Energy and Mineral Resources of New Mexico

Coal Resources

Gretchen K. Hoffman

VOLUME B

NEW MEXICO BUREAU OF GEOLOGY AND MINERAL RESOURCES
Memoir 50B

NEW MEXICO GEOLOGICAL SOCIETY
Special Publication 13B

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Coal Resources

Gretchen K. Hoffman

Edited by

Virginia T. McLemore,
Stacy Timmons,
and Maureen Wilks

Prepared in cooperation with
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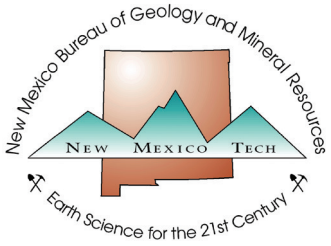

NEW MEXICO BUREAU OF GEOLOGY AND MINERAL RESOURCES

The New Mexico Bureau of Geology and Mineral Resources is a research and service division of New Mexico Institute of Mining and Technology. We are a non-regulatory agency that serves as the geological survey for the state of New Mexico.

New Mexico Bureau of Geology and Mineral Resources
801 Leroy Place
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geoinfo.nmt.edu

NEW MEXICO GEOLOGICAL SOCIETY

The New Mexico Geological Society is a tax-exempt corporation registered in the State of New Mexico that promotes interest in geology and associated sciences, fosters scientific research and publications, encourages cooperation among its members, and stimulates interest in New Mexico geology.

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Cover: A long coal train emerging from one of the Stag Canyon Coal Co.'s Dawson mines on its way to unload at the tipple, ca 1920. Mine southwest of Raton, New Mexico, Colfax County. *Photo courtesy of Phelps Dodge Corporation, New Mexico Bureau of Geology and Mineral Resources, Historic Photograph Archives, Socorro, NM 87801. Cover design by Brigitte Felix.*

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CONTENTS

Figures Preface

Figures

Tables Preface

Table

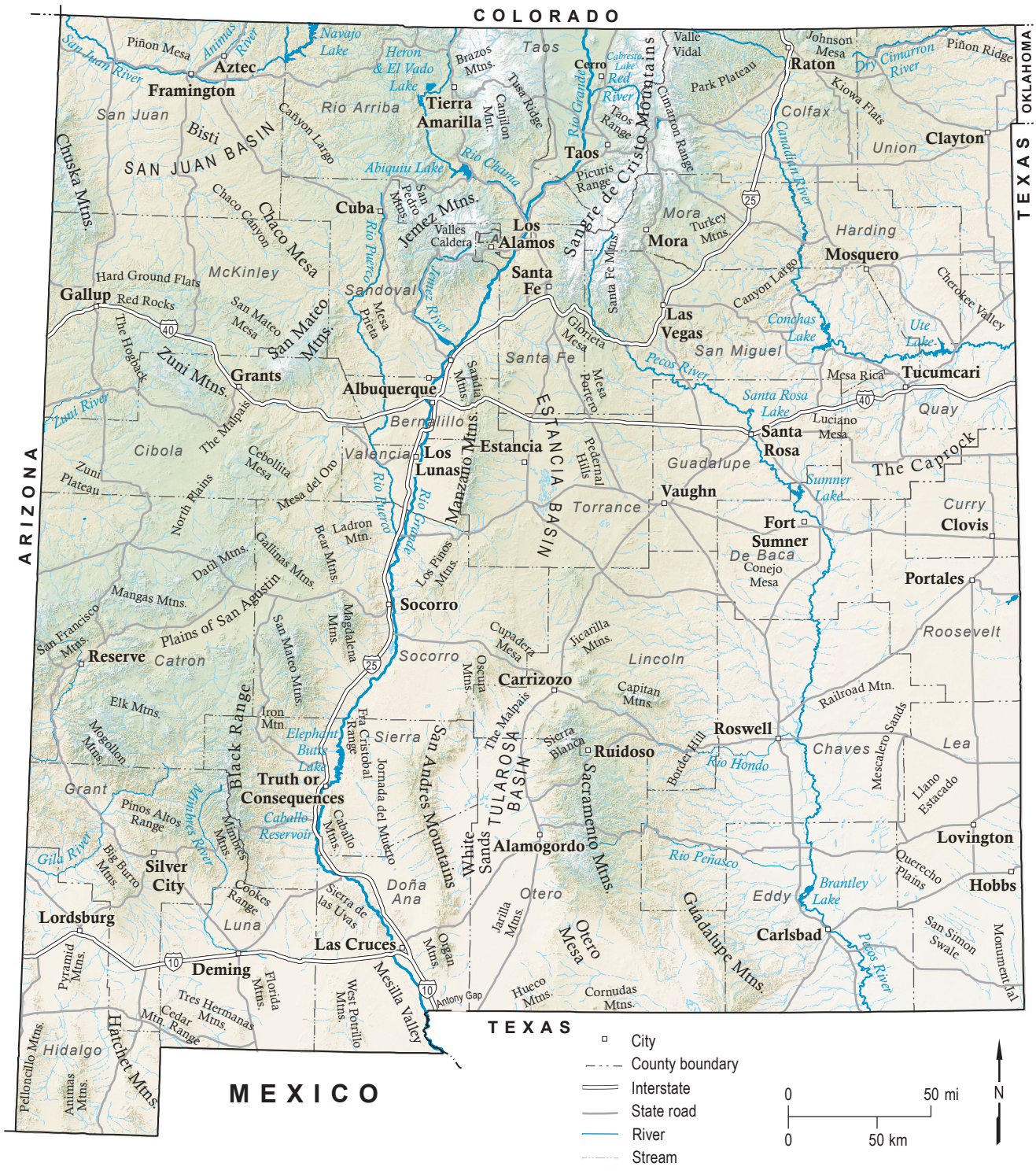


Figure 1. Geography of New Mexico, showing highways and major cities.

PREFACE

Virginia T. McLemore, Ronald F. Broadhead, Gretchen K. Hoffman, and Fraser Goff

New Mexico is called the Land of Enchantment, in part because of the diverse geologic formations of the state, which give rise to spectacular landscapes of mountains, valleys, mesas, canyons, rivers, deserts, and plains. Major cities are concentrated along the Rio Grande, including Albuquerque, Las Cruces, Rio Rancho, and Santa Fe, with smaller population centers in the southeast, eastern plains, and northwest, such as Roswell, Hobbs, Alamogordo, Carlsbad, Clovis, and Farmington (Fig. 1). New Mexico is the 5th largest state in terms of land area in the lower United States and contains five major physiographic provinces (Fig. 2): Great Plains, Basin and Range, Transition Zone, Colorado Plateau, and Southern Rocky Mountains. The rocks, which date back nearly two billion years, have undergone multiple major tectonic events that were accompanied by faulting and igneous activity (Figs. 3, 4). This rich geologic history has yielded a diversity of valuable energy and mineral deposits, which occur in all of the physiographic provinces in New Mexico, and in a variety of tectonic and geologic settings (Fig. 3). For more information on the geology of New Mexico, see Mack (1997), Mack and Giles (2004), and Price (2010). In addition, mining districts and prospect areas are shown and briefly described in McLemore (2017).

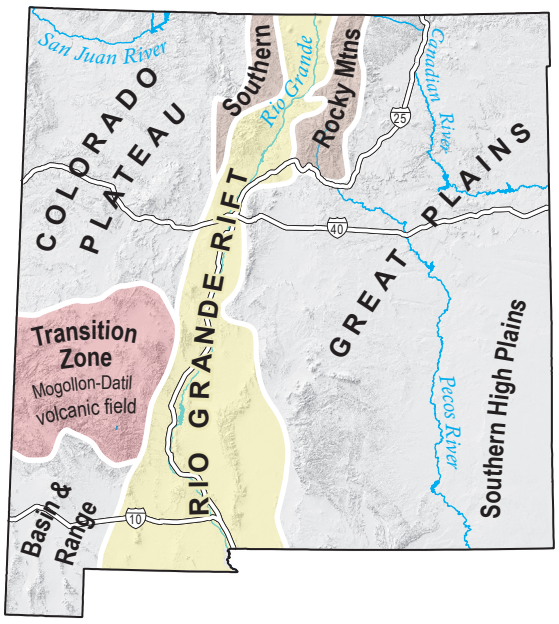


Figure 2. Physiographic provinces of New Mexico.

Rock collecting (or rock hounding), prospecting, and non-commercial gold panning are considered a casual use of public lands under most circumstances. **However, it is up to each individual to know the laws and land ownership.** For more information on mining claims and mineral leasing in New Mexico see McLemore (2017), BLM website (http://www.blm.gov/lr2000/), and New Mexico Mining and Minerals Division website (http://www.emnrd.state.nm.us/MMD/MARP/marpmainpage.html).

Importance of Energy and Minerals in New Mexico

New Mexico's mineral wealth is among the richest of any state in the United States. Oil and gas are the most important extractive industries in New Mexico in terms of production value (McLemore, 2017). In 2015, New Mexico ranked 6th in oil production, 8th in gas production, 10th in coal production, and 15th in non-fuel minerals production. Most of the state's mineral production comes from oil, gas, coal, copper, potash, industrial minerals and aggregates (Tables 1, 2). Other important commodities include a variety of industrial minerals (perlite, cement, zeolites, etc.), sulfuric acid, molybdenum, gold, uranium, and silver. New Mexico is fortunate to have geothermal resources in many locations. In December 2013, the Dale Burgett Geothermal Plant in the Animas Valley of southwest New Mexico started delivering up to 2 MW of electricity to the Public Service Company of New Mexico. Development of the Lightning Dock No. 2 project is underway with an additional 6 MW of generation planned.

