Basin

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The San Juan Basin is classified as an arid region: most of the area receives less than 10 inches of precipitation a year. Mean annual precipitation in marginal mountainous regions may be as much as 30 inches a year, but surface water is scarce, except for the San Juan River and its tributaries in the northern part of the basin. Most water users, therefore, depend on ground-water supplies. The San Juan Basin contains a thick sequence of sedimentary rocks (more than 14,000 ft thick near the basin center). Most of these are below the water table and therefore saturated with ground water (Fig. 1). Many of these are the very same strata that contain the energy resources of the San Juan Basin: coal, oil, gas, and uranium. Water plays a key but varying role in the development of each of these energy resources. The purposes of this paper are to 1) briefly describe the ground-water resources of the San Juan Basin and 2) suggest their role in energy-resource development there. Information presented comes from various previous studies done by the New Mexico Bureau of Geology and Mineral Resources, or by New Mexico Tech graduate students funded by the bureau.

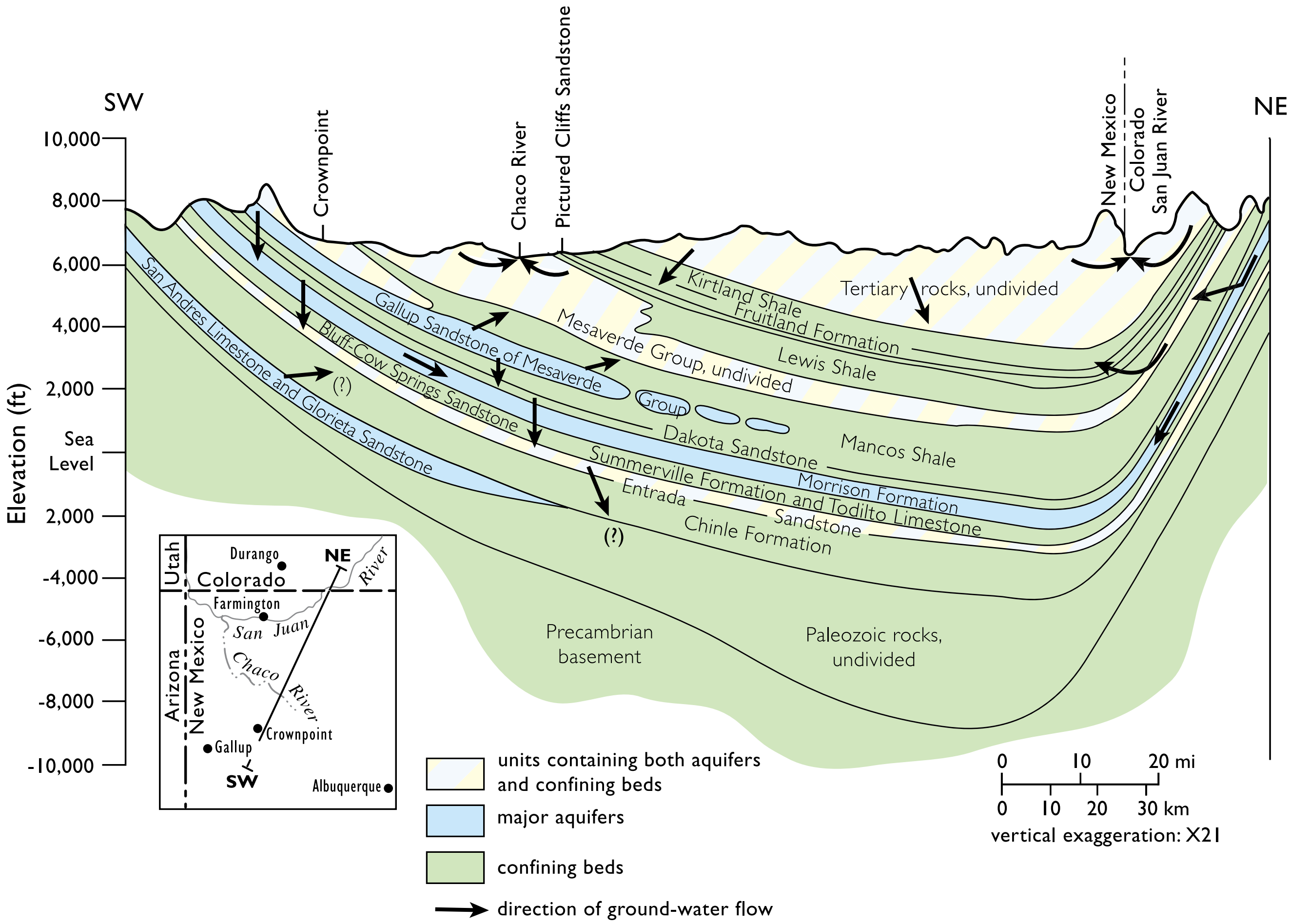

FIGURE 1 Hydrogeologic cross section of the San Juan Basin. Major aquifers are blue; confining beds are green; units containing both are crosshatched.

WHERE AND HOW DOES THE GROUND WATER OCCUR?

Ground-water occurrence may be described in three ways: the rock unit containing the ground water, the pressure condition under which the water exists, and depth to the ground water. Most of the useable ground water exists in rocks with open space between grains, rather than in fractures. The specific rock units yielding useful quantities of water to wells (aquifers) vary with location. In the northeastern part of the basin, sandstones of Tertiary age are the best targets for ground water. In the western and southern parts of the basin, the most successful wells tap Mesozoic sandstones. Only along the northern flank of the Zuni Mountains, east of Gallup, New Mexico, are productive wells completed in fractured rock (Permian limestone).

Most of the ground water in the San Juan Basin exists under confined (artesian) or semi-confined hydrologic conditions: under pressure, prevented from seeking its own level by an overlying rock unit of low permeability (aquitard). In the Mesozoic rocks of this region, the artesian sandstone aquifers are interbedded with shales that behave as low-permeability, confining aquitards. The Triassic mudrock sequence is the aquitard for the Permian limestone. By contrast, ground water in the alluvium along streams and in the shallow Tertiary sandstone aquifers is generally unconfined: the water is not under pressure, not overlain by an aquitard, and is open to the atmosphere through pores in overlying permeable rocks.

The depth to ground water varies from place to place, because of the slope of the water table and dip of the strata. The depth to water in unconfined aquifers is the depth to the top of saturation or the regional water table, which varies from less than 100 ft to several hundred feet, depending on the aquifer in question and the overlying topography. In the case of confined aquifers, there are two different depths to water: one before it is penetrated by a well, and one after penetration has occurred. Before well construction, the depth to water is the same as the depth to the top of the confined or artesian aquifer. Depths to the top of a specific confined aquifer also vary throughout the basin due to the dip of the strata. Depth to the Tertiary sandstones (for example, Ojo Alamo Sandstone) varies from less than 100 ft to as much as 4,000 ft; depth to the deepest sandstone aquifer widely used (Westwater Canyon Sandstone Member of the Morrison Formation) varies from less than 100 ft to nearly 9,000 ft.

After a confined aquifer is penetrated by a well, water rises above the top of the aquifer. The level to which it rises is called the potentiometric surface. Each artesian aquifer in the basin has its own potentiometric surface. The depth or elevation of this surface also varies across the basin, depending upon the dip of the strata and the pressure of the confined ground water.

WHICH WAY DOES THE GROUND WATER FLOW?

In the San Juan Basin, as elsewhere, ground water flows from higher elevation recharge areas (mountains), located around the basin margin, toward lower elevation discharge areas (rivers). Northwest of the continental divide, ground water flows toward the San Juan River or Little Colorado River. Southeast of the divide, it flows toward the Rio Grande.

HOW FAST DOES THE GROUND WATER MOVE?

The rate of water movement in an aquifer depends on its hydraulic properties (porosity and permeability) and the hydraulic gradient (steepness of the water table or potentiometric surface). Thus, the rate of movement varies from aquifer to aquifer. Ground-water modeling has suggested rates for total ground-water inflow and outflow in the basin. These rates are 20 cubic feet per second (ft^3/s) or approximately 9,000 gallons per minute (gpm) for the Tertiary sandstones and 40 ft^3/s or approximately 18,000 gpm for the Cretaceous and Jurassic sandstones.

HOW GOOD IS THE WATER?

Water is of good quality near basin-margin recharge areas, but deteriorates with distance along its flow path as it dissolves minerals. A general measure of water quality is salinity. This is commonly evaluated by specific conductance, a measure of a water's ability to conduct electricity. Values are reported in the strange unit of microSiemens/centimeter (uS/cm). The lower the number, the better is the water quality. Values of less than 1,000 uS/cm generally indicate potable water. Values for valley-fill alluvium are generally less than 1,000 uS/cm in headwater areas and greater than 4,000 uS/cm in downstream reaches, due to discharge of deeper water from bedrock. Specific conductance of water from sandstone aquifers ranges from less than 500 uS/cm near outcrop to almost 60,000 uS/cm at depth.

Bicarbonate content is relatively high in waters having specific conductance values of as high as 1,000 uS/cm. Sodium, sulfate, and chloride are major dissolved components in ground water having specific conductance values of as high as 4,000 uS/cm

HOW MUCH GROUND WATER IS THERE?

Ground water in most of the region is very old. Studies at the Navajo mine showed the long-term ground-water recharge rate to be very low (0.02 inches/yr). Pumping of aquifers far exceeds this recharge rate and thus results in the depletion of ground-water resources that cannot be replaced in the foreseeable future. It has been estimated that as much as 2 million acre-feet of slightly saline ground water (having less than 2,000 milligrams per liter of total dissolved solids) could be produced from the confined aquifers in the San Juan Basin with a water-level decline of 500 ft. Although that is a lot of untapped water, it is too salty for many uses and installing wells that could handle the anticipated 500-ft drop in water level would be very expensive.

WHAT ARE THE IMPLICATIONS FOR ENERGY DEVELOPMENT?

Water is an important component in the development of the basin's energy resources. Both water quantity and quality issues must be considered. Is there a sufficient supply of good-quality water for development needs? Does development impact local or regional water quantity and quality? The answers vary from resource to resource.

Coal Coal is currently being extracted by strip-mining methods. Water plays a key role in various aspects of such extraction, and water supply is therefore an issue. Large amounts of water are needed for the mine-mouth, coal-fired power plants (for steam generation) as well as for reclamation (especially revegetation). However, quality of water in the principal coal-bearing unit (Fruitland Formation) is poor (Fig. 2). Thus, water for coal-mining needs has historically come from the San Juan River, especially in the northern part of the basin. Irrigation associated with revegetation may flush salts from the unsaturated zone to the first underlying sandstone. Although the quality of ground water in that rock is so poor that it is not being used, it discharges to the San Juan River and may increase salt loads there.

Oil and Gas The main issue in petroleum extraction is the potential for contamination of fresh ground-water supplies by produced brine or hydrocarbon spills. On average, six barrels of water are produced

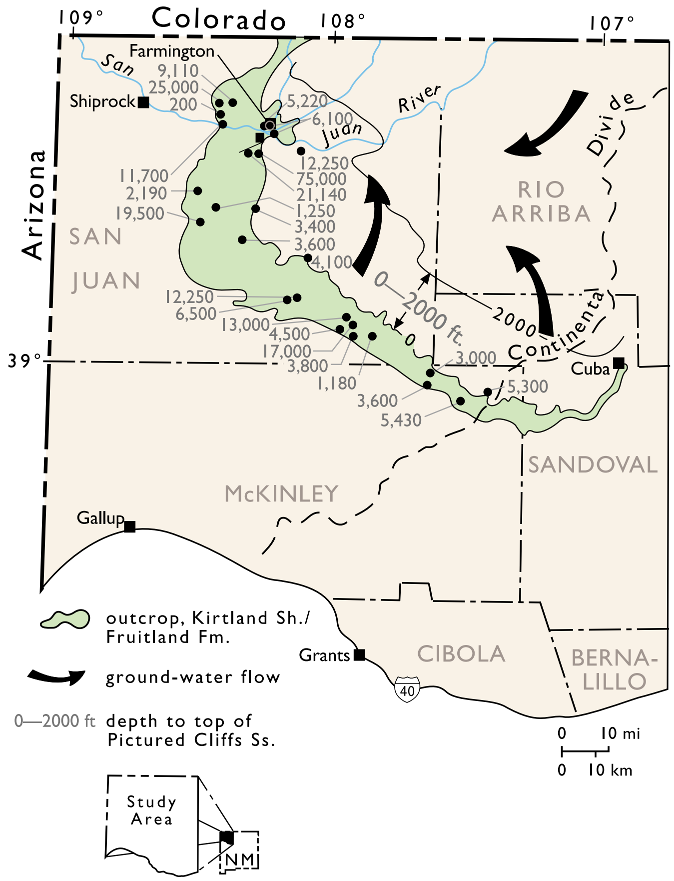

FIGURE 2 Generalized flow directions and quality of water in the Kirtland Shale/Fruitland Formation, undivided. Units shown are in µS/cm.

for every barrel of oil produced. The practice of collecting water and oil in unlined drip pits has been outlawed. However, confined brine may mix with shallower fresh water in older wells where casings and/or seals have deteriorated. The integrity of existing wells should be checked periodically, and abandoned wells should be properly decommissioned to prevent contamination.

