

BACKGROUND GEOLOGY OF THE SAN JUAN BASIN

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San Juan Basin



NEW MEXICO'S ENERGY, PRESENT AND FUTURE

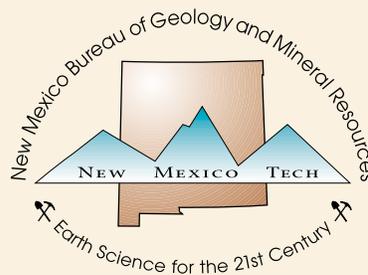
**Policy, Production, Economics,
and the Environment**

Brian S. Brister and L. Greer Price, Editors

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New Mexico Bureau of Geology and Mineral Resources
A Division of New Mexico Institute of Mining and Technology
2002

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.

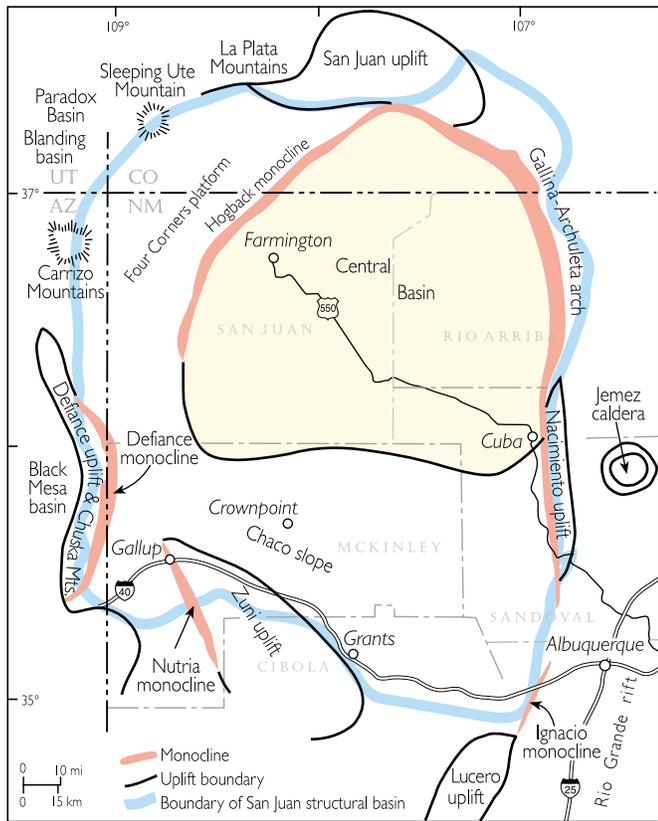


FIGURE 1 Structural features of the San Juan Basin and adjacent areas. From Craig, 2001.

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 non-marine (land or freshwater) types of deposition. These

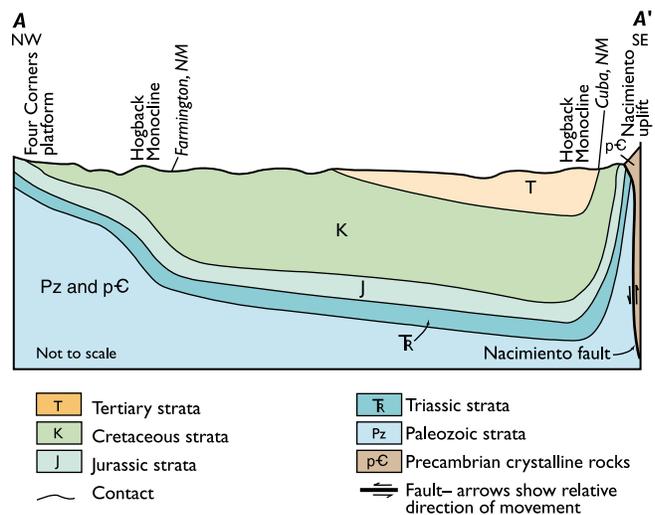


FIGURE 2 Diagrammatic east-west cross section of San Juan Basin, from Craig, 2001 (p. 8, comb. of section A and B).