A healthy energy and mineral industry is vitally important to the economy of New Mexico and to maintenance of public education and services (Table 2). The minerals industries provide property and corporate income taxes, while their ~35,000 direct employees contributed millions of dollars of personal

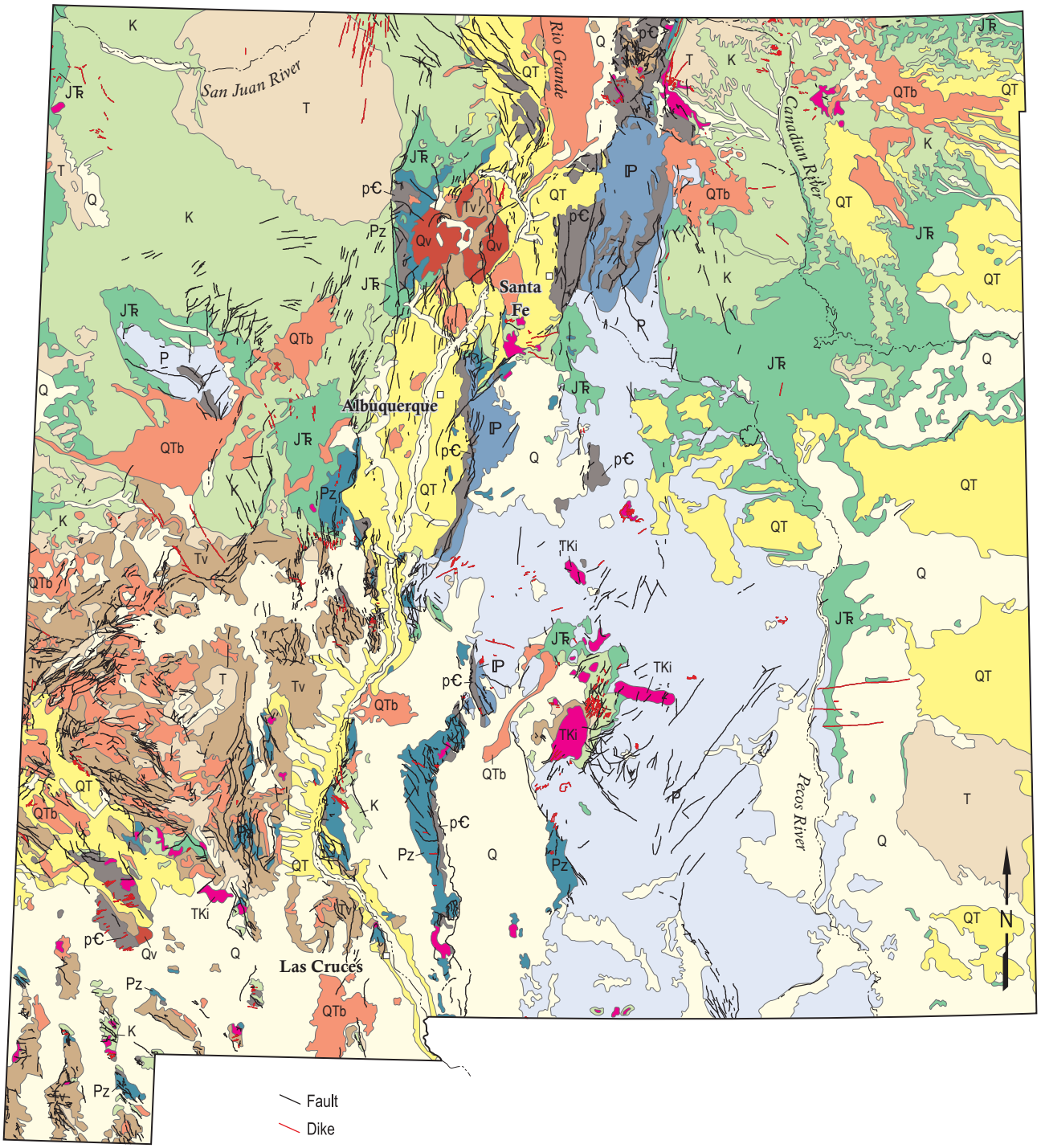


Figure 3. Simplified geologic map of New Mexico.

income taxes (New Mexico Energy and Minerals Division, 2016). The number of mines and actual tonnage of produced minerals has declined in recent years (McLemore, 2017). This decline is a result of numerous complex and interrelated factors. Some of the more important factors include declining profits in mineral operations, decreased quality of ore (for example, lower grades and more difficult ore to process), competition from the global market, and a shift from coal-generated electricity to alternative energy sources.

Table 1. Estimated total production of major commodities in New Mexico, in order of estimated cumulative value (data from USGS, 1902–1927; USBM, 1927–1990; Kelley, 1949; Harrer, 1965; USGS, 1965; Howard, 1967; Harben et al., 2008; Energy Information Administration, 2015; New Mexico Energy, Minerals and Natural Resources Department, 1986–2016). Figures are subject to change as more data are obtained. Estimated cumulative value is in real, historic dollars at the time of production and is not adjusted for inflation.

Commodity	Years of production	Estimated quantity of production	Estimated cumulative value ($)
Natural Gas	1921–2015	>75 trillion cubic feet	$169 billion
Oil	1922–2015	>6.4 billion barrels	$119 billion
Coal	1882–2015	>1.46 billion short tons	>$21.7 billion
Copper	1804–2015	>11.7 million tons	>$21.6 billion
Potash	1951–2015	>113 million short tons	>$15.6 billion
Uranium	1948–2002	>347 million pounds	>$4.8 billion
Industrial minerals**	1997–2015	>41 million short tons	>$2.7 billion
Aggregates***	1951–2015	>674 short tons	>$2.6 billion
Molybdenum	1931–2013	>176 million pounds	>$852 million
Carbon dioxide	1931–2015	>3.3 trillion cubic feet	>$726 million
Gold	1948–2015	>3.3 million troy ounces	>$486 million
Zinc	1903–1991	>1.51 million tons	>$337 million
Silver	1848–2015	>119 million troy ounces	>$280 million
Lead	1883–1992	>367,000 tons	>$56.7 million
Iron	1888–2015	>6.7 million long tons	>$23 million
Fluorspar	1909–1978	>721,000 tons	$12 million
Manganese	1883–1963	>1.7 million tons	$5 million
Barite	1918–1965	>37,500 tons	>$400,000
Tungsten	1940–1958	113.8 tons (>60% WO_3)	na
Niobium-tantalum	1953–1965	34,000 pounds of concentrates	na
TOTAL	**1804–2015**	**—**	**>$359 billion**

*Oil and gas values are estimated from production data provided by https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting/Reporting/Production/ProductionInjectionSummaryReport.aspx (New Mexico Oil Conservation Division Natural Gas and Oil Production, continuously updated, accessed 2/1/16) and estimated average commodity price. Minerals data are from New Mexico Energy, Minerals and Natural Resources Department (2016). **Industrial minerals include the combined total of several industrial minerals (e.g., perlite, cement, decorative stone, pumice, zeolites, etc.), but excluding potash and aggregates. ***Aggregates include only sand and gravel from 1951–1997, after 1997 aggregates include crushed stone and scoria. na–not available.

Table 2. Summary of mineral production in New Mexico in 2015, including oil and natural gas (New Mexico Energy, Minerals and Natural Resources Department, 2016, https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting/Reporting/Production/ProductionInjectionSummaryReport.aspx; Gould, 2015). na—not available.

Mineral	Production in 2015	Production rank in the U.S. in 2015	Production value in NM in 2015	Employment in NM (# full time jobs)	Reclamation employment in NM (# full time jobs)	State revenue generated from extractive industries	Federal revenue generated from extractive industries
Oil	147 million bbls oil	6	~$7,143,000,000	~30,000*	na	~$1,600,000,000*	na
Gas	1.23 trillion ft^3 gas	8	~$6,470,000,000	—	na	—	na
Copper	397,441,145 lbs	2	$996,838,033	1,878	4	$8,086,903	—
Coal	19,676,277 short tons	12	$691,047,434	1,341	118	$17,656,313	$10,243,850
Gold	20,438 troy oz	—	$23,708,980	—	—	$191,947	—
Industrial minerals	1,411,731 short tons	—	$87,305,356	413	11	$269,261	$213,816
Aggregates	8,169,753 short tons	—	$62,625,896	837	53	$3,092,285	—
Other metals (iron, manganese)	18,358 short tons	—	$165,223	18	—	$761,027	—
Potash	1,433,245 short tons	1	$659,505,518	1,194	12	$6,542,580	$8,133,012
Silver	56,983 troy oz	—	$895,610	—	—	$9,737	—
Uranium	none	—	—	11	11	—	—
Carbon dioxide	106 billion ft^3	—	$112,000,000	—	—	—	na
Total	**—**	**15 (excluding oil, gas, and coal)**	**~$16,247,000,000**	**~35,000**	**209**	**~$1,636,000,000**	**$18,590,678**

*Estimate includes oil, gas, and carbon dioxide.

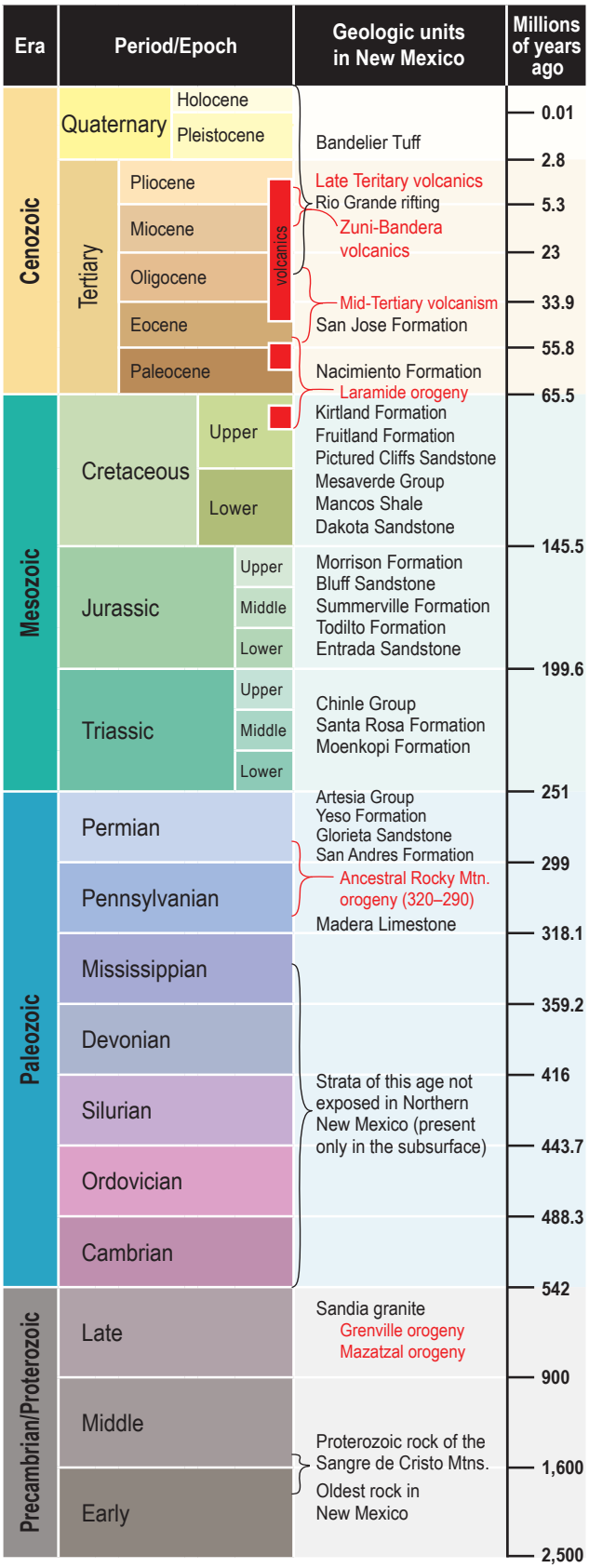


Figure 4. Geologic time scale. "Tertiary" is often used in these chapters to describe timing of events in the Paleogene and Neogene geologic periods.

New mines and petroleum drilling face a multitude of challenges, including water availability, water rights issues, public perceptions, a complex regulatory process and public opposition to petroleum drilling and mining.

Minerals and Society

The minerals industries (including oil and gas) play a vital role in the world economy by filling a persistent demand for the raw materials that are the foundation of our civilization. Our modern lifestyles are heavily dependent upon mining commodities that Americans use on a daily basis (Table 3). For example, petroleum, metals, and industrial minerals are used in every sector of construction and manufacturing. Coal, oil, gas, and uranium provide electricity and fuels. They are used in urban and industrial applications. Geothermal resources also provide electricity and heating (Table 3). Agriculture depends upon minerals for fertilizers and pesticides.

Mineral production in New Mexico and the world has increased dramatically in the last 100 years (Fig. 5, Wagner, 2002). Most industries no longer follow the casual mining and safety practices of the past. "*One of the greatest challenges facing the world today is integrating economic activity with environmental*

Table 3. Selected uses of commodities found in New Mexico.