Coalbed Methane Water is also produced in coalbed-methane development. Unlike the brine associated with petroleum extraction, this water may be fairly fresh. In an arid region like the San Juan Basin, such water should not be wasted by injecting it into a deep saline aquifer, as is often done with brine from oil wells. However, water rights must be obtained from the state engineer before it can be put to beneficial use. Work is under way to clarify this issue and develop a protocol for beneficial use of produced water. However, much more work is needed on the hydrologic system(s) involved, water treatment, technologies for reducing the quantities produced and markets for beneficial use.

Uranium Underground mining of uranium was once intense in the Grants mineral belt. Water supply was not an issue, as the large volumes withdrawn in dewatering (the process of pumping water out of the mine) from the major uranium-bearing unit (Morrison Formation) were of good quality and readily met water needs. Some of the freshest water in the basin is associated with the Morrison Formation (Fig. 3). However, both water quantity and quality were impacted in places. Ground-water modeling showed that had dewatering continued, water-level declines would have been felt all the way to the San Juan River by the year 2000. Dewatering also lowered artesian pressures such that vertical gradients were locally reversed (became downward instead of upward), permitting poor-quality water in one Cretaceous sandstone to flow downward into the underlying Jurassic sandstone aquifer containing good-quality water. Although that mining activity has ceased, sizable reserves of uranium remain in the ground. Such

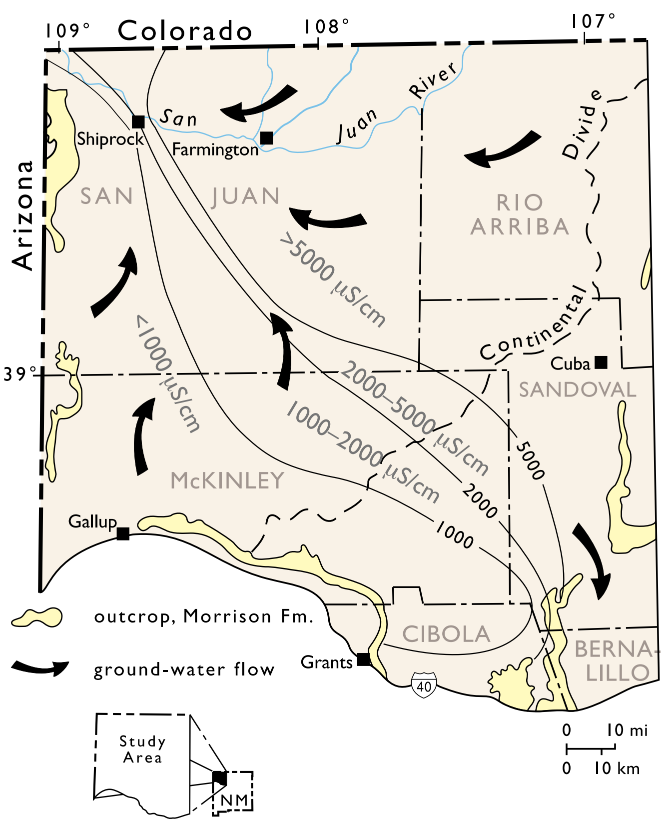

FIGURE 3 Generalized flow direction and quality of water in the Morrison Formation.

water-quantity impacts will recur should uranium prices warrant renewed underground mining. However, current interest centers on in situ extraction. The Navajo Nation and environmental groups are still protesting the feasibility of such mining, in view of the potential impact on ground-water quality.

SUMMARY

Ground water and energy development are intimately related in the San Juan Basin. As a result, there is both good news and bad news.

- *The good news:*

  1 Ground water is associated with the same rocks as the energy resources, so there may be a ready supply.

  2 Studies have shown that there are large amounts of water of moderate quality in various aquifers, at various depths, in various locations.

- *The bad news:*

  1 Ground water is associated with the same rocks as the energy resources, so it is vulnerable to quantity and quality impacts.

  2 Water demands are increasing among the major non-industrial water users, including Indian reservations, municipalities, irrigators, and ranchers.

  3 As demands of these users along the San Juan River and its tributaries grow beyond their present surface-water supplies, they will have to look to ground-water sources for additional water.

  4 At that point, energy developers in the San Juan Basin will be in direct competition for ground water with other users.

Thoughtful regional planning and frequent environmental surveillance will be essential for sound management and protection of ground water in this multiple water-use area. Successful energy development will be compatible with regional water-use goals.

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OIL AND NATURAL GAS ENERGY

DECISION-MAKERS FIELD CONFERENCE 2002

San Juan Basin

The Origin of Oil and Gas

Ron Broadhead, *New Mexico Bureau of Geology and Mineral Resources*

We will pass through a number of oil and natural gas fields during this field conference. The oil and gas that are produced from these fields reside in porous and permeable rocks (reservoirs) in which these liquids have collected and accumulated throughout the vast expanse of geologic time. Oil and gas fields are geological features that result from the coincident occurrence of four types of geologic features (1) oil and gas source rocks, (2) reservoir beds, (3) sealing beds, and (4) traps. Each of these features, and the role it plays in the origin and accumulation of oil and gas, is illustrated below (Fig. 1).

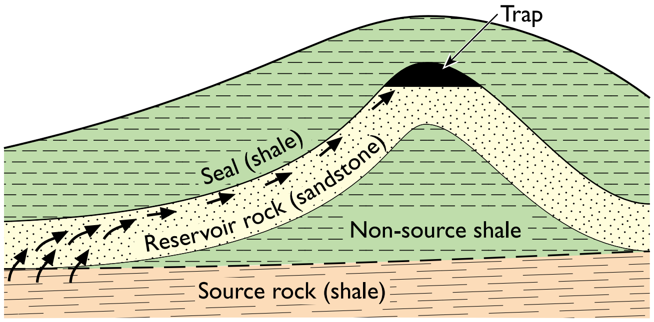


FIGURE 1 Natural accumulation of oil and gas.

OIL AND GAS SOURCE ROCKS

Oil and natural gas originate in petroleum source rocks. Source rocks are sedimentary rocks that formed from sediments deposited in very quiet water, usually in swamps on land or in deep marine settings. These rocks are composed of very small mineral fragments. In between the mineral fragments are the remains of organic material (usually algae), small wood fragments, or pieces of the soft parts of land plants (Fig. 2). When these fine grained sediments are buried by younger, overlying sediments, the increasing heat and pressure resulting from burial turns the soft sediments into hard layers of rock. If further burial ensues, then temperatures continue to increase. When temperatures of organic-rich sedimentary rocks exceed 120° C (250° F), the organic remains within the rocks begin to be "cooked," and oil and natural gas are expelled. It takes millions of years for these source rocks to be buried deep enough to attain these maturation temperatures. It takes many more millions of years to generate commercial accumulations of oil and natural gas, and for these accumulations to migrate into adjacent reservoir rocks.

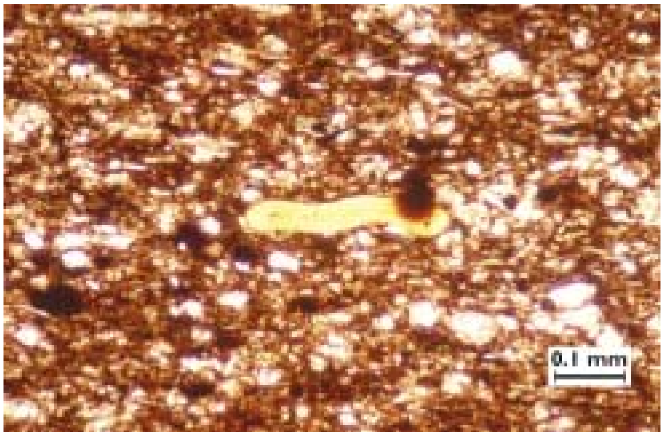


FIGURE 2 Microscopic image of a source rock with mineral grains (lighter colored material) and organic matter which is mostly algae remains (brown to black and yellow colored material). The source rock will usually act as a seal.

If the organic materials within the source rock are mostly wood fragments, then the primary hydrocarbon generated upon maturation is natural gas. If the organic materials are mostly algae or the soft parts of land plants, then both oil and natural gas are formed. By the time the source rock is buried deep enough to reach temperatures above 150° C (300° F), the organic remains have produced most of the oil they are able to produce. Above these temperatures, any oil remaining in the source rock or trapped in adjacent reservoirs will be broken down into natural gas. So, gas can be generated in two ways: it can be generated directly from woody organic matter in the source rocks, or it can be derived by thermal breakdown of previously generated oils at high temperatures.

OIL AND GAS RESERVOIR ROCKS

Oil and gas reservoir rocks are porous and permeable. They contain interconnected passageways of microscopic pores or holes between the mineral grains of the rock (Fig. 3). When oil and gas are naturally expelled from source rocks, they migrate into adjacent reservoir rocks.

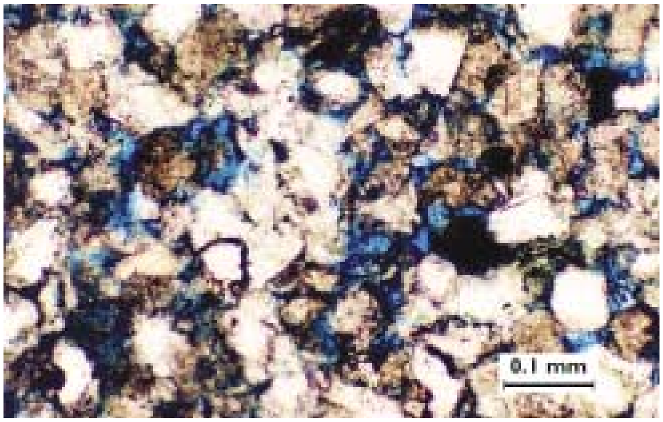


FIGURE 3 Microscopic image of a sandstone reservoir rock. The pore spaces (blue) may be occupied by oil, gas, or water.

Once oil and gas enter the reservoir rock, they are relatively free to move. Most reservoir rocks are initially saturated with saline ground water. Saline ground water has a density of more than 1.0 g/cm^3. Because oil and gas are less dense than the ground water (the density of oil is 0.82–0.93 g/cm^3; the density of natural gas is 0.12 g/cm^3), they rise upward through the water-saturated pore spaces until they meet a barrier of impermeable rock (Fig. 2)—a seal. Seals generally are very fine grained rocks with no pore spaces or pore spaces that are too small to permit the entry of fluids.

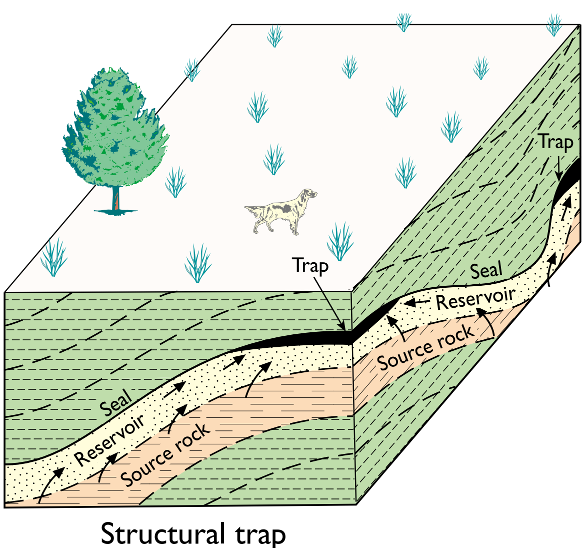


FIGURE 4 Folded strata that form a structural trap.