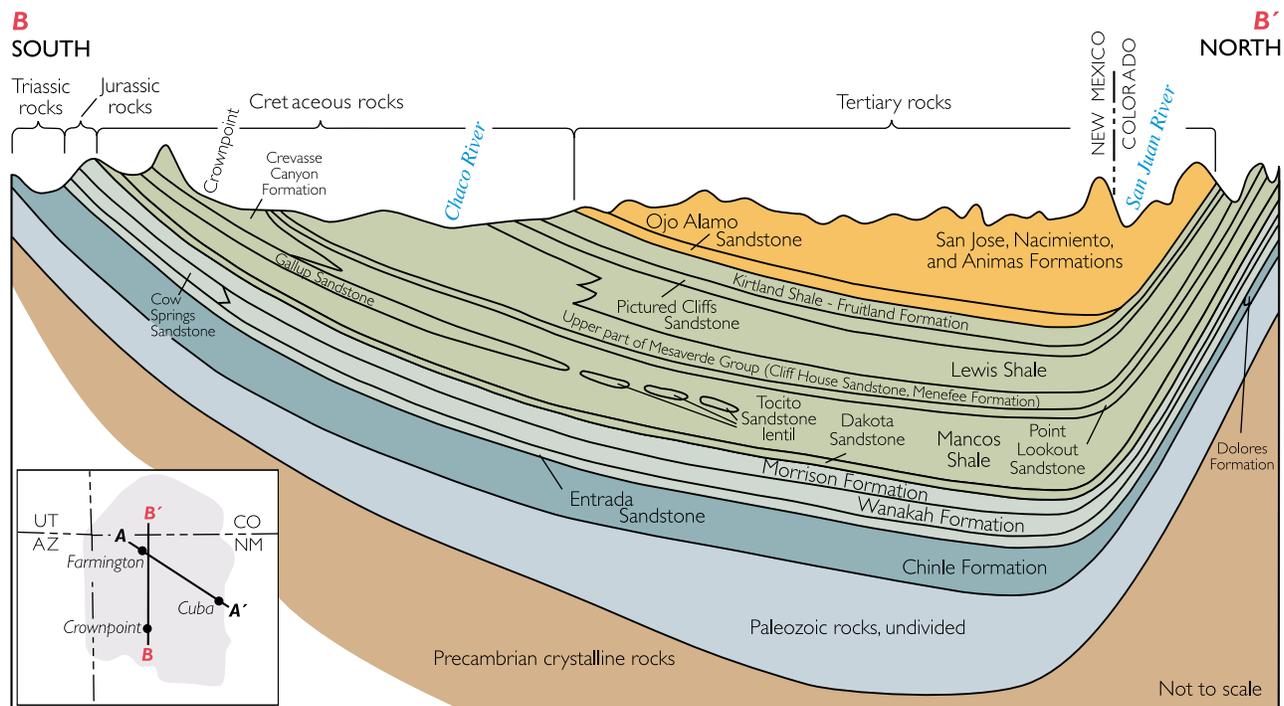


FIGURE 3 Diagrammatic southwest-northeast cross section of San Juan Basin, from Craigg, 2001 (p.12).

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.