Commodity	Selected Uses
Oil	Fuel, electricity generation, pesticides, fertilizers, chemicals, plastics
Gas	Fuel, electricity generation
Copper	Electrical wire, pipe, plumbing, motors, machinery, computers
Coal	Electricity generation, steel production, manufacture of cement, liquid fuel, chemical and pharmaceutical industries
Aggregates	Manufacture concrete and cement, road construction, railroad ballast
Molybdenum	Stainless and structural steel, superalloys, chemicals, cast iron
Potash	Agricultural fertilizers
Silver	Currency, jewelry, electronics, photography, silverware, mirrors
Gold	Currency, jewelry, electronics, computers, dentistry, glass
Uranium	Fuel for nuclear reactors, projectiles, shielding of radioactive materials
Perlite	Building construction materials, soil amendment, filter aid
Zeolites	Water purification, animal feed, sorbents
Rare earth elements	Catalyst, glass, polishing, re-chargeable batteries, magnets, lasers, glass, TV color phosphors
Geothermal resources	Electricity generation, space heating, greenhouse heating, aquaculture (fish farms), spas, and bath houses

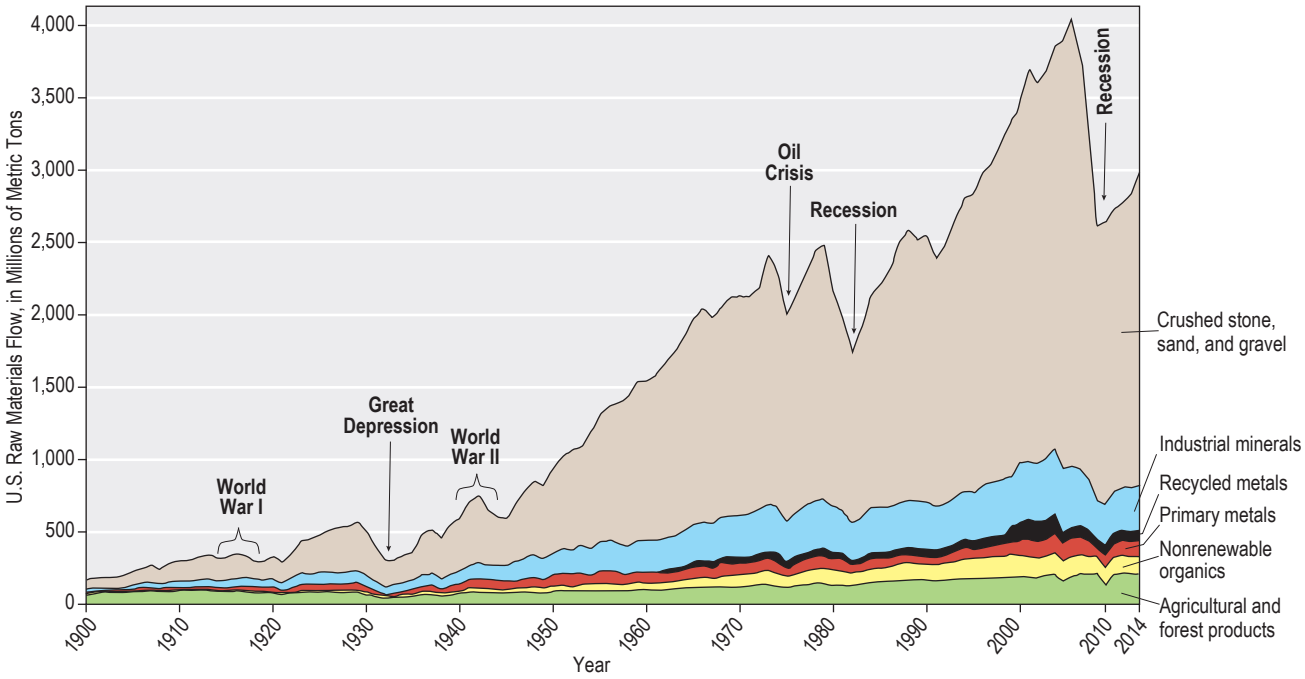


Figure 5. United States flow of raw materials by weight from 1900–2014. The use of raw materials increased dramatically during the last 100 years (modified from Wagner, 2002).

integrity and social concerns… The fulfillment of 'needs' is central to the definition of sustainable development" (IIED, 2002). The permitting process applied to most extractive industries includes archeological surveys, identification of rare and endangered species, and environmental monitoring during and after production. Today, another important aspect of mine planning in a modern regulatory setting is the philosophy, and often the requirement, that new mines and mine expansions must have plans and designs for closure. This philosophy is relatively new. It attempts to prevent environmental accidents common in the past and has increased the cost of mining.

Organization of this Series

This Memoir/Special Publication is the first modern summary of New Mexico's energy and mineral resources since work by the U.S. Geological Survey (USGS, 1965) and Howard (1967). This series of volumes is a joint publication of the New Mexico Bureau of Geology and Mineral Resources and the New Mexico Geological Society. This publication consists of six individual volumes under the theme of Energy and Mineral Resources of New Mexico.

Energy and Mineral Resources of New Mexico,
New Mexico Bureau of Geology and Mineral Resources, Memoir 50
New Mexico Geological Society, Special Publication 13

- **Petroleum Geology**
  by Ronald F. Broadhead, ***Volume A***
- **Coal Resources**
  by Gretchen K. Hoffman, ***Volume B***
- **Uranium Resources**
  by Virginia T. McLemore and William L. Chenoweth, ***Volume C***
- **Metallic Mineral Deposits**
  by Virginia T. McLemore and Virgil W. Lueth, ***Volume D***
- **Industrial Minerals and Rocks**
  by Virginia T. McLemore and George S. Austin, ***Volume E***
- **Overview of the Valles Caldera (Baca) Geothermal System**
  by Fraser Goff and Cathy J. Goff, ***Volume F***

SUMMARY

Coal mining is an important contributor to New Mexico's state budget and is the third largest source of state revenues from mineral and energy production. The state also receives royalties and rentals from coal leases on state and federal lands. Along with the economic impact of coal mining in the state, 66% of New Mexico's electrical energy needs are met by generating power from coal combustion (Energy, Minerals and Natural Resources Department, 2016, p. 51). Although coal-bearing rocks cover one-fifth of New Mexico, most New Mexicans have little direct contact or knowledge of coal or the coal industry. The northeast and northwest corners of the state have two major coal-bearing areas, the San Juan and Raton Basins. The Fruitland and Menefee Formations in the San Juan Basin and the Vermejo and Raton Formations of the Raton Basin are significant coal sequences and have been major producers. Production for all of New Mexico's coal areas from 1882–2015 is over 1.1 billion tons.

Coal has also played an important role in New Mexico's history. The early forts and settlements used coal as fuel for heating and blacksmithing. The proximity of coal deposits influenced the routes taken in constructing railroads in the New Mexico Territory after the Civil War. Many towns in New Mexico developed around the coal mining camps that supplied fuel to the railroads and smelters in the Southwest. Most of these coal camps are now ghost towns, particularly those in the smaller coal fields, but others developed into thriving communities such as Gallup and Raton. These communities still have diverse populations that reflect the nationalities of miners that came to work in the coal mines.

With the advent of electricity and the lack of water to supply hydroelectric power, coal became the fuel of choice for many power generating stations in New Mexico. However, new regulations related to carbon dioxide emissions set in 2014 by the U.S. Environmental Protection Agency has led to the shutdown of many coal-fired electricity-generating stations in New Mexico as they look for alternative energy sources. The switch to alternative energy sources such as natural gas, nuclear, solar, and wind has had an impact on the coal industry in New Mexico. Decreases in coal production will impact the state's economy with a loss of revenue from employment and severance taxes. Coal still plays a significant role in generating electricity in New Mexico and it will continue to be a part of the equation until other generating sources and their infrastructure can be developed. According to the Energy Information Administration (2014) New Mexico has 26% of the nation's coalbed methane proven reserves, second only to Colorado in the United States. Both the San Juan and Raton Basins have significant coalbed methane production and reserves. Depending on oil and gas prices, coalbed methane may be the future of coal development in New Mexico.

Loading facilities at Southwestern's Atherton Mine, near Gallup, New Mexico, McKinley County, April 15, 1933. *Photo by H. C. Stacher, New Mexico Bureau of Geology and Mineral Resources, Historic Photograph Archives, Socorro, NM 87801.*

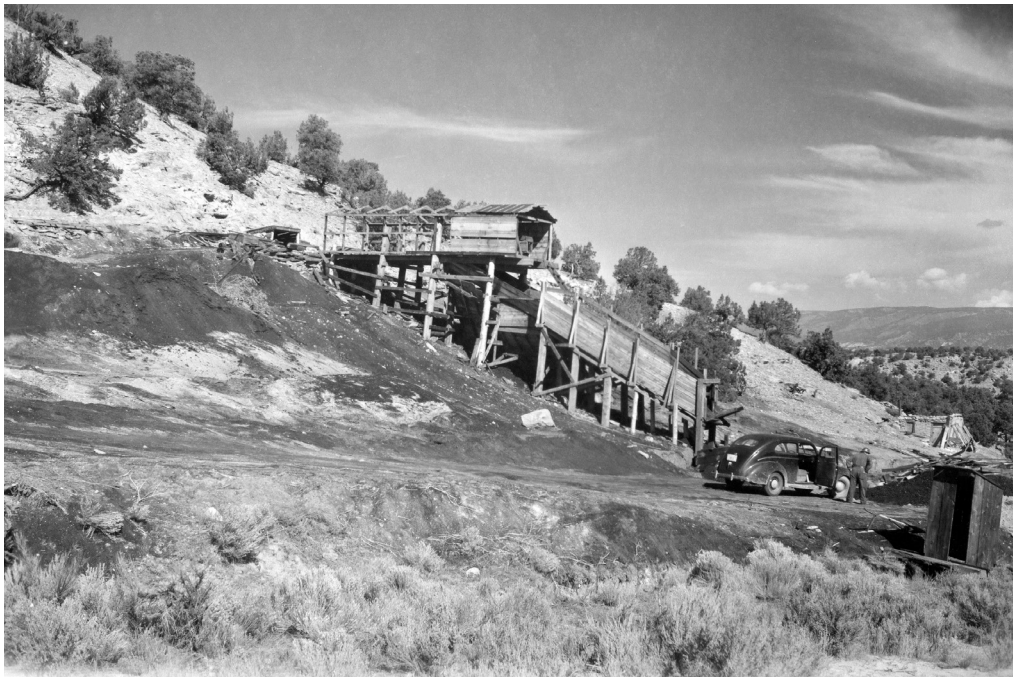
I. INTRODUCTION

New Mexico ranked 10th in United States coal production for 2015 (Energy Information Administration, 2015). Coal mining is an important contribution to New Mexico's state budget and is the third largest source of revenues from mineral and energy production. The state also receives royalties and rentals from coal leases on state and federal lands. In 2015, the coal industry directly employed and contracted 1,341 people and the payroll from the state's coal industry totaled $133.47 million (Energy, Mineral and Natural Resources Department (EMNRD) 2016, Table 1, p. 34). Along with the economic impact of coal mining in the state, 66% of New Mexico's electrical energy needs are met by generating power from coal combustion (Energy, Minerals and Natural Resources Department, 2016). Although coal-bearing rocks cover one-fifth of New Mexico, most New Mexicans have little direct contact or knowledge of coal or the coal industry. The exceptions are the New Mexicans who live in one of the few counties that have operating coal mines. The following chapter outlines coal formation and preservation, coal classification, and the major geologic periods of coal development.