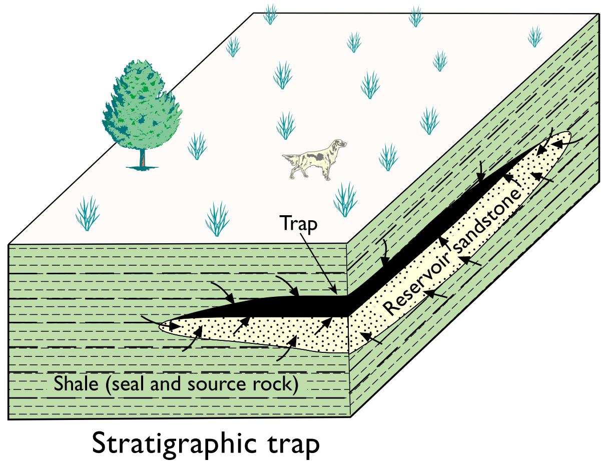


FIGURE 5 A discontinuous layer of sandstone that forms a stratigraphic trap.

OIL AND GAS TRAPS

Once in the reservoir rock, the oil and natural gas continue to migrate through the pore spaces until all further movement is blocked by the physical arrangement of the reservoir rock and one or more seals. This arrangement of the reservoir and seals is called a trap (Fig. 1).

There are two main types of traps: structural and stratigraphic (Figs. 4–5). Structural traps are formed when the reservoir rock and overlying seal are deformed by folding or faulting. Usually this deformation takes place tens of millions of years after deposition of the sediments that serve as seals and reservoir rocks. The oil and gas migrate upward through the reservoir and accumulate in the highest part of the structure (Fig. 4). If both oil and gas are present, the gas will form a layer (within the pore spaces) that rests above a layer of oil, because natural gas is less dense than the oil. The layer of oil will, in turn, rest upon the water-saturated part of the reservoir.

Stratigraphic traps (Fig. 5) are formed when the reservoir rock is deposited as a discontinuous layer. Seals are deposited beside and on top of the reservoir. A common example of this type of trap, of which there are many examples in the San Juan Basin, is a coastal barrier island, formed of an elongate lens of

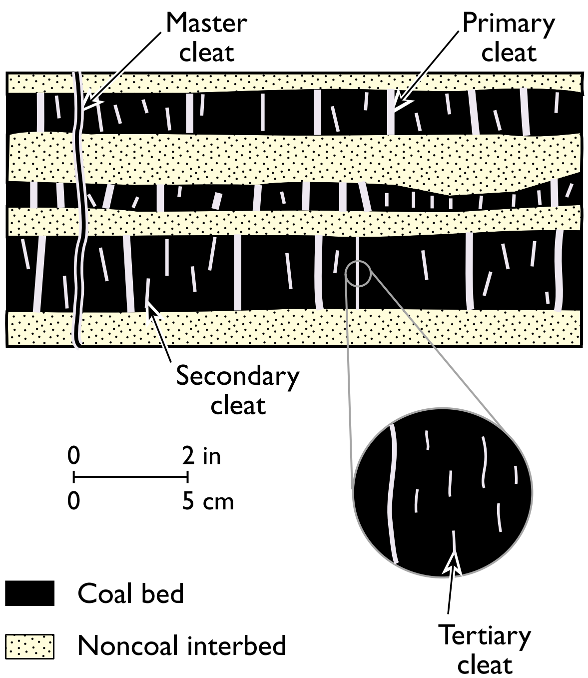


FIGURE 6 Diagram of vertical slice through coal reservoirs, showing vertical distribution of cleats (fractures) in the coal. From New Mexico Bureau of Geology and Mineral Resources, Bulletin 146.

sandstone. Impermeable shales that later serve as seals are deposited both landward and seaward of the barrier island. The result is a porous sandstone reservoir surrounded by shale seals. These same shales may also be source rocks.

COALBED METHANE

Coal can act as both a source rock of natural gas and a reservoir rock. When this is the case, coalbed methane ("coal gas") can be produced. The gas is generated from the woody organic matter that forms the coals. At shallow burial depths, relatively low volumes of gas may be generated by bacterial processes within the coals. At greater burial depths, where temperatures are higher, gas is generated thermally (as in conventional source rocks described above). Greater volumes of gas are generally formed by the thermal processes than by the bacterial processes. In the San Juan Basin gas has been formed through both processes.

Most coals are characterized by pervasive networks of natural fractures (Fig. 6). In the deep subsurface, these fractures are filled with water. The pressure exerted by this water holds the gas within the coal. In order to produce gas from the coal, first the water must be pumped out of the fractures. Once this is done, then the gas moves into the fractures, from where it may then be retrieved. The water that is first produced must be disposed of in a way that complies with existing regulations (see paper by Olson, this volume).

SUMMARY

Oil and natural gas are generated from the remains of organisms deposited in fine-grained sedimentary rocks along with the mineral grains that make up those rocks. As these source rocks are buried by overlying sediments, the organic matter is converted to oil and natural gas, first through bacterial processes and later by high temperatures associated with burial to a depth of several thousand feet. The oil and gas are then expelled from the source rocks into adjacent porous reservoir rocks. Because the oil and gas are less dense than the water that saturates the pores of the reservoir rocks, they rise upward through the pore system until they encounter impermeable rocks. At this point, the oil and gas accumulate, and an oil or gas field is formed.

The "Nuts and Bolts" of New Mexico's Oil and Gas Industry

Brian S. Brister, *New Mexico Bureau of Geology and Mineral Resources*

Since the early 1920s New Mexicans have enjoyed the benefits of a thriving petroleum (oil and natural gas) industry that today provides thousands of jobs and hundreds of millions of dollars in state revenues. However, relatively few citizens of the state have a basic understanding of, or appreciation for, the basic elements of petroleum production, processing, transportation, and distribution systems required for a viable industry. The "nuts and bolts" referred to here are the infrastructure and processes required for the industry to accomplish its job of delivering an end product to the consumer market. It is important to understand that all of the components of the production-through-distribution cycle are necessary in order for the industry to function and provide the fuels and products upon which we rely.

Petroleum industry infrastructure varies significantly depending upon the raw materials produced and the needs of the end user. Production in the San Juan Basin is dominated by natural gas, although crude oil is also produced. Production in the Permian Basin of southeastern New Mexico is dominated by crude oil, but natural gas production is also significant (see paper by Laird Graeser in this volume). End consumers are found all over the Southwest, with California being an important market, particularly for natural gas. This article will focus on infrastructure in the San Juan Basin, but common to the "oil patch" in general.

WHAT ARE OIL AND NATURAL GAS?

Natural gas and crude oil naturally reside in underground reservoirs. Crude oil, typically liquid at surface temperature and pressure, is a complex mix of hydrocarbon molecules (molecules that contain hydrogen and carbon) and non-hydrocarbon molecules. Crude oil in the reservoir often contains light hydrocarbons in solution that bubble out of the oil as natural gas at the surface (sometimes called "casinghead gas"). San Juan Basin oil reservoirs tend to have a significant amount of associated gas. In fact, today the gas from these wells is more volumetrically and economically significant than the oil. Oil-producing reservoirs in the San Juan Basin are limited to the flanks of the basin, whereas basin-center reservoirs are gas productive. Both crude oil and natural gas must be refined to yield the varied fuels and petrochemicals that we consume.

Gas in its natural state is somewhat different from the natural gas we consume, and it may or may not be associated with oil. As produced at the wellhead, natural gas is a mixture of light hydrocarbons including methane, ethane, propane, and butane. It also may contain variable amounts of nitrogen, carbon dioxide, hydrogen sulfide, and perhaps traces of other gases like helium. Condensate (a.k.a. "drip gas") is a light oil byproduct of cooling natural gas as it rises to the surface in the well. More than half of the natural gas produced in the San Juan Basin is from coalbed methane (CBM). CBM is a simpler mix of methane and carbon dioxide. Gas that is transported in major interstate pipelines and sold as burner-tip fuel for heating is almost all methane, with a heating value of 1,000 BTU per mmcf, where BTU stands for British Thermal Units and mmcf stands for million cubic feet of gas. This "standard" gas is what we rely upon as consumers. In order to produce standard gas, non-methane hydrocarbons (that increase BTU value), and non-hydrocarbons (that decrease BTU value) must be removed from the gas stream.

UPSTREAM AND DOWNSTREAM

The terms "upstream" and "downstream" are often heard, but what do they mean? Upstream operations are those that involve extracting crude oil or natural gas from a natural underground reservoir and delivering it to a point near the well site, such as an oil tank or gas meter. From here it is sold by independent producers to refiners or pipeline companies who may or may not be the ultimate marketers of the product. Downstream operations are those that include gathering, transporting, and processing of the oil or natural gas and distributing the final products, including standard natural gas and refined products like gasoline. A variety of processes and equipment are required in the upstream and downstream industries. Each step of the production-to-distribution cycle tends to create added value and employs skilled workers in well-paying New Mexico-based jobs.

UPSTREAM INFRASTRUCTURE

Although many companies continue to explore for new reservoirs, New Mexico is generally considered to be a "mature" petroleum province, in that a large number of reservoirs have been found and developed to full production potential. For this reason, there is extensive upstream infrastructure in the producing New Mexico counties. At one time these producing fields were the assets of major integrated oil companies, but today these fields have been largely divested to smaller independent producers, many of whom are headquartered here in New Mexico. Associated with these fields are the easily recognized pumpjacks and tank batteries (row of tanks) that dot our landscape. But there is more there than meets the eye. Figure 1 illustrates typical upstream equipment associated with individual or small clusters of wells.

Below the surface of the ground at each well, there are miles of steel alloy well casing designed to withstand the heat and pressure encountered in the underground environment, carefully treated to withstand a corrosive environment and remain functional through the predicted life of the field. Two or more casing strings are installed in each well, cemented into the drill hole in order to prevent contamination of fresh water and mixing of fluids between porous formations. Within the production casing is a string of production tubing, which conveys reservoir fluids to the surface. Where gas is produced, the gas flows under its own pressure up the tubing. In wells where liquids are produced, a downhole pump, driven by the pumpjack at the surface alternately raising and lowering a single string of interconnected solid rods, acts as a plunger to lift the liquid to the surface.

At the surface the wellhead caps the casing and tubing and directs the produced fluids toward temporary storage. Wellheads on gas wells, commonly called "Christmas trees," typically stand tall in order to provide

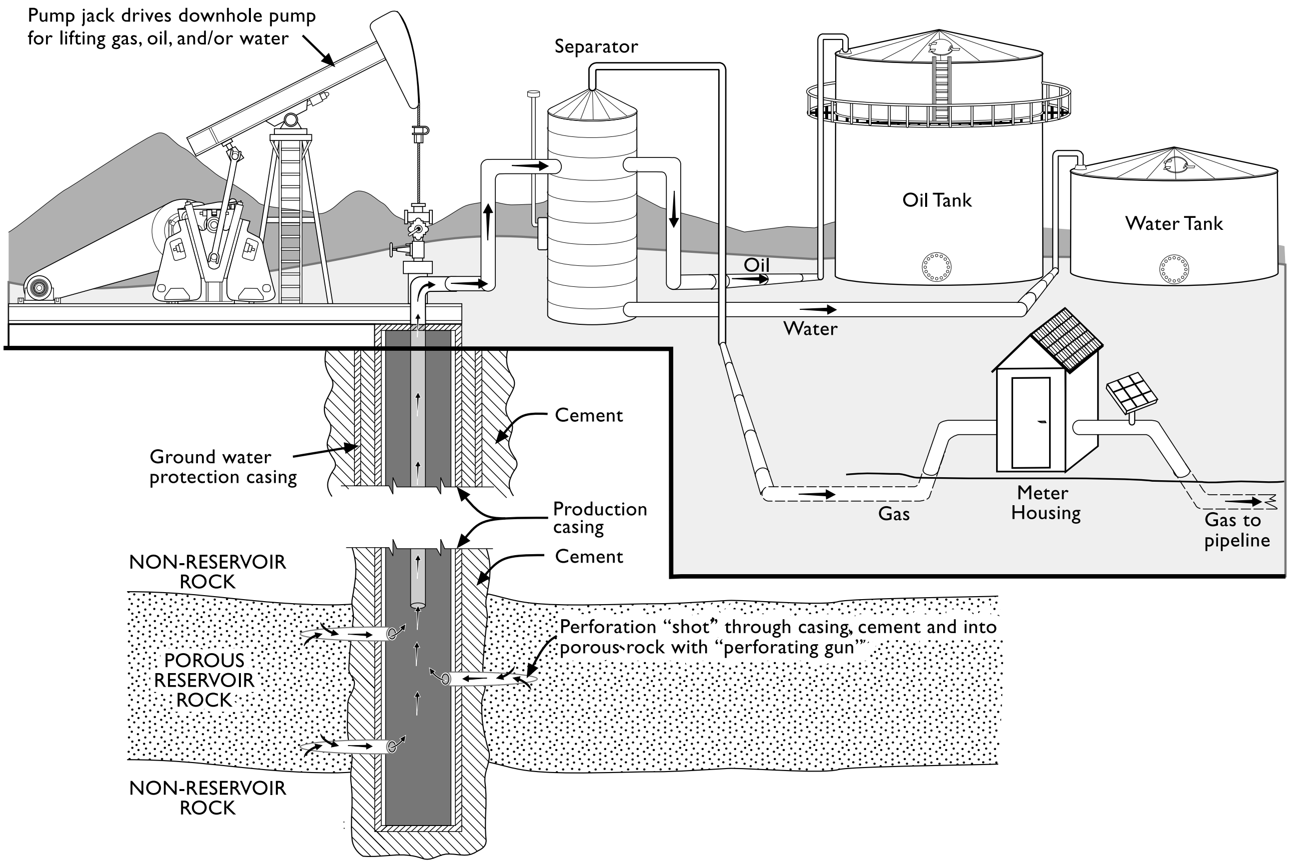


FIGURE 1 Upstream infrastructure of oil and natural gas production.