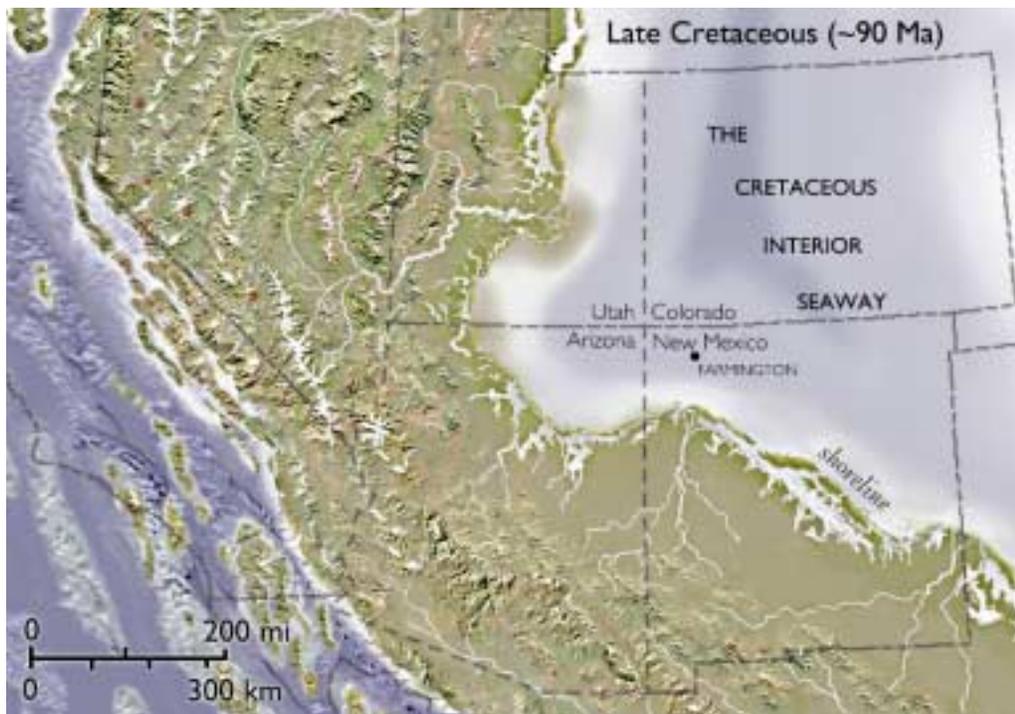


FIGURE 6 Snap shot of paleogeography of the Four Corners region during Late Cretaceous. Map courtesy of Ron Blakey.

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 wind-blown 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:

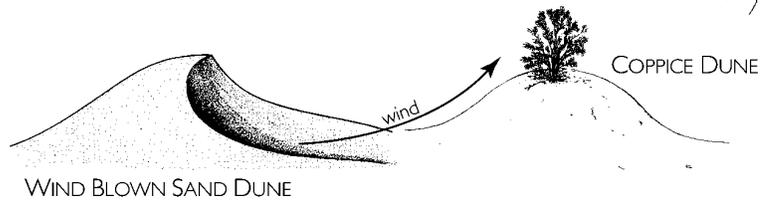
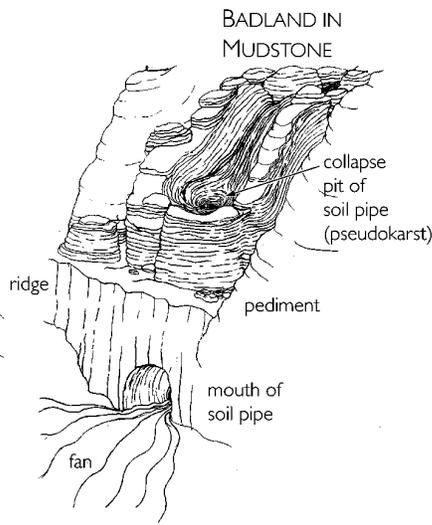
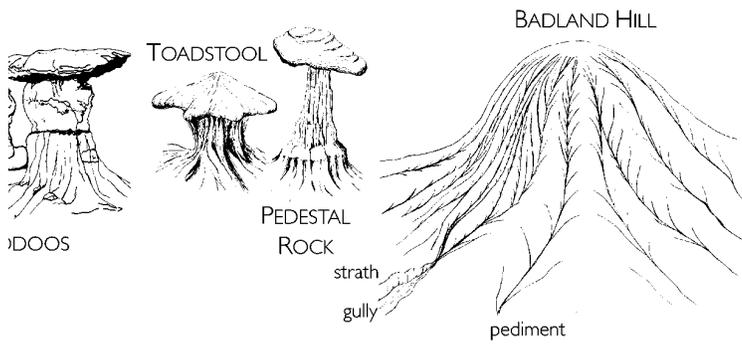
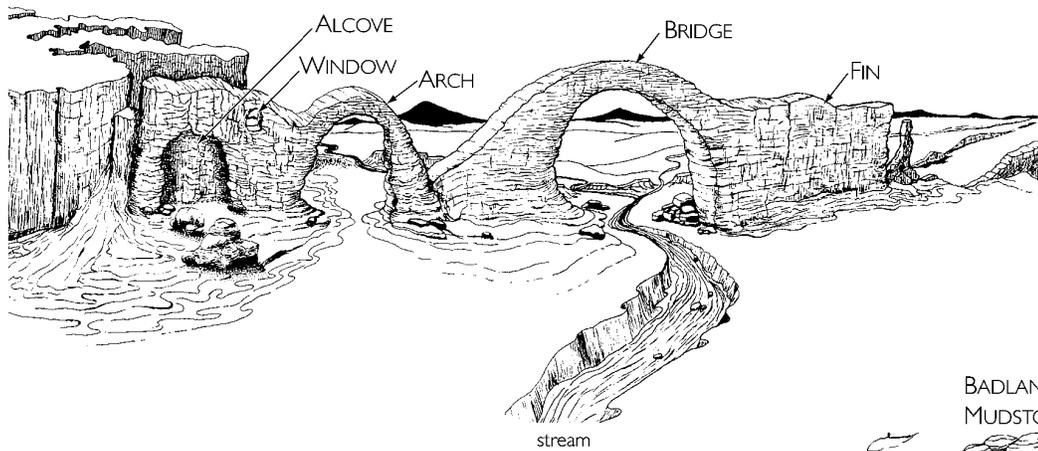
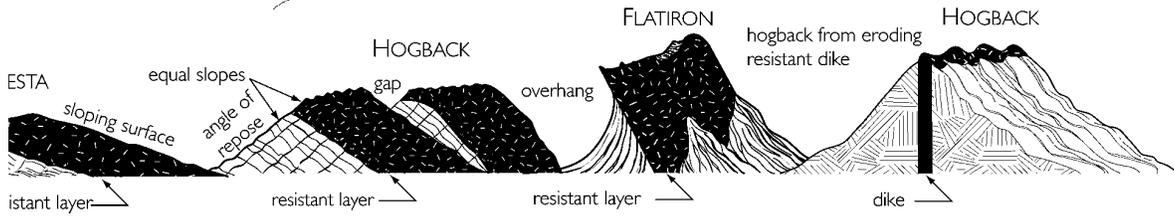
- Badlands illustrate the fastest changing, least stable, most dynamic end of a range in natural rates and processes in the landscape, in contrast to the more stable parts of the same landscape (such as the sand-covered uplands)
- Internal and external environmental influences may alter the flux of materials 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 mud-cracked 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