Table 1. Classification of coals by rank (ASTM D388-1977). This classification does not include a few coals, principally non-banded varieties, which have unusual physical and chemical properties and which come within the limits of fixed carbon or calorific value of high-volatile bituminous and subbituminous ranks. All of these coals either contain less than 48% dry, mineral-matter free fixed carbon or they have greater than 15,000 Btu/lb moist, mineral-matter free (American Society for Testing and Materials, 1981).

Class	Group	Fixed carbon limit, percent (dry, mineral-matter free basis)		Volatile matter limits, percent (dry, mineral-matter free basis)		Calorific value limits Btu per pound (moist, mineral-matter free basis*)		Agglomerating character
		Equal or greater than	Less than	Greater than	Equal or less than	Equal or greater than	Less than	
I. Anthracite	1. Meta-Anthracite	98	—	—	2			Nonagglomerating
	2. Anthracite	92	98	2	8			
	3. Semianthracite†	86	92	8	14			
II. Bituminous	1. Low volatile bituminous coal	78	86	14	22			Commonly agglomerating§
	2. Medium volatile bituminous coal	69	78	22	31	—	—	
	3. High volatile A bituminous coal	—	69	31	—	14,000‡	—	
	4. High volatile B bituminous coal	—	—	—	—	13,000‡	14,000	
	5. High volatile C bituminous coal					11,500	13,000	
		—	—	—	—	10,500	11,500	Agglomerating
III. Subbituminous	1. Subbituminous A coal	—	—	—	—	10,500	11,500	Nonagglomerating
	2. Subbituminous B coal	—	—	—	—	9,500	10,500	
	3. Subbituminous C coal	—	—	—	—	8,300	9,500	
IV. Lignite	1. Lignite A	—	—	—	—	6,300	8,300	
	2. Lignite B	—	—	—	—	—	6,300	

* Moist, mineral-matter free; moist refers to coal containing its natural inherent moisture but not including visible water on the surface of the coal.
† If agglomerating, classify in low volatile group of bituminous class.
‡ Coals having 69% or more fixed carbon on the dry, mineral matter free basis are classified according to fixed carbon, regardless of calorific value.
§ It is recognized that there may be non-agglomerating varieties in these groups of the bituminous class, and there are notable exceptions in high volatile C bituminous group.



Tipple and chute constructed by Western Coal Company at the new portal of the Sunny Slope mine, La Ventana coal field, Sandoval County, New Mexico, October, 22, 1944. *Photo courtesy of R. H. Allport, New Mexico Bureau of Geology and Mineral Resources, Historic Photograph Archives, Socorro, NM 87801.*

II. COAL DEPOSITS

Peat Development

Coal is a readily combustible rock formed by the compaction of decaying plant material deposited in ancient peat swamps or mires. Mire is a generic term to cover non-saline wetlands in which peat accumulates (Gore, 1983). Mires can develop in several depositional environments including fluvial, fluvio-lacustrine, and inland lacustrine. The Snuggedy Swamp of South Carolina is a modern analog for back-barrier estuarine coal-forming environments, similar to what is seen in the San Juan Basin coal-bearing sequences. A large number of mires develop in paralic environments and are the common source of coal deposits found in New Mexico. Mires are particularly common within the San Juan Basin. The following discussion specifically looks at this depositional environment.

Several factors control whether coal is actually developed and preserved from mires. Climate, tectonism, and eustasy control the mire type, vegetation growth, humification, local fluctuations in base level, and clastic sediment input (McCabe and Parish, 1992). Climate controls the plant productivity and determines the amount of organic material that can accumulate. Peat develops in climates where the precipitation exceeds evaporation, keeping the water table high. This balance is dependent on temperature. For example, at the equator, evaporation is high because of the temperature, but precipitation meets or exceeds the evaporation rate. In contrast, at high mid-latitude regions, the precipitation is low, but because the temperature is low, the evaporation rate is less than the precipitation.

The type and rate of vegetation growth is important and dependent on the supply of water and nutrients to the mire. Most mires develop in areas of low relief and have water flowing through them, providing nutrients to the plants (Fig. 1). The water table within the low-lying mires approximates the regional groundwater table. Raised mires typically occur in areas where high precipitation rates exceed evaporation rates, maintaining the water table in the mire above the regional groundwater level. A rising water table is necessary to accumulate significant amounts of organic matter and to create an environment that is starved of oxygen. In an environment without oxygen, plant material can be preserved and undergo decay. The decay of plant matter within the peat profile and the surface litter is called humification (Teichmuller, 1982). With the breakdown of the organic material, humic acids are created and the mire water becomes acidic, ranging in pH from 4.8 to 6.6 in a low-lying mire and pH <4 in raised mires, a pH 7 being neutral (Teichmuller and Teichmuller, 1982). Acidity is dependent on the plant communities, on the oxygen supply, the level of concentration of humic acids already in place, and the type of substrate material of the mire (Teichmuller and Teichmuller, 1982, p. 31).

Peat can accumulate in almost any climate on the passive margin of a basin where evaporation and precipitation are in equilibrium. However, the slow rate of base level rise on a passive margin does not allow for accumulation of thick coals. McCabe (1991) suggests that foreland basins are the optimal sites for peat accumulation because the rate of subsidence is slow enough to allow peat accumulation to meet or exceed the subsidence. Strike–slip basins have too great a subsidence rate, and rapid base level rise can cause flooding of mires, halting peat accumulation. The majority of peat accumulated north of 35° paleolatitude (including New Mexico and the San Juan Basin) during the Cretaceous is considered to have had a temperate of subtropical climate.

An increase in accommodation must approximate the accumulation rate of organic matter in the mire to develop significant peat deposits. Rising groundwater indicates a change in base level and subsidence, creating accommodation space. The net rate of accumulation of organic material by weight is slow; therefore, the rate of supply of clastic material must also be slow to allow for peat accumulation that will eventually form coals. It is critical that the peat is buried to begin the development of coals.

Coals are defined as combustible rocks with more than 50% by weight and more than 70% by volume carbonaceous material, including inherent moisture (Wood et al., 1983). Seventy percent volume carbonaceous material limits the percentage of

non-combustible clastic material (or mineral matter) to about 30%. Areas of stable fluvial channels or raised mires have the greatest potential to develop low-mineral matter coals with most of the material derived from the organic material.

Origin of Mineral Matter in Coal

Mineral matter within a mire will increase the overall ash content of the resulting coals. This mineral matter, which is derived from clastic sediment, becomes the inorganic, noncombustible portion of coal, consists of mineral and rock particles. These particles are introduced into the peat during deposition by either water or wind. Floods transport large amounts of sediment into the swamp, forming clastic layers called partings in the peat and ultimately the coal. Bioturbation at the base of the coal swamp may mix minerals into the peat. Mires downwind of volcanic activity periodically receive large amounts of volcanic ash. A layer of altered volcanic ash may form a tonstein, German for "clay stone," in the coal. Tonsteins commonly consist of kaolinite, smectite, and or mixed-layer clay minerals. Minerals introduced by wind or water include most clay minerals, quartz, feldspar, apatite, and heavy minerals, such as zircon and rutile.

Precipitated minerals may be finely disseminated particles or mineral aggregates in the coal. These minerals include siderite, pyrite, and chalcedony. During late stages of coalification, minerals precipitate along joints and in other voids in the coal. Late-forming minerals include calcite, dolomite, pyrite, quartz, and various chlorides. During secondary coalification, at greater depths and temperatures, chlorite may form by alteration of primary clay minerals.

Most (95%) of the minerals present in coal are composed of clay, pyrite, and calcite. Clay minerals make up 60–80% of the total mineral content of coal. The types of clay minerals are dependent on the chemical conditions at the site of deposition. Clay minerals can be detrital or secondary as precipitates from aqueous solutions. Fresh-water mires tend to favor in situ alteration of smectite, illite, and mixed-layer clay minerals to kaolinite because of the low pH. Illite is dominant in coals with overlying marine sediments, which develop in a moderately alkaline environment. Clay minerals can be finely dispersed throughout the coal or form layers.

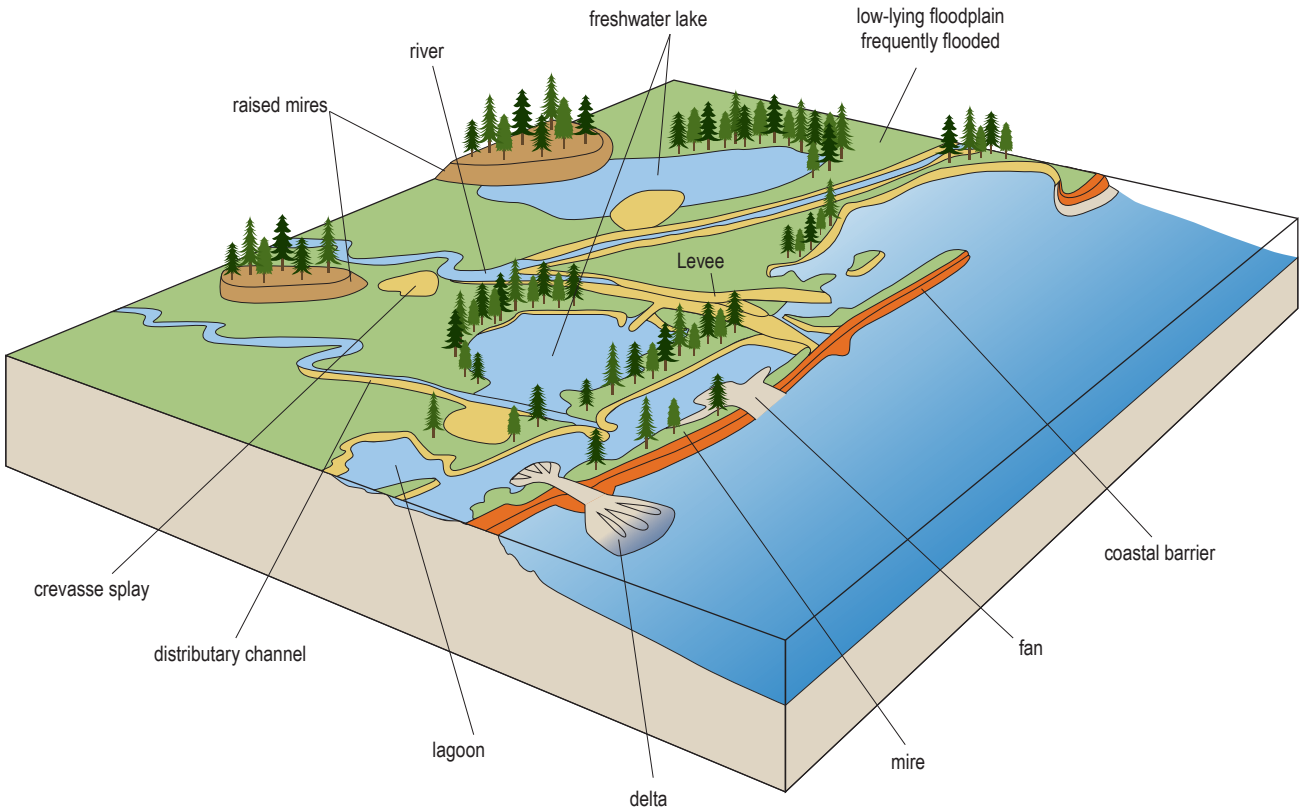


Figure 1. Location of mires in deltas and coastal barrier systems. Modified from Open University (2013).