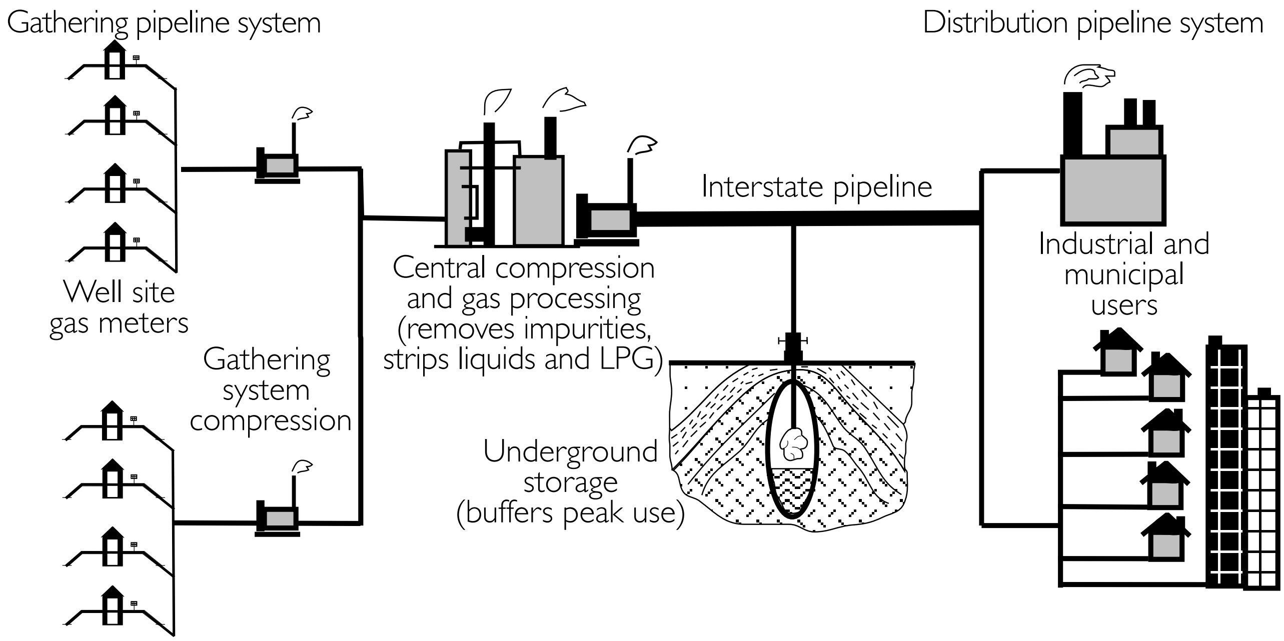


FIGURE 2 Downstream natural gas infrastructure.

working room for servicing the high-pressured well. After leaving the wellhead, the fluids will go to a separator in order to separate gas from oil and/or water that is sometimes produced from the well with the gas. Once separated, the oil flows to an above-ground storage tank, the water flows to a water tank, and gas flows through a meter and into a pipeline. If water is produced, there may be equipment nearby to pump it back into the reservoir to maintain reservoir pressure or the water may be trucked or piped to an approved subsurface-disposal facility.

DOWNSTREAM INFRASTRUCTURE

Downstream infrastructure includes a complex network of transportation, processing and refining, storage, delivery, and sales networks that span the continent.

In the San Juan Basin, oil is typically collected at or near the well site from the tank battery and trucked to a pipeline terminal, although some 20% is trucked directly to the refinery. Some larger fields may deliver oil directly to a pipeline. Either way, much of the crude oil arrives at a refinery (for example, the Giant Industries, Inc. Bloomfield refinery) via pipeline where it is then temporarily stored in above-ground tanks in a tank farm. The largest tanks may hold several million gallons.

The refinery processes the oil to create familiar end products such as gasoline, diesel, jet fuel, kerosene, lubricating oil, asphalt, and petrochemical feedstocks. Processes such as distillation and catalysis essentially “crack” the complex and heavy hydrocarbon molecules in the oil to create the various products. The reforming process creates desirable molecules following cracking, generally to increase octane of the gasoline fraction. Unwanted parts of the crude oil, such as sulfur, are removed in the scrubbing process.

The primary product of most refineries is transportation fuel, which is stored at the refinery tank farm awaiting shipment via product pipeline or truck transport to tank farms at distribution terminals near larger cities. These terminals are the hub for truck transportation to retail outlets.

Due to the low dollar value per volume of natural gas, trucking is not a viable option for transporting it; it must therefore be transported by pipeline. The processes and related infrastructure for gas production can be summarized in key components shown in Figure 2. Gas is compressible; as it is stuffed into a smaller space, its pressure rises. On the other hand, as pressure is reduced, it expands. This useful property provides the mechanism for gas to flow from one point to another (from high to low pressure) through the pipeline system. San Juan Basin gas wells produce relatively low-pressure gas that must undergo several stages of compression (pressure increase) upon leaving the well site gas meter. A gathering system of pipelines transports the gas to a central hub, where the gas is compressed before entering the next pipeline stage.

At strategic points along the pipeline system, but generally before it enters an interstate pipeline, the gas is processed at a gas plant (such as the Williams Field Services gas plant at Lybrook, New Mexico) to separate certain natural components from the standard quality "residue" gas desirable for interstate transport and distribution. The chemical characteristics of the gas produced at the well determine the processing that will take place. For example, if the natural gas is relatively high in carbon dioxide, as is typical for coalbed methane, an extraction facility uses an exothermic (heating) chemical reaction to extract the offending component. In this example, not only is the BTU value of the gas upgraded, but a corrosive component is removed, thus protecting the integrity of the interstate pipeline. Natural gas produced from conventional (non-coalbed methane) reservoirs tends to be rich in ethane, butane, and propane. These hydrocarbons are extracted through a cryogenic (cooling) process. Butane and propane are the components of LPG or liquefied petroleum gas (which stays liquid while pressurized) used as a natural gas substitute in areas not served by the natural gas pipeline system.

Once standard natural gas enters the interstate transportation pipeline system, it may move through several hubs. Along the way, gas may be temporarily stored at strategic places in underground salt caverns or old gas fields in order to meet seasons of peak demand. Gas is eventually delivered to a utility, which then delivers the gas through a distribution pipeline network to the consumer. Typically, natural gas changes ownership multiple times along the gathering, transportation, and distribution system.

WHAT DOES THE FUTURE HOLD?

The role of new and evolving technologies should never be discounted. We are ever more creative in improving the efficiency of our fossil fuel energy infrastructure. Such efficiencies are designed to extract more value from the raw material. Automation, safety improvements, and improved environmental compliance are on the forefront of engineering research. In the future the uses of oil and natural gas will likely change. A new trend is the increasing use of low-emission natural gas turbines to generate electricity during peak demand. Natural gas-based fuel cells powering portable electric motors may one day replace the gasoline-fueled internal combustion engine as the transportation engine of choice. Future improvements in processes and minimization of environmental impacts will ensure that New Mexico's home-grown oil and gas industry will continue to provide responsibly for the needs of New Mexico and the Southwest for many decades to come.

The Oil and Gas Industry in New Mexico—An Economic Perspective

Laird Graeser, *Independent Tax Consultant*

It has been said, "if you live in New Mexico, you're in the oil and gas business." This "old saw" has traditionally been undeniably true, and is, to this day, more true than generally held. The "oil patch" extends over four counties in the northwest part of the state, four counties in the southeast, and portions of four other counties elsewhere in the state (Fig. 1). The impacts of the industry on air and water quality, the environment, state and local revenues, and the overall state economy are pervasive. The values of crude oil and natural gas production are strongly linked to state-wide employment and the gross state product. Direct and indirect links simultaneously can be demonstrated with respect to state and local revenues – primarily gross receipts tax revenue. However, the purpose of this paper is to present a survey, not a detailed econometric analysis of these linkages.

PRODUCTION VOLUMES AND VALUES

San Juan Basin (northwest NM)	Permian Basin (southeast NM)	Other
McKinley (gas & oil)	Chaves (gas & oil)	Colfax (gas)
San Juan (gas & oil)	Eddy (gas & oil)	Harding (CO_2)
Sandoval (gas & oil)	Lea (gas & oil)	Quay (CO_2)
Rio Arriba (gas & oil)	Roosevelt (gas & oil)	Union (CO_2)

FIGURE 1 The oil patch in New Mexico (by county).

Note that over a long period of time, there does not appear to be a predictable relationship between gas price and gas volume (Fig. 2a). The lagging price change ten years after changes in volume is clearly spurious and not causal. On the other hand, plotting gas value (volume times price) in logarithmic terms shows that gas price drives the total value of gas, as should be expected (Fig. 2b). The other thing to note is that this strong link between gas value and gas price changed dramatically in 1972, at the time of the first oil embargo. At that time, strong increases in gas price were accompanied by decreases in gas volume, with corresponding modest increases in total value. Earlier—before about 1955—small changes in gas price caused a relatively strong change in gas value. The production response for the San Juan and Permian Basins is revealing (Fig.3). It is apparent that the production response in the San Juan—with its current emphasis on the exploration and production of coal seam gas—is very different than in the Permian. In neither basin, however, is the production response clearly dependent on price.

A similar interpretation can be posited for crude oil production and volume. Before the first oil embargo of 1972–73, oil volumes were moderately responsive to changes in oil price (Fig. 4). After a decade-long re-equilibration, oil volumes from the early 1980s to the present became quite responsive to price changes.

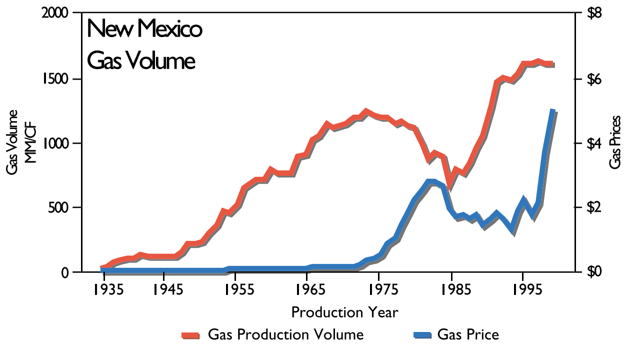


FIGURE 2A New Mexico gas production volume and gas price over time.

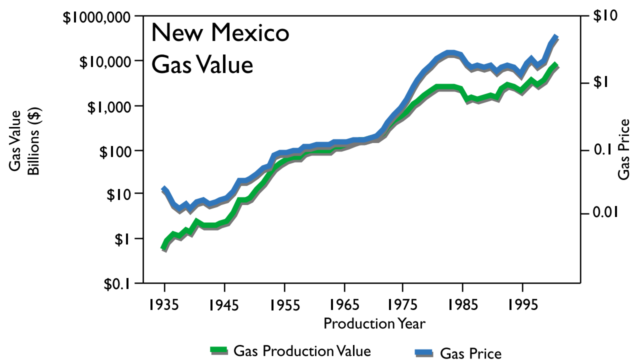


FIGURE 2B New Mexico gas production value and gas price over time.

STATE AND LOCAL TAX REVENUE

Energy in its various forms—crude oil, refined gasoline, natural gas, and electricity—has been a disproportionate candidate for taxation. Currently, there are six taxes imposed directly on oil and gas extraction and processing (Fig. 5):

1 Oil and Gas Severance Tax
2 Conservation (and Reclamation) Tax
3 Emergency School Tax
4 Oil and Gas Ad Valorem Production Tax
5 Natural Gas Processors Tax
6 Oil and Gas Ad Valorem Equipment Tax

Unfortunately, because of the complexity of deductions and rates, it is difficult to determine an effective tax rate on sales or production value without a great deal of work and assumptions about price. Some of the taxes historically have been specific excises, based on volume, not value. Other taxes are based on sales value, but these allow significant deductions from sales value to determine production (wellhead) value. The two ad valorem property taxes have a complicated rate structure dependent upon location of production. Further complicating the calculation is the recent proliferation of contingent tax rates and economic development incentives expressed in rates and base. The details of the taxes are discussed below.