Virginia T. McLemore, *New Mexico Bureau of Geology and Mineral Resources*

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

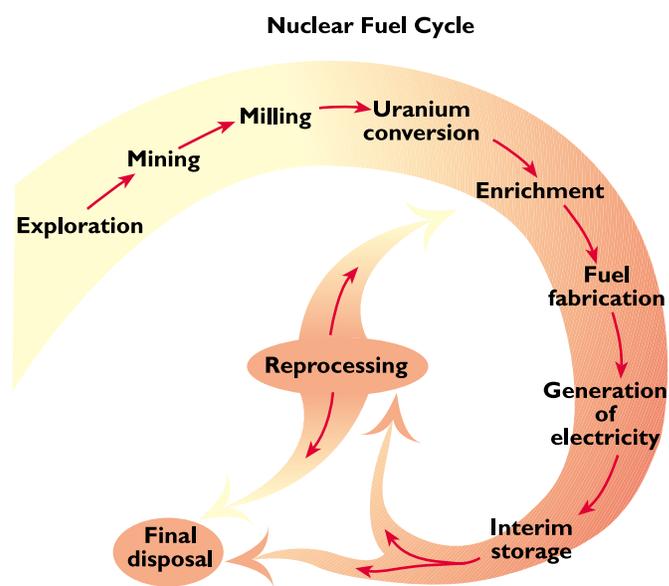
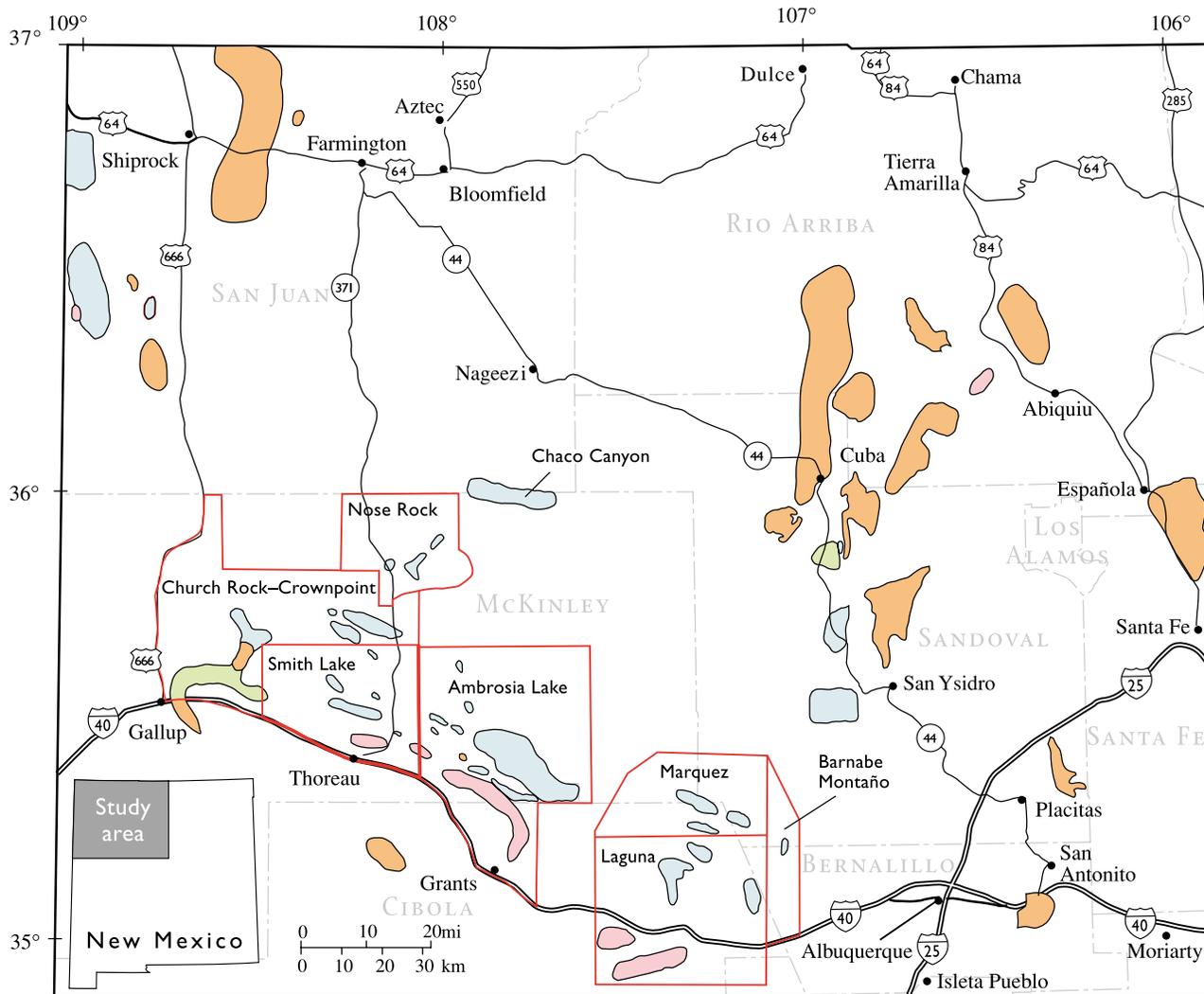


FIGURE 3 The nuclear fuel cycle (Uranium Information Centre Ltd., 2000; Energy Information Administration, 2001).



- | | | | |
|---|--|--|---|
|  | Morrison Formation (Jurassic) sandstone uranium deposits |  | Limestone uranium deposits |
|  | Other sandstone uranium deposits |  | Other sedimentary rocks with uranium deposits |
| | |  | Mining districts |

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	348,321,000¹	1948–2000	100
Total in United States	922,870,000¹	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). ¹Approximate numbers rounded to the nearest 1,000 lbs.

Total U.S. production from McLemore and Chenoweth (1989) and Energy Information Administration (2001).