Preservation and Rank

Preservation of peat in the geologic record is not guaranteed; sedimentation must continue without subsequent erosion of the peat. The peat must be buried and compressed by the pressure from the weight of the overlying sediments, which were deposited over time by wind, rivers, lakes, and seas. Compaction of the plant material forces out some oxygen, hydrogen, and other volatile matter, leaving mostly carbon behind in the peat. Depending on the type of organic material, about 10 ft of peat produces 1 ft of bituminous coal. Heat flow from nearby igneous activity or from the regional geothermal gradient, along with time, are the most effective elements in transforming peat to lower rank coals, such as lignite or subbituminous coal. With enough thermal maturation lower rank coals become higher rank coals like bituminous coal or anthracite.

Rank classification is determined by calorific value and fixed carbon content. Calorific value is measured in British thermal units per pound (Btu/lb); essentially the amount of energy necessary to raise the temperature of one pound of liquid water one degree Fahrenheit. Calorific value determines rank for coals with Btu values up to 14,000 Btu/lb. Fixed carbon is the solid residue other than ash, obtained by burning coal in the absence of air. Percent of fixed carbon within a coal is used to determine the rank of coals with calorific value greater than 14,000 Btu/lb (Table 1).

Lignite is the lowest rank of coal; American Society for Testing and Materials defines it as having less than 8,300 Btu/lb on a moist, mineral matter free basis (Table 1, American Society for Testing and Materials, 1981). Subbituminous coals range from 8,300–11,500 Btu/lb. Bituminous coals overlap with subbituminous from 10,500–11,500 Btu/lb. The subbituminous coals in this range are non-agglomerating coals, meaning that an agglomerate button capable of supporting a 500-gram weight did not form during determination of the volatile matter (Wood et al., 1983). High-volatile bituminous coals range from 10,500–14,000 Btu/lb. Medium and low-volatile bituminous coals are classified by the percent of fixed carbon and volatile matter. The amount of fixed carbon content determines higher rank. The highest rank coals are anthracites, which have less than 14% volatile matter and greater than 86% fixed carbon. When rank is determined from coal samples that conform to the ASTM testing methods the value is referred to as apparent rank. This term is used in discussing the rank of coals in the various New Mexico coal fields sections that follow.

Coal Resource Classification

Coal resources in the United States are classified by U.S. Geological Survey guidelines (Wood et al., 1983). The classification system quantifies total amounts of coal in the ground before mining as original resources and after mining as remaining resources. Resources included tonnage estimates for coal determined by summing the estimates of identified and undiscovered deposits of coal with specified thickness for different ranks with less than 6,000 ft overburden. Reserves are identified recoverable deposits that are considered economic at the time of classification. Categories of reserves are based on thickness of coal, depending on rank, and thickness of overburden. Demonstrated reserves include measured and indicated reserves. Measured reserves are calculated on coal thickness projected ¼ mile from point of measurement and indicated reserve are based on ¾ mile projection of coal thickness from point of measurement. Inferred reserves are based on projecting known coal thickness 3 miles from point of observation. Demonstrated and inferred reserves are included in what is called identified reserves. Because of the lenticularity of coals in New Mexico, demonstrated reserves are the preferred way of reporting reserves in the discussions that follow.

Geologic Periods of Coal Development

Land plants evolved on the Earth during the Devonian Period about 400 million years ago (Ma), but plant cover was not abundant enough to form peat mires that would become coal until 320 Ma during the Pennsylvanian Period. Although coal deposits are found in most geologic time periods since 320 Ma, there are two major coal-forming time periods throughout the world: 1) the Pennsylvanian to Permian Periods and 2) the Cretaceous Period to Eocene Epoch. Pennsylvanian-Permian coal deposits (320–268 Ma) make up most of the anthracites and high-grade bituminous coals. Eastern U.S. coal fields in the Appalachian Mountains and in the Interior Provinces are Pennsylvanian and Permian in age (Fig. 2). The Cretaceous and Eocene are the next major coal-forming times, as shown by coal deposits on every major continent from this time period. The rank of coals developed during this time range ranges from lignite to anthracite. In the United States, coals in the Rocky Mountains, Northern Great Plains, and the Gulf Coast regions (Fig. 2) are upper Cretaceous to Paleocene (100–56 Ma) in age.

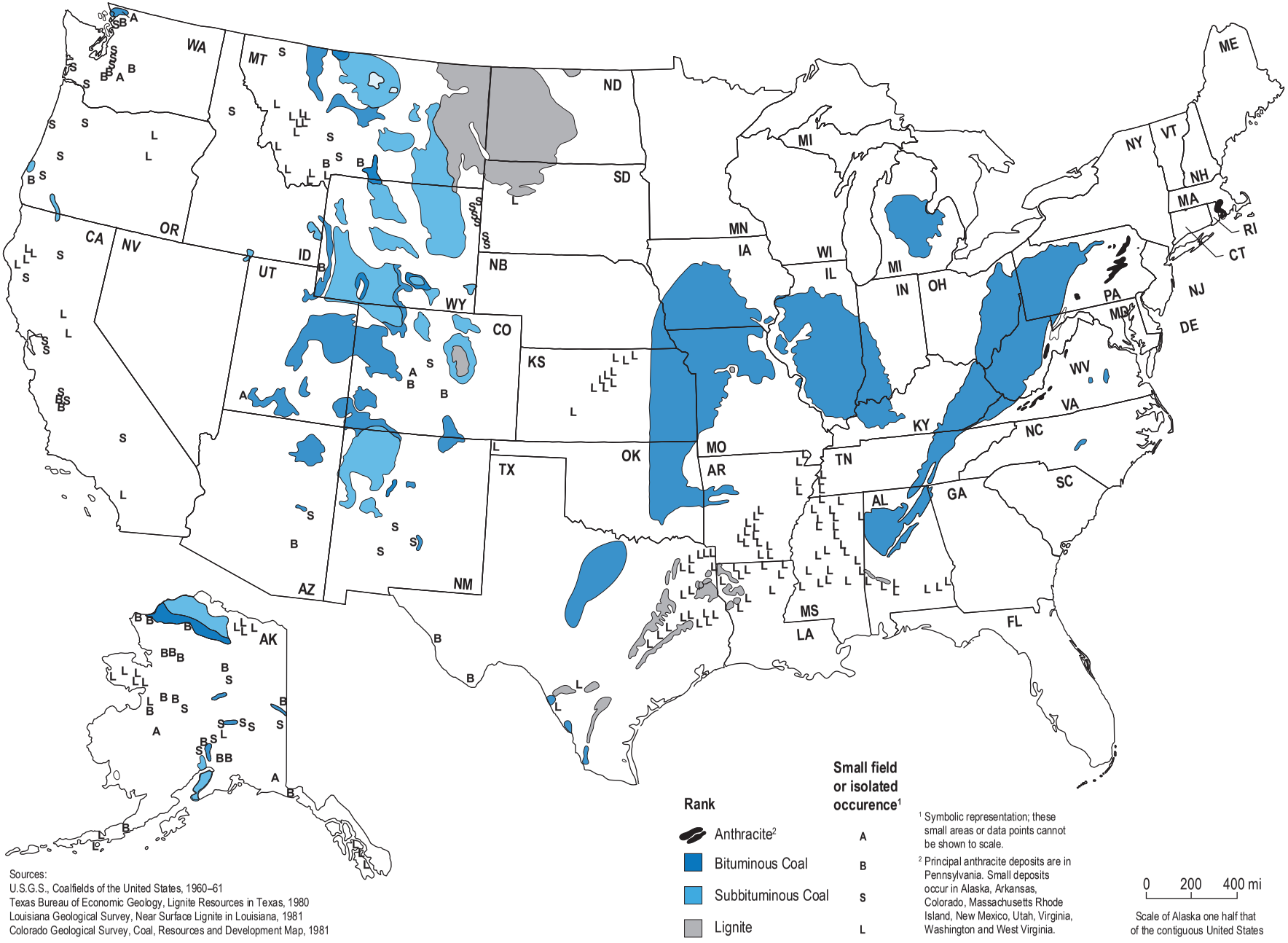


Figure 2. Coal-bearing areas of the United States (Energy Information Administration, 1996).

III. ECONOMICS OF COAL

The presence of coal in an area does not ensure that the coal will be mined. Several factors beside the thickness and quality of the coal determine whether a coal deposit is economic, including: 1) the technology available for extraction, 2) distance to a market and 3) available transportation network. Throughout the history of mining coal in New Mexico, these factors have changed along with the end use of coal. Spanish settlers used small amounts of coal several centuries ago for home heating by mining outcrops on a sporadic basis. Anthracite was mined in the Cerrillos field (Fig. 3) as early as 1835. Mining on a significant scale began in New Mexico in 1862, when U.S. Army troops from Fort Craig opened the Government mine in the Carthage field to supply coal for blacksmithing at Forts Selden, Bayard, and Stanton (Fig. 2, Hoffman and Hereford, 2009). Several of the smaller fields in the state were developed during the 1890s and early 1900s because railroads needed a nearby source of coal for fuel. Mining began in the 1880s in the southern San Juan Basin near Gallup supplying the Atchison Topeka and Santa Fe Railroad. In the 1890s, many narrow gauge railroads were built in the northeast part of the San Juan Basin to transport lumber. Coal for these operations came from mines near Monero and Lumberton. In the 1880s, railroad expansion in northeast New Mexico and the demand for good coking coal from smelters in the Southwest created a coal mining boom in the Raton Basin. Coking coals have high volatile matter content and when heated in the absence of air, these coals form a hard, porous solid composed of amorphous carbon called coke. Coke is used in the production of iron and steel in the smelting process. To meet the demands for Raton Basin coking coal, production increased and exceeded 1 million short tons in 1899 (Fig. 4). With the onset of World War I, nearby smelters, factories, and railroads increased output, and therefore the demand for coal increased, pushing coal production to over 4 million short tons in 1918. During this period, all mining was done by underground methods. The main underground method was room and pillar, whereby coal is extracted from coal beds creating rooms and pillars of coal are left on regular intervals within the seam to support the roof and control air flow in the mine. Although there had been some safety improvements and mechanization of extraction methods, mining continued to be a labor-intensive and dangerous process.

Railroads converted to diesel fuel and households and industry switched to natural gas, causing a decline in the state's coal production to less than 1 million short tons in 1950, reaching a low of 85,212 short tons in 1958 (Fig. 4). Several economically marginal coal-mining areas lost their markets when rail lines were abandoned for more direct or economic routes. Underground coal mining in New Mexico decreased significantly in the 1950s and 1960s as the railroads continued to convert to diesel.