In addition to the taxes enumerated here, oil and gas well servicing and well drilling are considered construction services and subject to the gross receipts tax. In addition, multi-state and multinational corporations produce and market most of New Mexico's oil and gas. These corporations pay corporate income tax to New Mexico on apportioned net profit.

1 OIL AND GAS SEVERANCE TAX

A severance tax is imposed on all oil, natural gas or liquid hydrocarbons, and on carbon dioxide severed from the ground and sold. The tax is based on sales value. The tax rate is 3.75% of the sales price at or near the wellhead on oil, carbon dioxide, other liquid hydrocarbons, and natural gas. An "enhanced oil recovery" tax rate of 1.875% is applied to oil produced from new wells using qualified enhanced-recovery methods. Before January 1, 1994, only carbon dioxide projects qualified. Thereafter any secondary or tertiary method could be used. The lower rate applies to production for the first five or seven years after bringing the enhanced project into production.

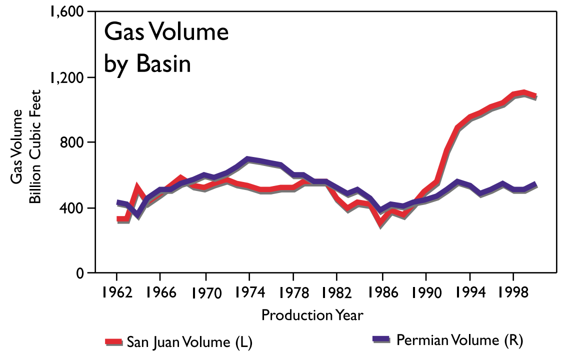


FIGURE 3 New Mexico gas production by basin.

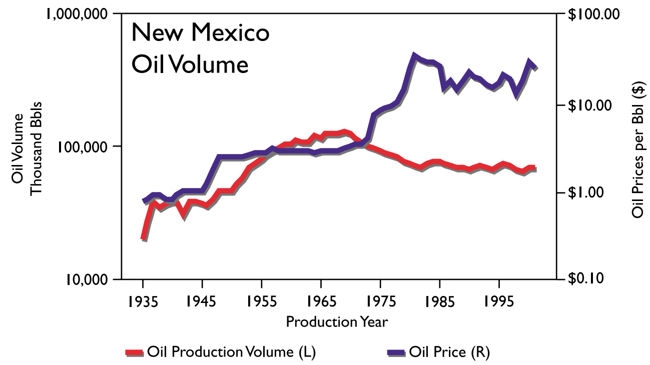


FIGURE 4A New Mexico oil production value and oil price over time.

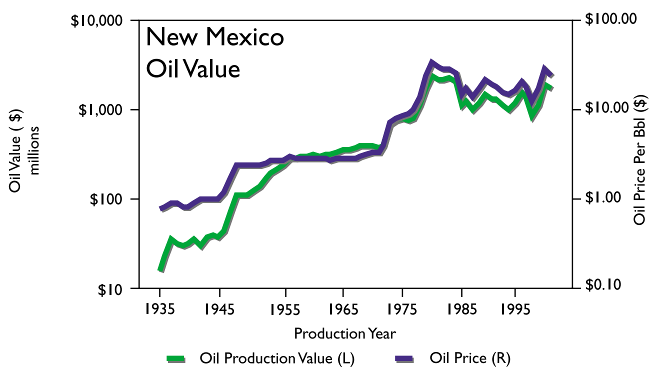


FIGURE 4B New Mexico oil production value and oil price over time.

In 1995 a 50% credit was authorized for projects approved by the Oil Conservation Division that restore non-producing wells to production, or that increase the production from currently producing wells. Originally, qualification for the credit required a well to have been shut in for a specific two-year period. In 1999 the credit was extended to any well shut in for a period of two years beginning on or after 1/1/93.

In 1995 an "intergovernmental oil and gas tax credit" was enacted to ameliorate dual taxation of oil and gas production on Indian lands. The credit is against state production taxes for taxes paid to Indian tribes on production from new wells drilled on Indian land after June 30, 1995. The credit amount is the smaller of 75% of the Indian production taxes or 75% of the state production tax.

In 1999 several severance tax incentives were provided to oil and gas producers hard hit by a severe oil price slump. The Marginal Wells Conditional Tax Reduction provides either a 50% or a 25% reduction in both oil and gas severance tax and oil and gas emergency school tax to stripper wells when prices are low. Stripper wells are oil wells that have been certified by the Oil Conservation Division to have produced less than 10 barrels per day in the previous calendar year and natural gas wells certified to have produced less than 60 mcf per day in the previous calendar year.

Special price-contingent oil and gas severance tax rates were also enacted in 1999. When prices are at or below $15 per barrel for oil or $1.15 per mcf of natural gas, the oil and gas severance tax rate is 1.875%. A 2.8125% rate applies when prices are more than $15 but not more than $18 per barrel for oil or more than $1.15 but not more than $1.35 per mcf for natural gas.

The severance tax is distributed to the state severance tax bonding fund, with any excess after meeting severance tax bonding fund obligations being distributed to the severance tax permanent fund.

2 OIL AND GAS CONSERVATION TAX

A conservation tax is levied on the sale of all oil, natural gas, liquid hydrocarbons, carbon dioxide, uranium, coal, and geothermal energy severed from the soil of the state. The measure of the tax is 0.18% or 0.19% of the taxable value of products (sales price less deductions for state, federal, and Indian royalties), depending on the balance in the oil and gas reclamation fund. If the balance in that fund is over $1 million, the lower rate goes into effect. Tax is due on the 25th day of the second month after the close of the month in which the taxable event took place. Since July 1991 a monthly advance payment of conservation tax has been required from high-volume producers. Proceeds from the tax are distributed to the state general fund and the oil and gas reclamation fund.

Fiscal year	1996	1997	1998	1999	2000	2001 est.
OIL:						
Volume (million Bbls)	74.69	74.05	72.43	66.32	67.72	71.04
Value ($)	$1,338.30	$1,571.30	$1,148.20	$832.40	$1,648.30	$1,390.70
Derived price ($/Bbl)	$17.92	$21.22	$15.85	$12.55	$24.34	$19.58
NATURAL GAS:						
Volume (Bcf)	1,506	1,575	1,619	1,606	1,628	1,623
Value ($)	$2,133	$3,350	$3,349	$2,737	$4,142	$6,255
Derived price ($/mcf)	$1.42	$2.13	$2.07	$1.70	$2.54	$3.85
TAX COLLECTIONS (in million $):						
Oil & gas:						
O & g severance tax	$105.91	$153.34	$152.15	$106.36	$165.13	$315.58
Conservation tax (o & g only)	$5.05	$7.47	$8.04	$5.44	$8.68	$16.46
Emergency school tax	$102.22	$151.36	$153.68	$107.85	$169.51	$329.03
Ad valorem:						
O & G production tax	$1.79	$3.04	$2.83	$2.01	$3.41	$6.54
General obligation bond fund						
County treasurers	$26.25	$39.40	$38.55	$27.62	$45.52	$83.82
Natural gas processors tax	$24.57	$13.89	$12.84	$11.28	$12.26	$12.11
O & g equipment tax						
General obligation bond fund	$0.38	$0.41	$0.51	$0.60	$0.46	$0.58
County treasurers	$5.50	$5.00	$7.20	$8.02	$6.09	$7.26

FIGURE 5 Oil and gas tax collections. Source: Taxation and Revenue Department records provided by Tax Research and Statistics Office.

3 OIL AND GAS EMERGENCY SCHOOL TAX

An emergency school tax is imposed for the privilege of engaging in the business of severing oil, natural gas or liquid hydrocarbons, and carbon dioxide from New Mexico soil. A 3.15% rate is imposed on the net taxable value of the products listed, with the exception of natural gas, which is taxed at 4%. Net taxable value is defined as the actual price received for products at the production unit, less federal, state, or Indian royalties and the cost of transporting oil or gas to the first place of market. Tax payments are due on the 25th day of the second month after the close of the month in which the taxable event took place. A monthly advance payment equal to the average monthly payment made in the previous year is required from high-volume producers. The school tax is distributed to the state general fund each month.

In 1999 a non-refundable one-time drilling credit of $15,000 was made available for the first 600 new crude oil or natural gas wells drilled between January 1, 1999, and June 30, 2000. The Marginal Wells Conditional Tax Reduction, also enacted in 1999, provides either a 50% or a 25% reduction in both oil and gas severance tax and oil and gas emergency school tax to stripper wells when prices are low.

Special price-contingent oil and gas emergency school tax rates were enacted in 1999. When prices are at or below $15 per barrel for oil or $1.15 per mcf of natural gas, oil and gas emergency school tax rates are 1.58% and 2%, respectively. When prices are more than $15 but not more than $18 per barrel for oil or more than $1.15 but not more than $1.35 per mcf for natural gas, oil and gas emergency school tax rates are 2.36% and 3%, respectively.

4 OIL AND GAS AD VALOREM PRODUCTION TAX

An ad valorem tax is levied monthly on the sale of all oil, natural gas, liquid hydrocarbons, and carbon dioxide severed from the soil of the state. The ad valorem tax is based on the assessed value of products. The tax rate is the property tax rate for the taxing district in which products are severed. This rate changes annually, effective each September 1. Assessed value is equivalent to 50% of market value less royalties. The tax is due on the 25th day of the second month after the close of the month in which the taxable event took place. A monthly advance payment of ad valorem tax is required from high-volume producers. The ad valorem tax is distributed monthly to the applicable property tax beneficiaries, primarily counties and school districts.

5 NATURAL GAS PROCESSOR'S TAX

A natural gas processor's privilege tax is levied on processors based on the value of products processed. Before July 1, 1998, the tax rate was 0.45% of the value of the products processed. In 1998 landmark legislation, the tax was totally revamped, with tax imposition being shifted entirely to the processing plants. Tax is measured by the heating content of natural gas at the plant's inlet, measured in million British Thermal Units (mmbtu). The rate is set initially at $.0065 per mmbtu but will be adjusted every July 1. The adjustment factor is equal to the average value of natural gas produced in New Mexico the preceding calendar year divided by $1.33. The rate starting January 1, 1999, will be similarly adjusted. New deductions are added for gas legally flared or lost through plant malfunction. Deductions for the value of products sold to any federal or New Mexico governmental unit or any non-profit hospital, religious, or charitable organization when such products are used in the conduct of their regular functions were repealed.

The natural gas processor's tax is due within 25 days following the end of each calendar month in which sales occurred. A monthly advance payment of processor's tax is required from high-volume producers. Revenue is distributed to the state general fund.

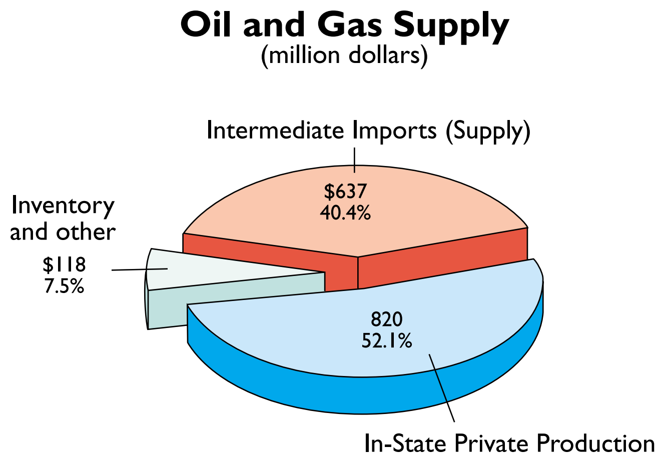
6 OIL AND GAS AD VALOREM EQUIPMENT TAX

An ad valorem tax is levied annually on assessed value of equipment used at each production unit. Assessed value is equivalent to 9% of the previous calendar year sales value of the product of each production unit. The tax rate is the certified property tax rate for the taxing district in which products are severed.

The Taxation and Revenue Department is required to prepare a tax statement on or before October 15. Payment is due on November 30. The production equipment tax is distributed to property tax beneficiaries, primarily counties and school districts.