State	ore (million tons)	\$30 per lb grade (% U ₃ O ₈)	U ₃ O ₈ (million lbs)	ore (million tons)	\$50 per lb grade (% U ₃ O ₈)	U ₃ O 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 U₃O₈. 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% U₃O₈. 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.

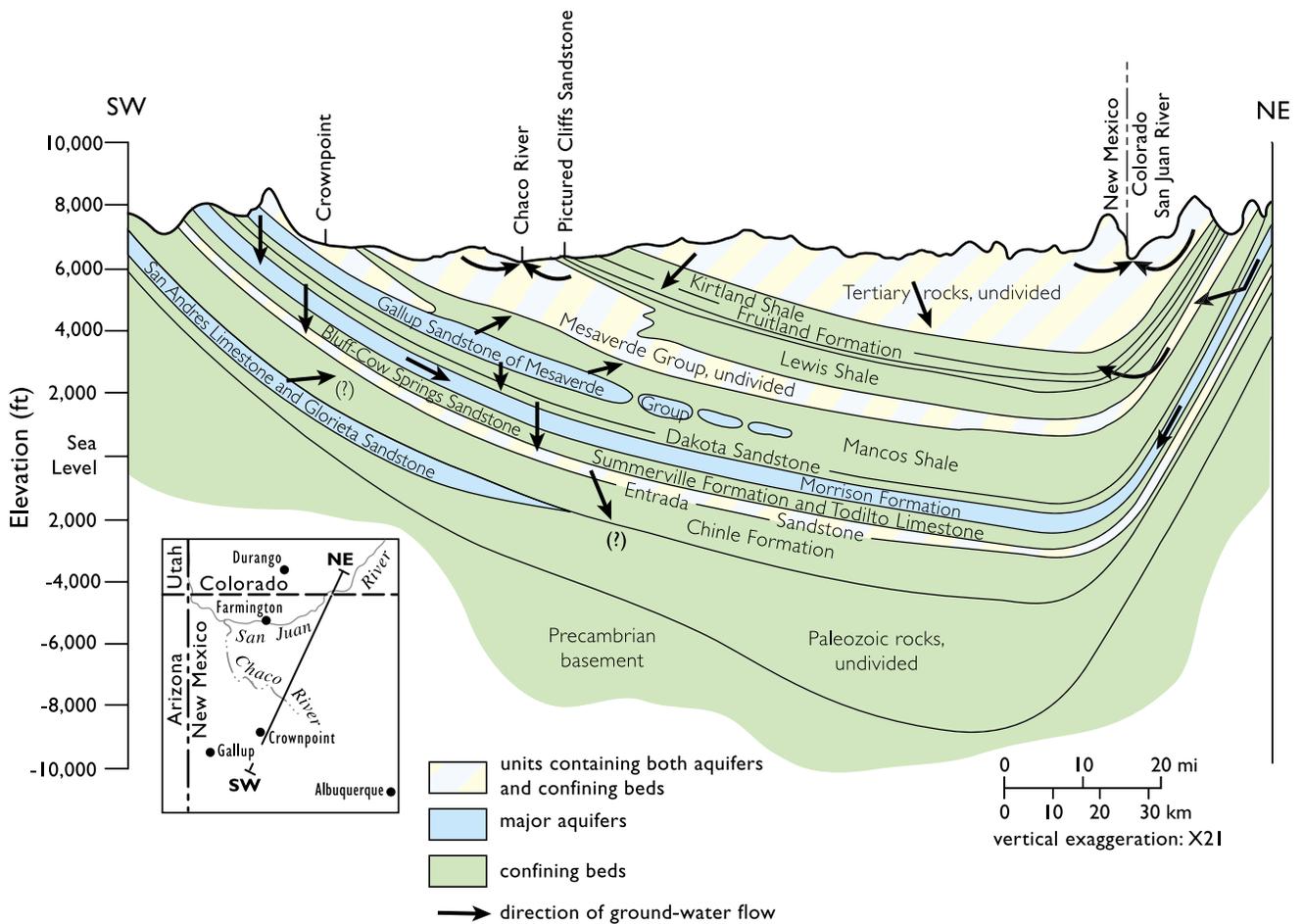


FIGURE 1 Hydrogeologic cross section of the San Juan Basin. Major aquifers are blue; confining beds are green; units containing both are crosshatched.