Coal production increased dramatically in the early 1960s with the introduction of large-scale surface mining in McKinley and San Juan Counties in northwest New Mexico. The combination of inexpensive surface minable coal and the increased demand for electric power in Arizona, New Mexico, and California led to the opening of many mines in the San Juan Basin. The McKinley mine near Gallup (Fig. 3), operated by Pittsburg and Midway Coal, opened in 1962 and the Navajo mine operated by Utah Construction and Mining opened near Fruitland in 1963. Public Service Company of New Mexico (PNM) and Western Coal Company's San Juan mine, which was north of the San Juan River, began surface mining coal in late 1972. In 1977, Utah International (previously Utah Construction and Mining) began contract mining at the San Juan mine, and in 1980, PNM sold its assets to Utah International (Nickelson, 1988). In 1986, San Juan mine became a part of BHP and is now operated by the San Juan Coal Co., which is a wholly owned subsidiary of BHP Billiton. In February of 2016, Westmoreland acquired the San Juan mine. The Navajo and San Juan mines continue to mine coal in 2015 and, as of the year 2000, the San Juan mine switched their operations from surface to longwall underground mining. After nearly 30 years of production, the increased depth of the coal available for surface mining became economically prohibitive and beyond the limitations of the equipment. McKinley mine, one of the longest operating surface mines in the San Juan Basin, closed in 2010 because the economic surface coal had been mined out.

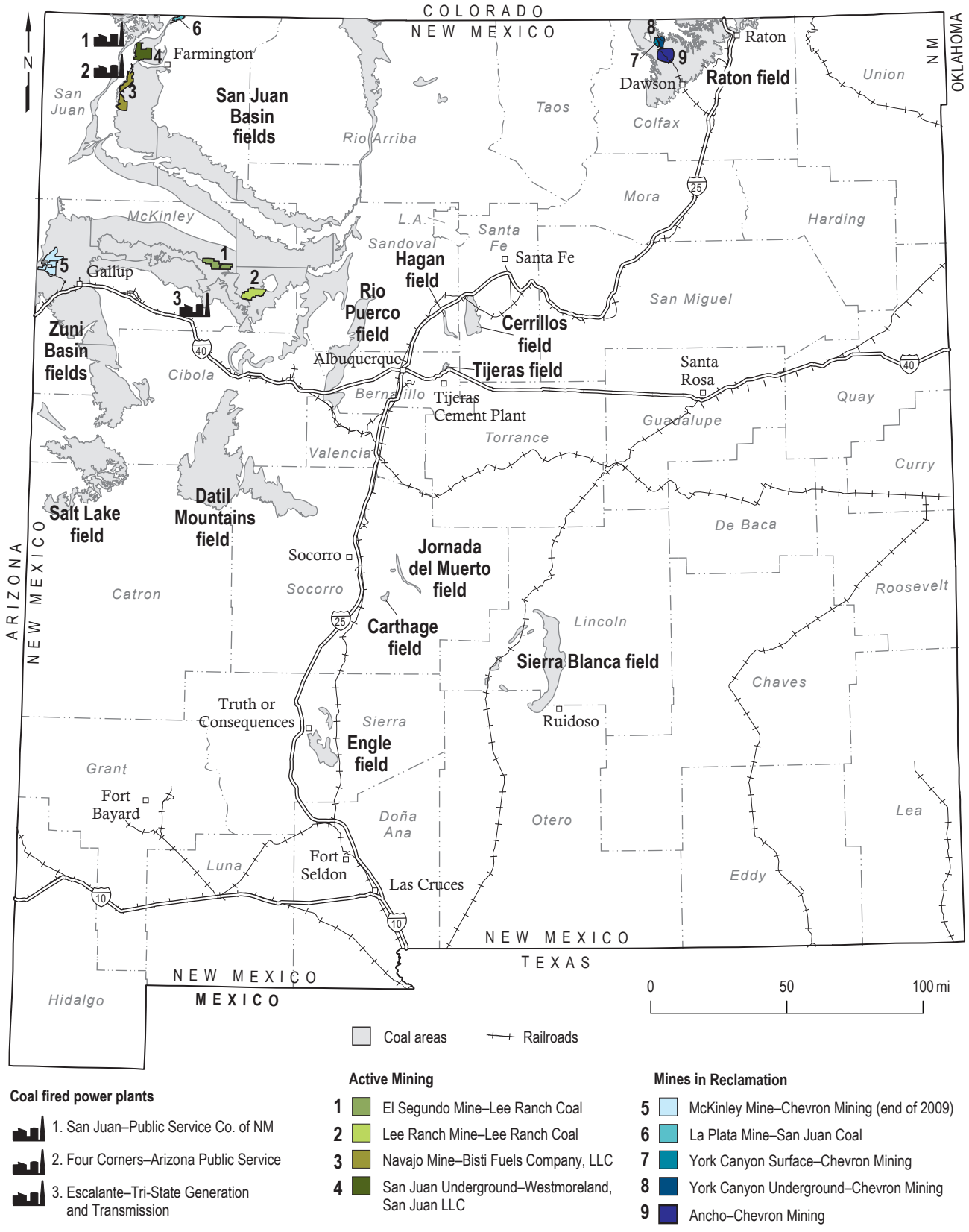


Figure 3. Coal fields of New Mexico, from Hoffman et al. (2009). Mines are surface operation unless specifically noted in legend. Lee Ranch Mining suspended in 2016.

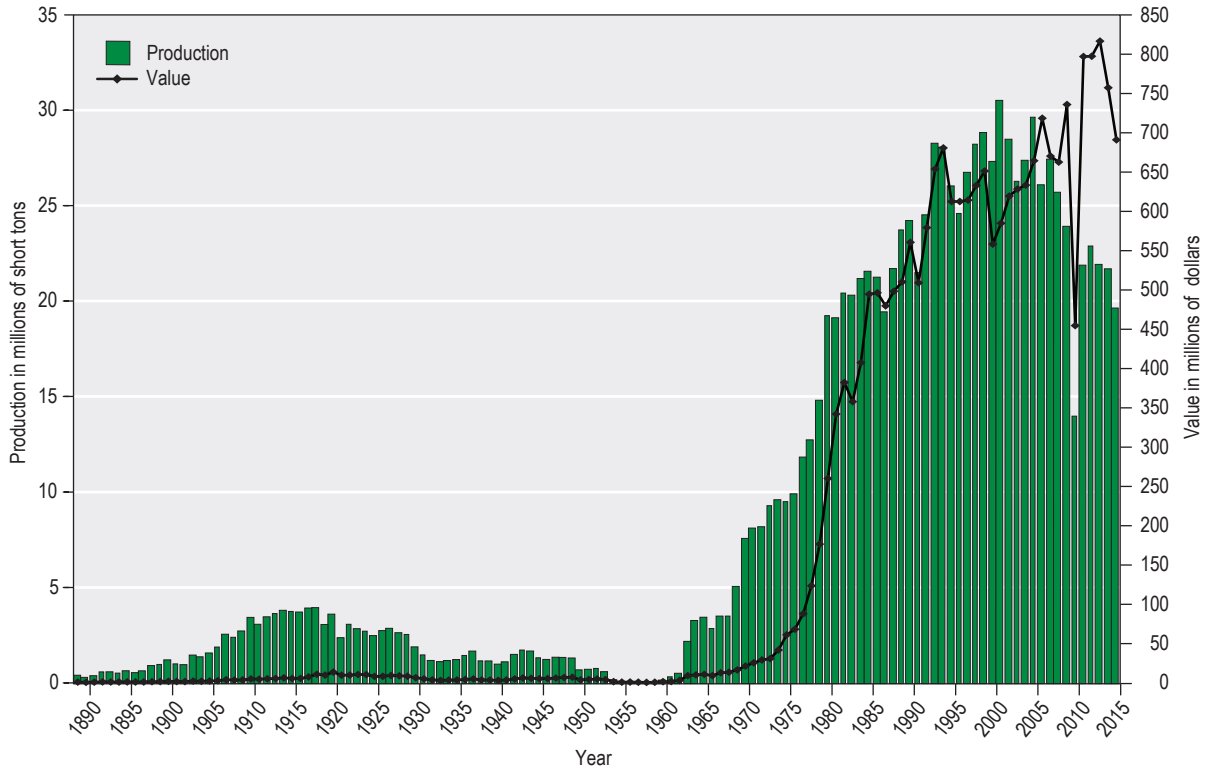


Figure 4. Coal production and value 1899–2015.

Near Raton, the Kaiser Coal Corp. York Canyon No. 1 underground mine began operations in 1966 and their West York Strip mine opened in 1972. Underground mining was still economic in the Raton area for two reasons: first, the rugged topography of the region limited the development of surface mines, and second, the high quality of the Raton coal was in demand. The York Canyon mines (Fig. 3, York Canyon No. 1 and West York Strip) supplied metallurgical grade coal to Kaiser's steel mills in California. The Kaiser Cimarron underground mine, also known as the Upper York Exploration mine, began production in 1985. With the decline of the U.S. steel industry during the 1980s, Kaiser needed to sell their coal holdings in the Raton area. The sale of the Kaiser Coal Corporation York Canyon Complex and other coal holdings in the Raton Basin to Pittsburg and Midway Coal Mining Co., a subsidiary of Chevron Mining, was completed in February 1989. In 1995, the last of the underground mines in the York Canyon complex closed because of roof and floor stability problems and the need for a better ventilation system. The Ancho surface mine closed in mid-2002. There are no current coal mining operations in the New Mexico part of the Raton Basin; today, the operations in the area use coal bed methane production to extract energy from coal.

By the 1970s, several factors influenced the coal mining industry in New Mexico and the nation. The Coal Mine Health and Safety Act of 1969 and the Surface Mine Control and Reclamation Act of 1977 added many safety and reclamation regulations that coal producers had to comply with, increasing the mining costs and forcing many of the small operators to close. The Clean Air Act, introduced in 1970, and its amendment in 1990 limited sulfur emissions from burning coal by 90%. This led to the development of the Powder River Basin in Wyoming and Montana, where there are vast reserves of low-sulfur coal. The Powder River Basin has 25 billion tons of economically recoverable low-sulfur coal resources accessible by surface mining with today's technologies (Scott and Luppens, 2013). In comparison, the San Juan Basin has about 12 billion tons of coal in demonstrated underground and surface reserves, but not all of this coal meets compliance standards (Energy Information Administration, 2011). When burned, compliance coal emits 1.2 lbs or less of sulfur dioxide (SO_2) per million Btu, equivalent to 0.72% sulfur/lb of 12,000 Btu coal (Energy Information Administration, 1993). Development of the Powder River Basin has influenced the entire U.S. coal market. The 50–100-ft thick, low-sulfur coal beds in this region result in very low coal prices because of very little waste material being moved during coal extraction ($13.92/ton

as of 2015), and the extensive rail network in Wyoming allow Powder River Basin coal to be shipped anywhere in the country and to be competitively priced with local sources. As of 2015, 42% of the nation's total coal production comes from the Powder River Basin.

Although New Mexico coals are relatively low in sulfur content, the cost of mining these coals is relatively high and New Mexico coal cannot be easily transported long distances. The cost of coal production is increased by the geology of the coal-bearing units with multiple, relatively thin coal seams and the necessary removal of interburden between these seams. New Mexico does not have a rail transportation network covering the entire state (Fig. 3). The mines near Farmington are all near to the power plants that they serve; therefore, they do not need long-distance transportation. The proximity of the mine to the power plants is referred as a mine-mouth situation. Instead of coal, electricity is transported from these mine-mouth power plants to markets in Arizona, New Mexico, and California. The Lee Ranch and El Segundo mines northwest of Grants (Fig. 3) have rail spurs linking to the main rail line so that they can transport their coal to nearby power plants in Arizona and New Mexico. The Lee Ranch and El Segundo coal are economic because of the quality of the coal and it meets the specifications of the boilers at these plants.