IMPACT OF OIL AND GAS PRODUCTION ON THE STATE'S ECONOMY

Roughly 6% of New Mexico's Gross State Product (GSP) is attributable to production of oil and gas in the state. Oil and gas production contributes an unusually large amount to Gross State Product with a minimal contribution to value added from wages and salaries (and proprietorship profit). For the average industry, 39% of production value is used to pay



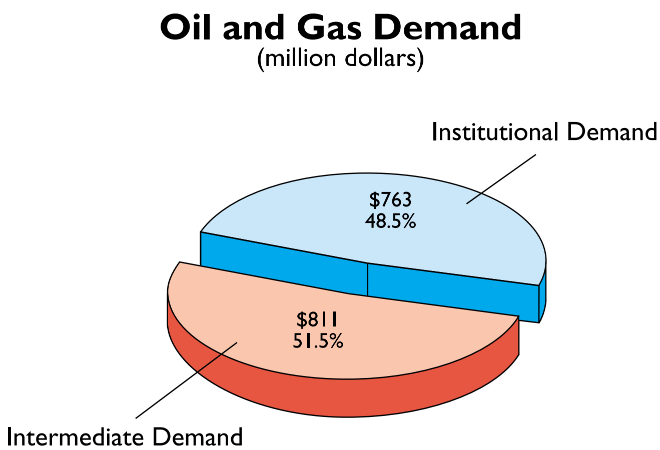


FIGURE 6 New Mexico oil and gas supply and demand.

salaries and 65% of GSP value added is contributed by wages and salaries paid. For oil and gas production, these percentages are about 18% and 25%. This is certainly not unexpected for primary mineral production, but is interesting nonetheless. The computer equipment industry also is heavily capital intensive, with a ratio of about 17% of production value devoted to wages and salaries, but 50% of contribution to GSP. Apparently, most of the value of computer equipment is retained as implicit or explicit return to capital. The other important export industry in New Mexico is agriculture and other mining. This is also capital intensive with 26% of production and 54% of contribution to GSP in the form of wages and salaries.

Oil and gas production is sold in the state for manufacturing purposes and sold outside the state for energy and subsequent manufacturing. Figure 6 shows imports, exports and supply-demand balance for oil and gas production. The institutional demand is primarily exports to surrounding states for process and manufacturing uses.

IMPACT ON REVENUES OF OIL AND GAS PRODUCTION

The life of a revenue estimator for the New Mexico state government is interesting. The old Chinese curse says, “may you live in interesting times.” This curse is the motto for trying to predict the flow of revenue from the oil and gas industry. During the gas price bubble which lasted throughout fiscal year 2000, gas prices paid to New Mexico’s producers exceeded $5 per mcf. Because the General Fund’s sensitivity to an increase in gas price is over $10 million per $0.10 change in gas price, these unexpected prices led to soaring revenue collections. Just as abruptly, prices collapsed as California learned how to adapt to a new energy delivery and price regime. Revenue estimates were revised up and down by over $100 million over the period from first estimates to final collections. Severance taxes have had a variable history in the General Fund. Figure 7 illustrates a modest variation. However, this is only a part of the true impact of oil and gas severance over time. First and foremost, a substantial portion of oil and gas have been produced from state and federal lands in New Mexico. Fifty percent of the royalties and bonus payments from production on federal lands accrue directly to the state general fund. For production on state-owned lands, producers pay royalties in addition to the various severance taxes. These royalties add to the corpus of the land grant permanent fund. The corpus generates income (primarily as interest on corporate bonds). This interest does accrue to the General Fund. For a more complete picture of the importance of oil and gas severance to the state general fund, then, we must sum direct General Fund severance taxes, rents and royalties, and interest paid. Figure 8 exhibits both the direct impact and the total impact measured by the total General Fund. This impact peaked in the “Big Mac” era (1981–82) at 47% of the General Fund. The current level (before the expansion of direct severance revenues during 1999–2000 and 2000–2001) is about 23%. This is money that the state’s resident taxpayers do not have to pay for critical government services.

SUMMARY AND CONCLUSION

By any measure, the oil and gas extraction industry has been and continues to be an important source of revenues to state and local governments; an important source of employment, although for a declining number of workers; and a generator of production value

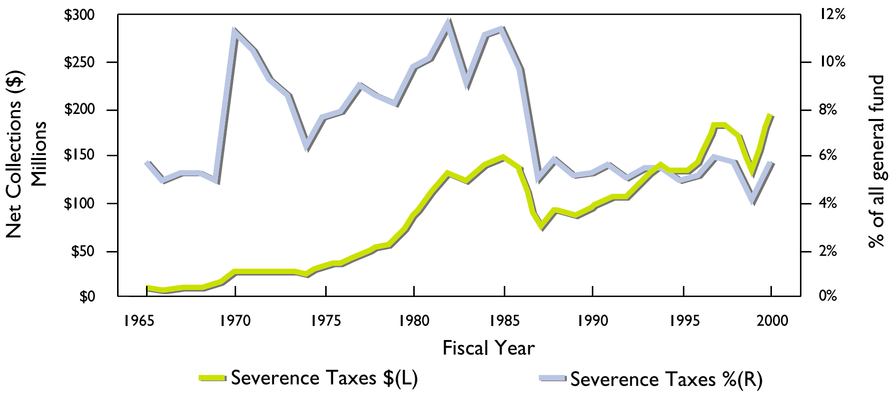


FIGURE 7 General Fund Revenues—severance taxes by amount and percent of all general fund revenues.

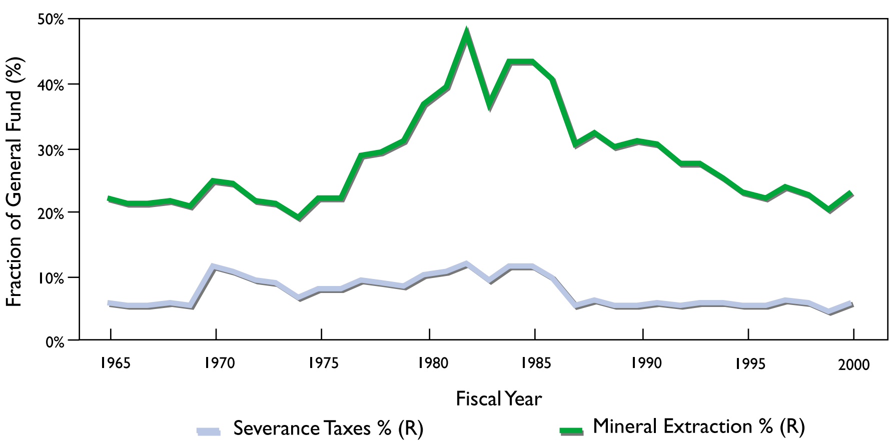


FIGURE 8 General Fund Revenues—severance taxes, rents and royalties, interest by amount and percent of all general fund revenues.

helping to sustain New Mexico's economy. There continues to be a great deal of validity to the phrase that opened this paper, "if you live in New Mexico, you're in the oil and gas business." The industry is still pretty healthy and will continue to prosper, no matter what the energy future of the United States. Under a balkanized model of energy deregulation, each of the western states will license a number of high-efficiency natural gas turbines. The operators of these new generating plants will buy all the natural gas the state can produce. New fields are ready to come on line and produce for years to come. Under an energy-province model of energy deregulation, power will be produced in New Mexico with a combination of improved coal burning, base load generating plants and peak load gas turbine plants located close to the source of natural gas. With either variant, New Mexico's place in the energy production future of the western United States is assured. However, state policymakers must constantly check that tax, environmental, and employment laws and regulations to not unduly dampen the apparently bright future for the state.

A number of sources of information have been tapped for this report. In some cases, the data are old and at least partially defective. At minimum, the state should invest whatever money is required to have access to the best, most timely, and accurate data and analysis available. New Mexico's energy future is not so certain that the state can afford to take its eye off the ball.

Environmental Regulation of the Oil and Gas Industry in New Mexico

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The Oil Conservation Division (OCD) is the only state regulatory agency other than the New Mexico Environment Department (NMED) that administers several wide-ranging water quality protection programs. Some of these programs were developed and remain separate from the state's Water Quality Act, which, until the advent of various federal programs, controlled other discharges to ground water. Among the discharges regulated by OCD are surface and underground disposal of water and wastes produced concurrently with oil, natural gas, and carbon dioxide; waste drilling fluids and muds; and wastes at crude oil recovery facilities, oil field service companies, refineries, and natural gas plants and compressor stations. Many of these activities are regulated under the New Mexico Oil and Gas Act, which authorizes the OCD to set requirements for proper drilling, completion, plugging, and abandonment of wells. Additional authority is granted OCD under the New Mexico Geothermal Resources Act, and under administrative delegation as a constituent agency of the Water Quality Control Commission under the New Mexico Water Quality Act. Below is a summary of the impact of these legislative acts.

OIL AND GAS ACT

When the New Mexico Oil and Gas Act created the Oil Conservation Commission in 1935, it authorized rulemaking for prevention of waste and to protect correlative rights, but it did not specifically address freshwater protection. However, the original act did require that dry or abandoned wells be plugged in such a way as to confine fluids to their existing zones. Under these and other provisions of the statute, the OCD adopted rules regarding drilling, casing, cementing, and abandonment of wells. These activities by themselves provide some freshwater protection.

In 1961 the Oil and Gas Act was amended to allow the OCD to make rules protecting freshwater from the disposal of drilling and production waters. Under the 1961 amendments, the state engineer designates which water is to be protected. Currently, protection is afforded all surface and groundwater having 10,000 mg/l or less total dissolved solids (TDS), and all surface water having over 10,000 mg/l TDS that impacts protectable ground water.

Under the Oil and Gas Act, statewide regulations can be adopted after notice and hearing. Rules specific to a particular practice, operator, or geographic area may also be issued as the OCD orders. When an order is approved for a specific operator, it serves as a permit. Using one or the other of these methods, OCD administers requirements for underground injection of produced waters and nonhazardous production fluids, for surface disposal of such fluids, and for disposal of non-recoverable waste oils and sludges from oil production and treating plants.

WATER QUALITY ACT

The New Mexico Water Quality Act provides the statutory authority to OCD for environmental regulation of downstream facilities such as refineries, natural gas plants and compressor stations, crude oil pump stations, and oil field service companies. Discharges to groundwater at these facilities are controlled under Water Quality Control Commission (WQCC) regulations. As a constituent agency of the WQCC, OCD has been delegated authority to administer the regulations at these facilities and at geothermal operations. State water quality regulations at other non-oil field facilities are administered by the New Mexico Environment Department.

The New Mexico Water Quality Act specifically prohibits the WQCC from exercising concurrent jurisdic-

Act	Number	Year passed	Year amended
New Mexico Water Quality Act	74-6-l through 74-6-17, NMSA 1978	1967	1978
New Mexico Oil and Gas Act	70-2-1 through 70-2-38, NMSA 1978	1935	1978
Geothermal Resources Act	71-5-1 through 71-5-24, NMSA 1978	1975	1978

tion over oil and gas production activities that may cause water pollution and are regulated by the OCD through the Oil and Gas Act. The delegation to OCD of WQCC authority effectively eliminates this conflict, because the same staff administer both sets of regulations, applying whichever is applicable to the regulated facility.

GEOTHERMAL RESOURCES ACT

Regulations adopted under the Geothermal Resources Act (71-5-1 through 71-5-24, NMSA 1978) are similar to those of the Oil and Gas Act. Its provisions control drilling, casing, and cementing of geothermal wells. Production volume of geothermal fluids is also regulated so that the geothermal reservoirs will not be depleted or unfairly appropriated by a particular user. The act and its regulations specify that activities be conducted in a manner such that human health and the environment are afforded maximum reasonable protection, and that disposal of produced waters be in such a manner so as not to constitute a hazard to useable surface or underground waters.

Unlike the Oil and Gas Act, the Geothermal Resource Act has a clause allowing concurrent jurisdiction with other state regulatory agencies. This means that WQCC regulations are also applicable. Again, these responsibilities have been delegated to the OCD; in practice only storage and disposal of geothermal fluids is currently being regulated via discharge permits. Other operational aspects (drilling and production) are covered through permits issued under the Geothermal Resources Act.

IMPLEMENTATION

Environmental activities are implemented by the Oil Conservation Division's Santa Fe office and four district offices. In addition to matters related to oil and gas production, the Santa Fe office staff process, approve, or set hearings on applications for (1) surface disposal or underground injection of salt water, (2) water flooding used in secondary oil recovery or pressure maintenance, and (3) surface treatment and disposal facilities. The above activities, with the exception of surface disposal and waste oil recovery/treating plant applications, are performed by OCD's petroleum engineers. Those exceptions are reviewed by OCD Environmental Bureau staff. OCD Environmental Bureau staff also provide valuable input and guidance in the application process, especially with regard to possible impacts on groundwater from production and underground injection.