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 (ft³/s) or approximately 9,000 gallons per minute (gpm) for the Tertiary sandstones and 40 ft³/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 hav-

ing 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

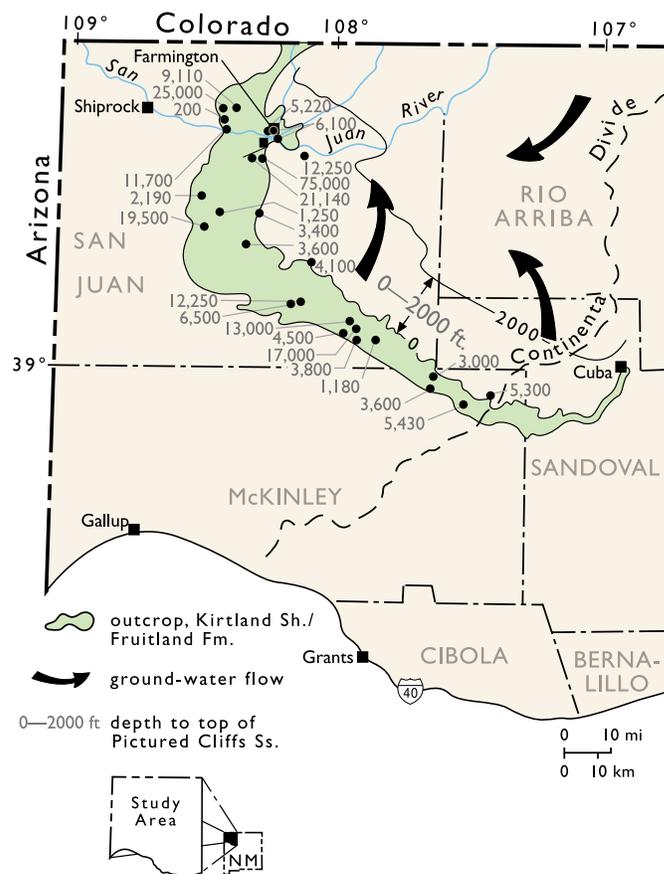


FIGURE 2 Generalized flow directions and quality of water in the Kirtland Shale/Fruitland Formation, undivided. Units shown are in $\mu\text{S}/\text{cm}$.

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

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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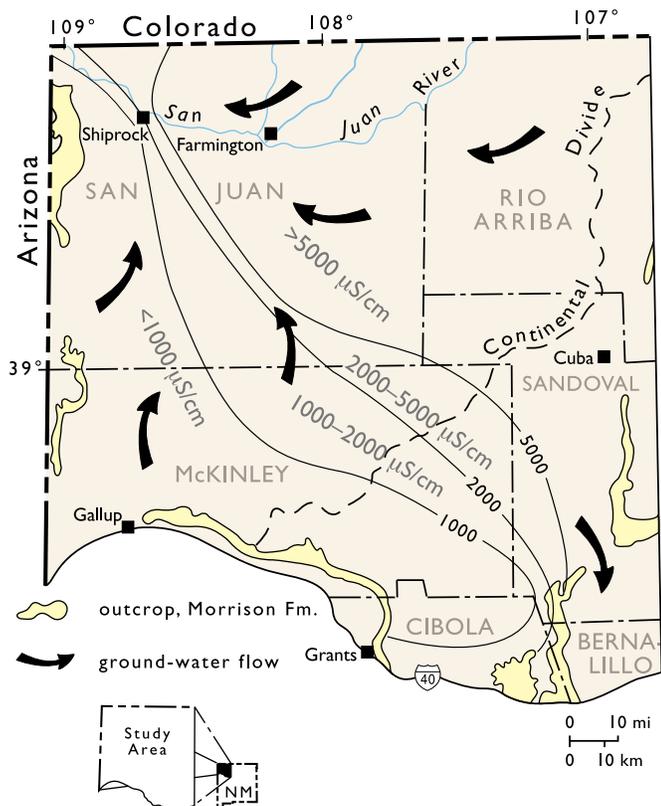


FIGURE 3 Generalized flow direction and quality of water in the Morrison Formation.