Trends in New Mexico coal production mirror the national trends of increased productivity from fewer surface mines (Maksimovic and Mowry, 1993), largely because of technological advances, including the use of computers and global positioning systems that are integrated into the mining equipment. From 1988 through 1993, New Mexico annual total coal production exceeded 20 million short tons. In 1988, nine mines were producing in the state; eight of them were surface mines and one was an underground mine in the Raton field. By 1992, the number of operating mines decreased to seven, six surface and one underground, and the 1993 total production of 28,294,480 short tons (EMNRD Annual Report, 1994) was greater than the previous record high of 21,736,854 short tons in 1988 (Hatton, 1988–1994). In 2005, production reached 29,650,833 short tons (EMNRD Annual Report, 2006) with five coal mines operating in the state. Of the five mines, four were surface and one was an underground operation (Figs. 3, 4). Annual production has decreased since this high because of the downturn in the overall U.S. economy; however, the general trend is toward greater productivity at the remaining mines primarily because of technology.

New Mexico's coal industry follows another national trend; the number of companies involved in operating the State's coal mines has decreased from five in 1988 to three in 1993. With the closure of the Pittsburg and Midway mines, a subsidiary of Chevron Mining, the Ancho mine near Raton and McKinley mine northwest of Gallup (Fig. 3), only two coal companies have operations in New Mexico (as of 2015). These companies are BHP Billiton (Navajo mine), and its subsidiary San Juan Coal Co. (San Juan) and Lee Ranch Coal Company, which is a subsidiary of Peabody Energy (Lee Ranch and El Segundo mines). The decreased number of companies operating mines is partly because of the high cost of operating large coal mines while complying with the necessary reclamation and safety regulations. Only large companies or conglomerates are financially able to keep these operations going and remain competitive. The environmental constraints on generating stations have also had an impact on coal mining and will be a large factor on future coal production (see Hoffman, 2014a,b). The Navajo Nation has signed an agreement in 2013 to purchase the Navajo mine from BHP. BHP will continue management of the mine until 2016. BHP has sold the San Juan mine to Westmoreland Coal Company, a Colorado based company. Westmoreland took over operations Feb. 1, 2016.

Coal continues to supply a large portion of the U.S. electricity (30.4%; Energy Information Administration, 2016), but the use of coal has declined since 2007 due to slow growth in the economy, price competition from natural gas, and increased use of renewable technologies. Use of coal to supply electricity to the public and industrial applications will depend on emission policies and on natural gas production in the U.S. from domestic shale deposits. In addition to more plentiful supplies of natural gas, the price advantage of coal over natural gas for electrical generation will decrease. Other factors, such as lower emissions and the efficiency of natural gas plants to produce electricity, will affect coal production in the future. Stricter emission regulations set by the EPA have both the San Juan and Four Corners generating stations near Farmington shutting down four older units and to install non-catalytic reduction technology on the remaining units. Public Service of New Mexico plans to replace some of the power generated by coal with a natural gas facility. Public Service of New Mexico announced in March of 2017 that the San Juan Generating Station will no longer be economically viable after 2022 and will expedite the company's transition away from generating electricity from coal. This announcement comes a few years after an agreement with the State of New Mexico and other interested parties to close two of the plant's four coal units by December 2017. These changes will result in lower coal production in the New Mexico.

IV. COAL-BEARING AREAS AND FIELDS IN NEW MEXICO

Pennsylvanian coal outcrops are found in north-central New Mexico at several localities in Santa Fe County, southeast of Taos, northwest of Las Vegas, north of Pecos, and in the subsurface in southeast New Mexico (Shomaker et al., 1971, 177–179). These beds are some of the western-most Pennsylvanian-age coal in the United States. Pennsylvanian coal beds and laminae in north-central New Mexico are mainly in the Sandia Formation of the Magdalena Group, although some coals occur in younger units. Thicker beds (~4 ft) are impure, lenticular, and replaced in many places by channels that are filled with pebbly sandstone (F. Kottlowski, written communication, 1993). Pennsylvanian-age coal was mined for local use along the Pecos River, northwest of Las Vegas and in northeast Santa Fe (Kottlowski, 1963), in the 1890s and early 1900s. However, the Pennsylvanian-age coal lacks commercial importance in today's market.

Most of the coal in New Mexico is concentrated in the northern half of the state, primarily within the San Juan and Raton fields (Fig. 3). These two locations are two arcuate subsurface basins formed during the Laramide Orogeny (80–40 Ma). The San Juan Basin is on the southeast margin of the Colorado Plateau, and the Raton Basin is between the Sangre de Cristo Mountains and the High Plains; both basins extend into Colorado. The remaining small coal fields in the state are in the Southern Rocky Mountains and northern Basin and Range physiographic provinces. Outliers of the San Juan Basin are the Salt Lake, Datil Mountains, Tierra Amarilla, and Rio Puerco fields.

Coal fields outside the major basins include the Cerrillos field, southwest of Santa Fe; the Hagan and Tijeras fields, northeast of Albuquerque on the east side of the Sandia Mountains; the Jornada del Muerto and Carthage fields, southeast of Socorro; the Sierra Blanca field, coal-bearing outcrops encircling Sierra Blanca, northwest of Ruidoso; and the Engle field east of Truth or Consequences (Fig. 3).

In addition to these defined coal fields, thin Cretaceous coal beds, locally used for heating and cooking in homes (home fuel) before 1900, occur in the southern San Andres Mountains, northeast of Las Cruces, and in the northeast corner of the state.

Coal-Bearing Rocks

During the Late Cretaceous (100–66 Ma), foreland basins stretched along the western margin of the Western Interior Seaway. Most of the Late Cretaceous coals developed in nearshore coastal plain environments. San Juan Basin coals are concentrated in three major coal-bearing sequences that, in ascending order, are: the Crevasse Canyon, Menefee, and Fruitland Formations. The Raton field has two coal-bearing sequences: the Vermejo and the Raton Formations (Pillmore, 1969). The Vermejo Formation coal and lower coal zone within the Raton Formation are Late Cretaceous; coal in the upper Raton Formation is Paleocene in age. In some areas, the Dakota Sandstone (early Late Cretaceous) contains thin coal beds and coal laminae, but these have been mined only in a few localities and on a small scale. Outcrops of the Tres Hermanos Formation, the Crevasse Canyon, and Menefee Formations in the southern San Juan Basin delineate most of the small coal fields outside the major basins.

Late Cretaceous nomenclature

The Mesaverde type locality at Mesa Verde National Park is limited to the Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone. The Mesaverde Group, as defined by Beaumont et al. (1956), includes the Crevasse Canyon. Beaumont et al. (1956) revised the nomenclature in the southern San Juan Basin as a result of the extensive mapping done by the U.S. Geological Survey in the western and southern parts of the San Juan Basin. As mapping progressed on the southwest side of the San Juan Basin, the workers recognized other coal-bearing units within what was originally called the Mesaverde Formation. These coal-bearing units are prevalent in the Gallup area where there is no Point Lookout Sandstone and

where the Menefee and Crevasse Canyon are undifferentiated. The Gallup coal area is beyond the extent of the shoreline where the Point Lookout was deposited; therefore no Point Lookout Sandstone is present between the coal-bearing sequence of the Gibson Coal Member (Crevasse Canyon) and Cleary Coal Member (Menefee Formation). When Sears (1925) mapped the Gallup area, he used the term Mesaverde Formation for the strata above the Mancos Shale that were lithologically similar to the Mesaverde Formation in northwestern New Mexico—southwestern Colorado. He divided the units that he recognized into five members of the Mesaverde Formation: the Gallup sandstone, Dilco coal, Bartlett barren, Gibson coal, and the Allison barren members of the Mesaverde Formation. The workers who were mapping the coal-bearing units carried many of these unit names eastward along the southern part of the San Juan Basin (Sears, 1936, Dane, 1936, Hunt, 1936). Beaumont et al. (1956) revised the nomenclature in the San Juan Basin by raising the Mesaverde to group status and accepting the Crevasse Canyon as a formation (Allen et al., 1954) that is part of the Mesaverde Group between the Gallup and Point Lookout sandstones; both the Gallup Sandstone and Point Lookout Sandstone are recognized as formations. In Beaumont et al. (1956), the Cleary Coal Member of the Menefee was proposed as the new name for the upper part

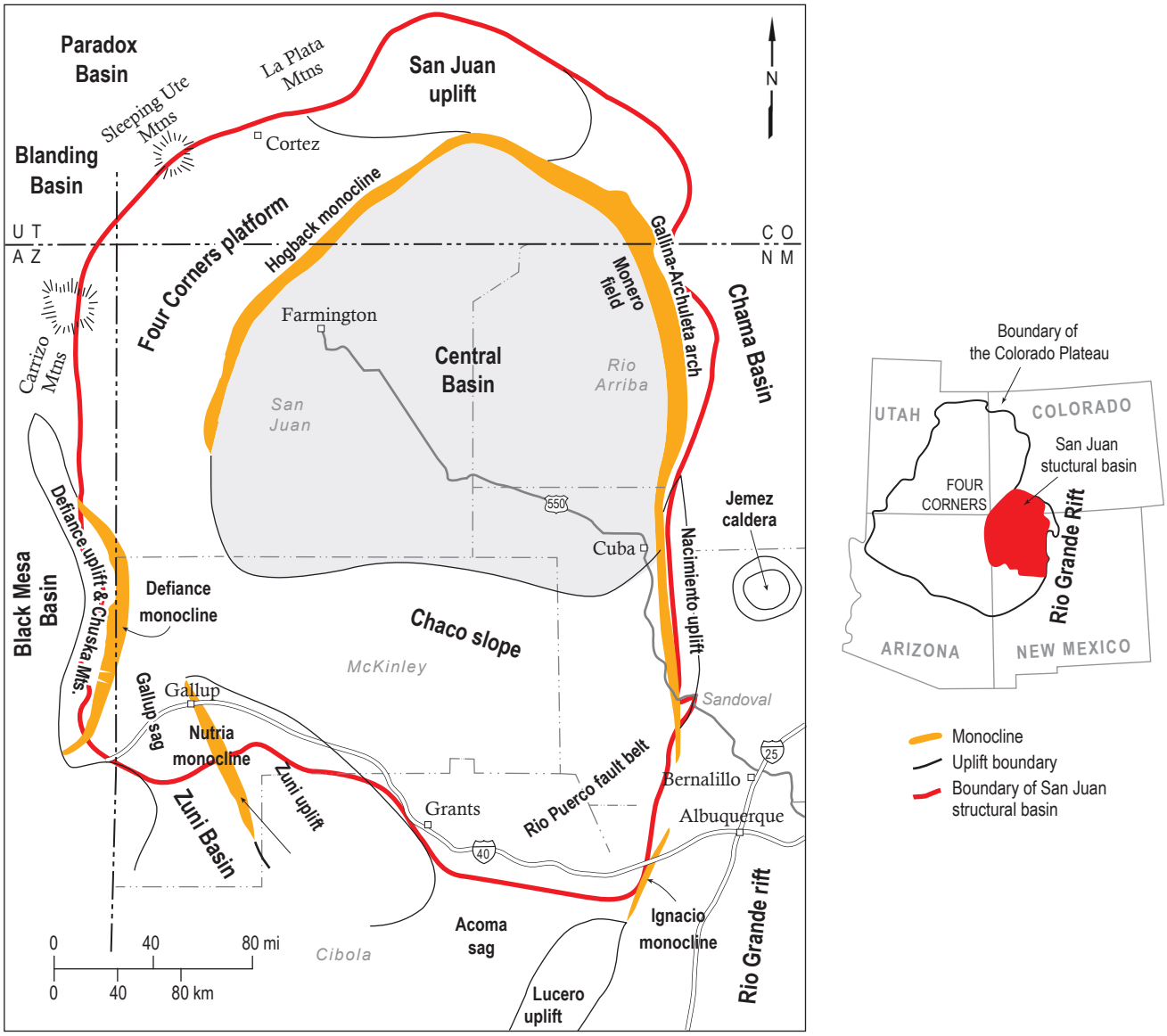


Figure 5. Structural features of the San Juan Basin and adjacent areas. Chaco Slope is are south of the Central Basin, starting approximately at the subaerial exposure of the Pictured Cliffs Sandstone. Modified from Craigg (2001).