The OCD Environmental Bureau, formed in 1984, performs water protection activities not carried out under other OCD programs. These activities include permitting of oil refineries, natural gas plants and compressor stations, oil field service companies, brine production wells, and any other oil field-related discharges to ground water. Bureau staff also perform inspections and sample at these facilities, investigate groundwater contamination, sample groundwater at domestic wells and other locations suspected of having contamination, and supervise groundwater cleanup and remedial actions. The Environmental Bureau coordinates OCD environmental programs and responds to information requests from industry, federal and state agencies, and the public. The Environmental Bureau researches, writes, and proposes additional regulations for freshwater protection to the Oil Conservation Commission, and the bureau prepares and updates guidelines to assist industry in complying with regulatory requirements. The Environmental Bureau performs these activities with a staff of seven: two hydrologists, a petroleum engineer, a chemical engineer, an environmental engineer, and two geologists.

Daily activities performed by OCD district staff provide protection for freshwater from field production activities. All permits to drill, complete, work-over, and plug oil, gas, and injection wells are reviewed and approved by district staff, including a district geologist. The review ensures proper casing and cementing programs. Field inspectors witness required cementing and testing of production and injection wells and respond to complaints of possible rule violations. Field inspectors also collect water samples, supervise cleanup of minor spills and leaks, and provide first response to oil and gas related environmental problems.

ENVIRONMENTAL CONCERNS

The state of New Mexico is heavily dependent on groundwater as a public resource. Approximately 90% of New Mexico's population depends on groundwater aquifers as a source of domestic water. Consequently, the OCD Environmental Bureau has concentrated its efforts on preventing the contamination of freshwater by oil and gas operations, and resolving groundwater contamination that results from oil field practices.

New Mexico's reliance on groundwater makes the enforcement of OCD and WQCC rules and regulations an important activity. The costs to the public for loss of freshwater resources, and to industry for remediation of contaminated groundwater, are large. Whereas the costs to industry for preventative measures are not negligible, they are a fraction of those incurred in the remediation of contaminated groundwater. The OCD currently has discharge permits for more than 350 oil field facilities, 55 of which have active ongoing groundwater remediation projects. Roughly 90% of the cases are the result of disposal practices that are no longer allowed under current rules and regulations, such as the use of unlined pits for waste disposal. The remaining 10% of these cases can be attributed to leaks and spills during oil and gas production operations. Notably, there have been no cases of groundwater contamination from a disposal activity permitted under the discharge permit program.

Most of OCD's efforts are in the area of preventing groundwater contamination, partly because of the cost effectiveness of this prevention and partly because of the need to protect groundwater for future uses. Preventative measures are implemented through the enforcement of regulations and rules requiring discharge plans and permits for oil field production activities, gas plants, compressor stations, refineries, crude oil pump stations, and other major potential contaminant sources. The goal of the permitting system is to work cooperatively with industry to keep groundwater contaminants contained, and to provide for early detection and prompt remediation of leaks and spills.

All injection wells, refineries, oil field disposal facilities, gas plants, and most mainline compressor stations have approved discharge plans or other operational permits. The OCD is also bringing smaller scale potential contamination sources under the discharge permit system, including those at field gas compressor stations, crude oil pump stations, and oil field service companies. Refinery and gas plant permitting is difficult and time consuming, due to the age of several facilities and to documented pre-existing contamination at most operating and abandoned sites. Permitting has been facilitated by coordinating remediation activities with other agencies, and by separating issues of past contamination and associated remedial actions from current groundwater protection disposal requirements within the discharge plan.

Groundwater protection measures are also implemented by review and revision of OCD rules related to disposal of produced water and other oil field wastes, as necessary. The first groundwater protection rules were issued in the early 1960s, when the New Mexico Oil Conservation Commission banned (with some exceptions) disposal of produced water in unlined pits in areas of southeastern New Mexico with protectable fresh waters. Before 1986 no restrictions on direct discharge of oil field-produced water or related wastes existed in the San Juan Basin, due both to the lack of known cases of groundwater contamination, and to the quality of water produced in the basin. Current OCD rules prohibit discharges to unlined pits in areas vulnerable to groundwater contamination in the San Juan Basin.

SUMMARY

The Oil Conservation Division has an ongoing freshwater protection program staffed by persons knowledgeable in several engineering and scientific specialties needed for proper implementation of the program. The division is cognizant of potential contamination due to oil and gas activities, and enforces and revises state rules as necessary to protect this resource. The OCD will continue to review existing disposal practices and regulations over time and propose regulatory modifications to protect the state's groundwater resources. Current and upcoming issues that the OCD is working on include changes in the hydrogen sulfide rules for protection of public health, drafting of rules for on-site waste management, permitting of all production pits, and a study of aging infrastructure.

Proper staffing is always crucial for successful programs, and OCD, like other agencies, has found that the demands for services by industry and the public are sometimes in conflict with budgetary constraints brought on by the general economic situation of the oil and gas industry and of the state. Since it administers many state oil field regulatory programs, OCD is able to tailor and implement these programs in such a way as to provide maximum effectiveness with available staff, and with a minimum of bureaucratic requirements.

Foreseeable Development of San Juan Basin Oil and Gas Reservoirs

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The San Juan Basin is one of the most strategic gas-producing basins in the U.S. because of its annual volume of production and the market it supplies. New Mexico is the third largest natural gas-producing state in the United States. The San Juan Basin contributes approximately 68% of the natural gas produced annually in the state of New Mexico, or 1.048 trillion cubic feet. In addition, 3.2 million barrels of oil have been produced to date from the basin. The value of these commodities in 1999 was $2.46 billion dollars. The primary market is the southwestern U.S. The San Juan Basin is California's largest single source of natural gas. With the sixth largest economy in the world, California looks to natural gas to fuel its growing need for electric power generation.

Natural gas will continue to be a dominant source of energy and income for the state of New Mexico for the foreseeable future. Figure 1 illustrates the total natural gas reserves by state and region as of January 1, 2000. New Mexico has the third highest reserve base of 15.5 trillion cubic feet (Tcf) of gas, of which roughly 80% (12.4 Tcf) is in the San Juan Basin. Reserve revisions in 1999 added 462 billion cubic feet to the state's resource.

San Juan Basin gas- and oil-producing reservoirs are well defined by the 20,000 wells that have been drilled in this basin. The potential for expansion of pool boundaries is limited; therefore the main emphasis in development is infill drilling (increasing the density of wells) in existing gas reservoirs to increase recovery. Infill drilling is necessary in low-permeability reservoirs where the current spacing between wells is insufficient to efficiently drain the reservoir.

HISTORICAL DEVELOPMENT OF OIL AND GAS IN NEW MEXICO

Initial development in the region began in the early 1920s. Early oil discoveries in the Paradox Formation and Dakota Sandstone (Fig. 2) on the western flank of the basin were prolific. Natural gas discoveries in the Farmington Sandstone, the Pictured Cliffs Sandstone, and the Mesaverde Group began in the late 1920s. However, there was little development until the late 1940s and early 1950s, because of the lack of market demand. In the late 1940s the Dakota Sandstone was developed as a "deep" major gas reservoir. In 1951 El Paso Natural Gas Company completed an interstate pipeline supplying gas to California markets and thus spurred rapid development, particularly of the Pictured Cliffs and Mesaverde reservoirs. These plays can be categorized as unconventional, because of their low permeability and corresponding low productivity without stimulation treatments, which increase reservoir productivity by improving fluid flow properties. Stimulation has evolved from early completions where nitroglycerin bombs were dropped into wells, to modern hydraulic fracturing technology.

By the middle to late 1970s, stimulation techniques and market improvements had progressed to such a degree that the New Mexico Oil Conservation Division ruled in favor of infill drilling the Blanco Mesaverde pool (1975) and Basin Dakota pool (1979) to 160-acre per well spacing. This resulted in a slight increase in production (Fig. 3). Weak market demand during the 1980s, however, resulted in no significant development. The erratic production history reflects the repetitive shutting-in of wells during periods of sub-economic gas prices.

The Fruitland Formation coalbed-methane play in 1989 had a significant impact on gas production in the San Juan Basin. The daily production rate doubled to 3 billion cubic feet with the successful completion of Fruitland coal wells (Fig. 3). At the same time, both pipeline capacity and market demand were sufficient to sell this additional gas.

In the last several years, reduced well spacing has been considered economically viable. The Blanco Mesaverde pool was approved in 1998 for 80-acre spacing, and the Basin Dakota pool is currently being pilot tested for feasibility of producing at 80-acre spacing. This will capture additional reserves not available in 160-acre spaced development and will improve deliverability from the pools.

The current production rate from the San Juan Basin is approximately 3.0 billion cubic feet per day. Roughly half of this production comes from the Fruitland coalbed-methane pool. Fruitland production has reached a peak and is beginning to exhibit signs

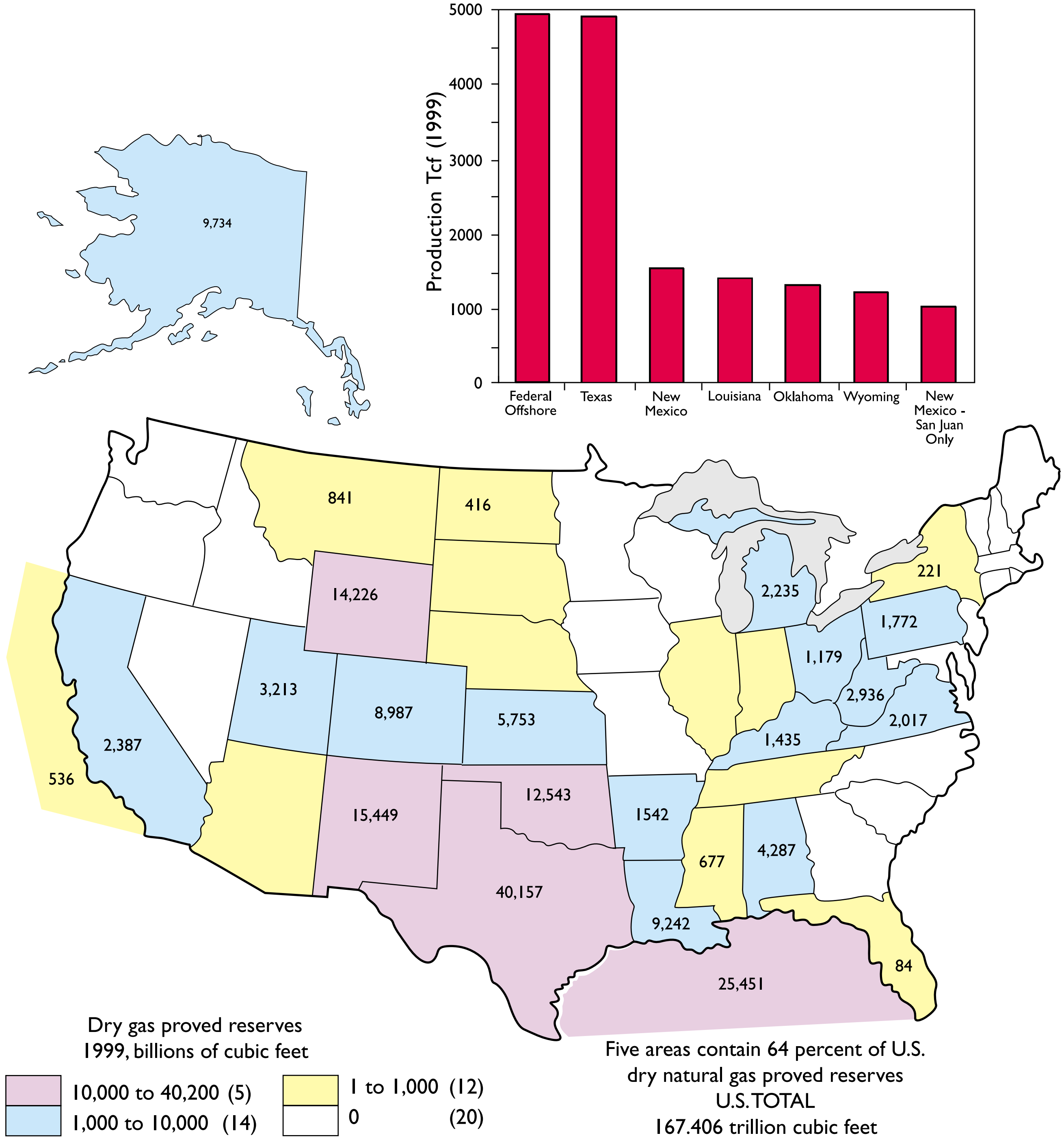

FIGURE 1 Dry gas proved reserves and production by area (1999). Source: EIA, Office of Oil and Gas. Natural gas production by state in trillion cubic feet (1999).

Era	System	Formation	Production	20-year predicted development (no. of wells)
CENOZOIC	TERTIARY	San Jose Formation	Gas	
		Nacimiento Formation	Gas	100
		Ojo Alamo Sandstone	Gas	
MESOZOIC	CRETACEOUS	Kirtland Shale Farmington Sandstone	Gas/oil	0
		Fruitland Formation	Gas	3140
		Pictured Cliffs Sandstone	Gas	1432
		Lewis Shale	Gas	4697
		Mesaverde Group: Cliff House Sandstone	Gas	
		Mesaverde Group: Menefee Formation	Gas	
		Mesaverde Group: Point Lookout Formation	Gas	
		Mancos Shale: Upper Mancos Shale/Tocito Sandstone	Gas/oil	300
		Mancos Shale: Gallup Sandstone/Carlile Shale	Gas/oil	
		Mancos Shale: Greenhorn Limestone		
		Mancos Shale: Graneros Shale		
		Dakota Sandstone	Gas/oil	6846
	JURASSIC	Morrison Formation		
		Wanakah Formation Todilto Limestone		
		Entrada Sandstone	Oil	80
	TRIASSIC	Chinle Formation		
PALEOZOIC	PERMIAN	Cutler Formation		
	PENNSYL-VANIAN	Hermosa Formation: Honaker Trail Formation Paradox Formation Pinkerton Trail Formation	Gas?	20
		Molas Formation		
	MISSIS-SIPPIAN	Leadville Limestone		
	DEVONIAN	Elbert Formation		
	CAMBRIAN	Ignacio Quartzite		
PRECAMBRIAN				

FIGURE 2 Generalized stratigraphy and predicted foreseeable development of the San Juan Basin, New Mexico.

of declining; therefore, alternative sources of gas need to be found to make up the loss. The other major producing reservoirs contribute 0.75 (Mesaverde), 0.35 (Dakota), and 0.25 (Pictured Cliffs) billion cubic feet per day. Further development of the Mesaverde and Dakota reservoirs will yield the best short-term potential for increasing gas recovery and thus maintaining the deliverability out of the basin.

This change in focus from coal to other formations reflects the historical trend in development. During the early 1990s the Fruitland coal dominated the development with approximately 75% of the total activity. This rapid development has declined, and the Mesaverde Group has recently become the major target of activity.

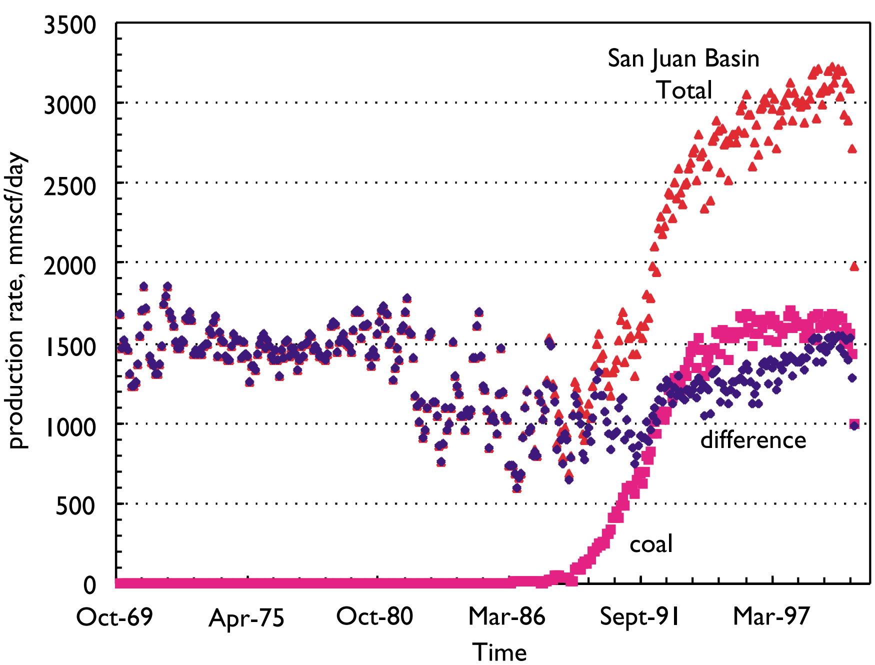

FIGURE 3 Total gas production (million cubic feet per day) from the New Mexico portion of the San Juan Basin and the contribution of the Fruitland Coal to this total.

FORESEEABLE DEVELOPMENT

In 2001 New Mexico Tech completed a study for the U.S. Bureau of Land Management to estimate foreseeable development in the basin over the next twenty years. The focus was to determine future reservoir development (drilling and completion of new wells and recompletion of old wells) reasonably supported by geological and engineering evidence, and to estimate the associated surface impact of such development. The methods used to make this determination consisted of a review of reservoir characteristics and historical production, predictive engineering production modeling, and presentation of data and conclusions in multiple formats including a report, databases, and GIS-based map displays (Engler et al., 2001).

For the major producing reservoirs, two approaches were used to predict development potential. The first was a survey of companies operating in the San Juan Basin, obtaining their perspective on future development based on current reservoir management practices. The second approach applied engineering techniques developed by the New Mexico Institute of Mining and Technology to predict optimal infill drilling in naturally fractured, low-permeability gas reservoirs of the basin.

The study predicted 16,615 total available subsurface completions in the New Mexico part of the San Juan Basin over the next twenty years. (A completion is defined as the means to effectively communicate the wellbore with the reservoir and successfully obtain hydrocarbons.) These results are subject to three assumptions: (1) sufficient and expanding natural gas take-away capacity of the pipeline system out of the basin, (2) well abandonment rate increases of 5% per year, and (3) minimal impact of future exploration. Figure 2 (last column) shows the results by reservoir and includes both major and minor producing reservoirs, and anticipated emerging and exploratory plays.

A significant reduction in this number of completions will occur as a result of opportunities for commingling and dual completion of wells. Commingling is an allowed practice of combining gas flow from two distinct reservoirs in the same wellbore. Similarly, dual completion produces gas from two distinct reservoirs in the same wellbore; however, the gas streams are not mixed until each can be gauged. With an estimated 25% decrease in wellbores, the total number of locations of surface disturbance becomes 12,461. In other words, multiple completions would reduce the number of locations to be built. This rate equates to an average of 623 wells per year and is consistent with current activity (approximately 640 wells per year average for 1999 and 2000

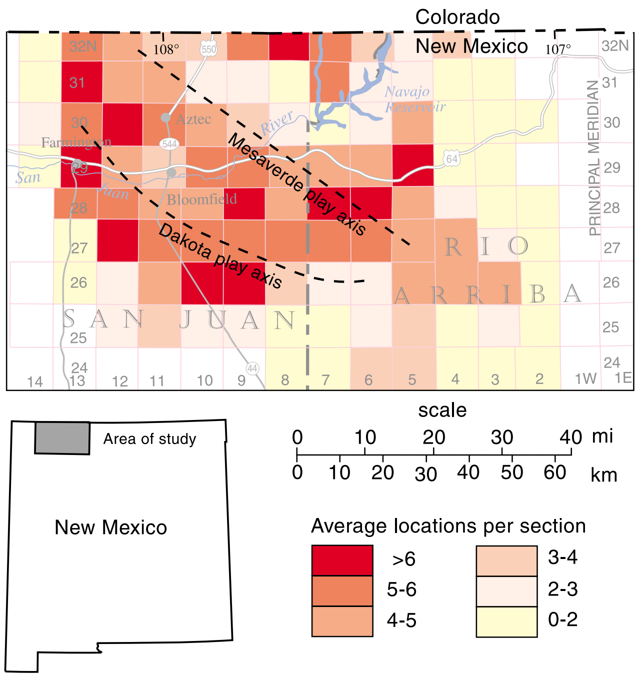

FIGURE 4 Distribution map of the average number of total locations (all reservoirs) per square mile averaged over township areas.

combined). This rate assumes continuation of a favorable regulatory environment that supports this level of development.

A location density map (number of wells per 36-square-mile township; Fig. 4) illustrates the anticipated distribution of the total number of completions (12,461) after commingling or dual completing. The trend of highest predicted activity is approximately northwest to southeast and parallels the trend of the Mesaverde and Dakota plays. Federal lands comprise approximately 80% of the leasehold of the San Juan Basin. Consequently, the total number of locations (12,461) affecting federal lands must be reduced proportionately to 9,970. There will also be a need for additional surface facilities, including pipelines, compressors, and processing facilities to recover the gas efficiently and transport it to market.

The role that evolving technology will likely play cannot be over emphasized. We anticipate new and improved drilling and completion technologies—improved techniques to drill directional and horizontal wells, for instance. This would result in increased gas recovery and a reduction in surface disturbance. Improved completion technologies might include advances in stimulation design, equipment, processes, and materials. Historically, the evolution of stimulation has played a key role in development and well efficiency. Continued advances are anticipated and will benefit both existing and new wells, and may promote the commingling of zones, thereby reducing the number of wells to be drilled.

CONCLUSIONS

Significant gas resources are available in the San Juan Basin for years to come, but recovery of these reserves will require additional development, primarily in the form of infill drilling. Approximately ten thousand wells will be drilled on federally managed lands in the next twenty years, based on the New Mexico Tech study. This analysis was confirmed by an industry survey, administered by New Mexico Tech and completed concurrently with the geologic and engineering study. The San Juan Basin gas supply is important to the U.S. and to the overall economic health of New Mexico. Industry's continued success in providing large quantities of readily available gas, at a reasonable price, is directly related to decisions made by governmental entities. The challenge is to balance oil and gas development with land use issues and environmental concerns.

RESOURCES

Engler, T. W., Brister, B. S., Chen, H. and Teufel, L. W., 2001, Oil and gas resource development for San Juan Basin, New Mexico: A 20-year, Reasonable Foreseeable Development (RFD) scenario supporting the resource management plan for the Farmington Field Office, Bureau of Land Management (contact the field office for a copy of the CD-ROM).

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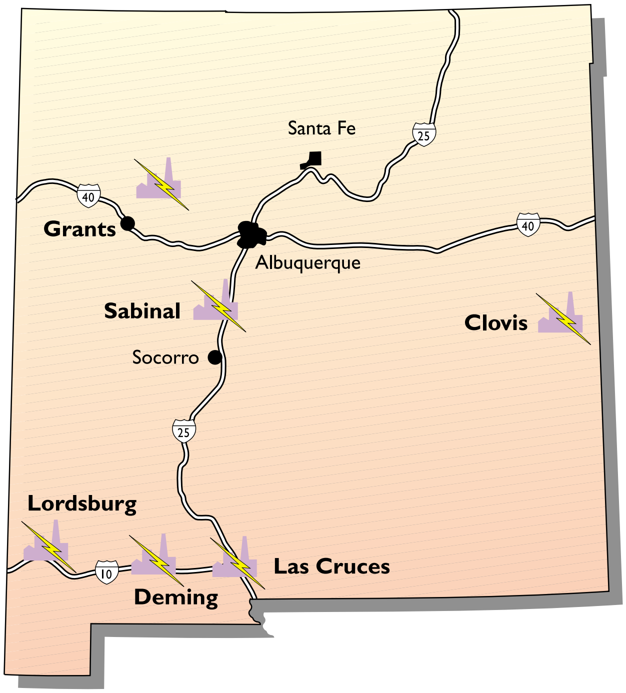
Planned New Mexico Power Plants

Grants	300-megawatt, coal-fired plant, St. Louis, Mo.-based Peabody Energy
Sabinal	145-megawatt, gas-fired plant, Houston-based Cobisa Corp
Clovis	600-megawatt, gas-fired plant, Houston-based Duke Energy
Lordsburg	80-megawatt, natural gas-fired plant, Public Service Company of New Mexico.
	160-megawatt, gas-fired plant, Denver-based Tri-State Generation and Transmission
Deming	560-megawatt, gas-fired plant, Houston-based Duke Energy
Las Cruces	225-megawatt gas-fired plant, Public Service Company of New Mexico



Seven new power plants are currently being planned or are in construction. These plants will meet peaks in local demand and export excess power to the Southwest. Many are natural gas-fired to take advantage of reduced air emissions, reduced water usage, and New Mexico's abundant natural gas.