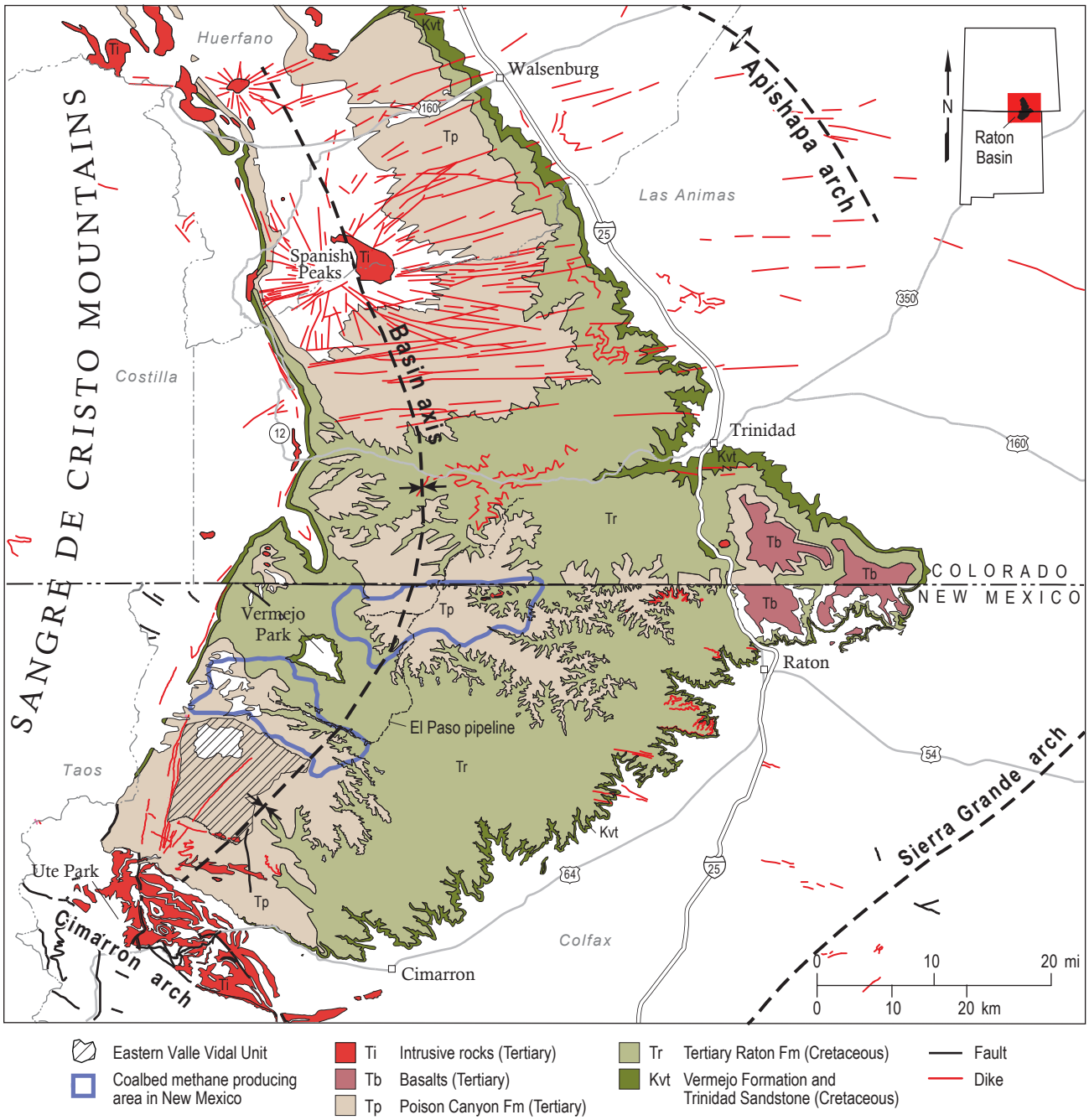


Figure 6. Geology and structural features of the Raton Basin, Colorado and New Mexico. Geology derived from New Mexico Bureau of Geology and Mineral Resources (2003) and Tweto (1979).

of the Gibson Coal Member. The Mesaverde Group, as defined by Beaumont et al. (1956), includes units from the base of the Gallup Sandstone through the Cliff House Sandstone. The Mesaverde Group is seen on the Geologic Map of New Mexico (Dane and Bachman, 1965). When speaking of the Mesaverde Group, Molenaar (1977, p. 164) said, "In the southern San Juan Basin and areas farther south, the base of the Mesaverde is placed at the base of the Gallup."

Most of the geologic investigations done by Beaumont, Sears, and Hunt were on the coal-bearing sequences in the southern San Juan Basin and outlying coal areas, including the Crevasse Canyon in the Mesaverde Group. Therefore, this nomenclature is seen in much of the coal geology literature for the San Juan Basin. Whenever possible in this chapter, the specific formation or member will be used when describing the units in the different coal areas.

Structural Geology of the Coal-Bearing Basins and Other Areas

The San Juan Basin is a roughly asymmetrical circular structural depression. The depression is deeper in the northeastern part of the basin. Late Cretaceous and Paleocene strata dip steeply into the basin on the northwest along the Hogback monocline and on the east along the Gallina-Archuleta arch and Nacimiento uplift (Fig. 5). Gentle dips predominate in the south and southwest sections (Chaco slope) of the basin. The deepest part of the basin is about 30 mi west of the Monero field on the northeast edge of the basin. In the deepest part, the Late Cretaceous coals are as much as 9,000 ft below the surface. Along the southern edge of the San Juan Basin, several structural features influence the Late Cretaceous coal-bearing units (Fig. 5), particularly where faulting is more prevalent. These structural features are described in detail within the field discussions.

The Raton Basin is an arcuate, asymmetrical syncline, extending from southeast Colorado into New Mexico. The Raton Basin is bounded by the Sangre de Cristo Mountains on the west and the low Sierra Grande arch on the east (Fig. 6). The east limb has gentle dips of 1–5°NW and lacks significant faulting (Wanek, 1963). Faulting and steep dips, with vertical to overturned beds, are both associated with the Sangre de Cristo Mountains on the western edge of the basin. The Vermejo Park anticline, which is prominent in the New Mexico part of the basin, is the result of a buried intrusive (Pillmore, 1976). To the south is the Cimarron arch that separates the Raton Basin from the Las Vegas Basin.

Outside the San Juan and Raton Basins, faulting and igneous activity has influenced the smaller fields. The Rio Puerco, Carthage, and Jornada del Muerto fields on the edge of the Rio Grande rift, are cut by many faults that create small blocks. Igneous intrusives in the Cerrillos field have metamorphosed nearby Late Cretaceous coal to semianthracite and anthracite. Both the Datil Mountains and Sierra Blanca fields have thick layers of Tertiary and Quaternary volcanic rocks overlying large areas of the coal-bearing strata. Faulting and intrusive dikes intersect the coal-bearing units in the Sierra Blanca and Cerrillos fields.

V. LATE CRETACEOUS AND PALEOCENE COAL-BEARING SEQUENCES IN NEW MEXICO

Introduction and Geologic Setting

In the Late Cretaceous, the Colorado Plateau and adjacent areas were part of the large Western Interior Seaway. The folding and thrusting tectonic activity of the Sevier Orogeny developed foreland basins during this time, which were prime areas for the development of coal-bearing sequences from Northern Mexico to Western Canada. In New Mexico, the San Juan Basin is the major area encompassing these Late Cretaceous deposits. The San Juan Basin covers more than 26,000 mi^2 in northwestern New Mexico and adjoining southwestern Colorado. Approximately 600 mi^2 are underlain by surface-minable coal. Coal in the San Juan Basin is part of a thick, Late Cretaceous-age sequence deposited during many of the major transgressions and regressions of the northwest-trending (approximately N55°W) shorelines of a Western Interior epicontinental sea. Most of the coal deposits were formed in coastal mires that were developed subparallel to the shoreline. These coal deposits consist of four intertonguing and laterally correlative facies from southwest to northeast: 1) floodplain and lacustrine deposits, typically lenticular sandstones and shales, 2) coastal deposits of shale, siltstone, coal, and channel sandstone, 3) beach and nearshore sediments including extensive sandstones, lagoonal siltstones, and interbedded sandstones and shales; and 4) offshore marine deposits of the neritic and sublittoral zones composed principally of fossiliferous shales, lenses of fine-grained sandstones and siltstones, and thin beds of argillaceous limestone (Beaumont, 1973).

The basal Dakota Sandstone (Cenomanian Age) marks the first major marine transgression of the Late Cretaceous seaway in the San Juan Basin (Fig. 7). The Dakota is a variable sequence of marine sandstone, lacustrine shale, non-marine shale and coal (Shomaker et al., 1971). The only minable coal of the Dakota is in southwestern Colorado, near Cortez (Fig. 5). The Mancos Shale and its members represent the marine section of the first transgressive phase, overlying and intertonguing with the Dakota Sandstone. Subsequent regression of the shoreline (R-1 of Molenaar, 1983a) during the Turonian Age resulted in deposition of the marine Atarque Sandstone in the Salt Lake field and the equivalent Atarque Sandstone Member of the Tres Hermanos Formation present in other areas of the state. The Atarque is overlain by the coal-bearing Moreno Hill Formation in the Salt Lake field, but the Atarque is the basal member of the Tres Hermanos Formation, which is north of the Salt Lake field in the Zuni area, and to the southeast in the Datil Mountains and Carthage fields. The Moreno Hill is, in part, laterally equivalent to the coal-bearing Carthage Member of the Tres Hermanos Formation (see Fig. 7). The Tres Hermanos deposition was limited to a wedge south of Gallup, which includes the Zuni Basin (Figs. 5, 7), Datil Mountains and, in south central New Mexico in the Carthage, Jornada del Muerto and Sierra Blanca fields (Fig. 3). To the north, the Carthage Member grades laterally into the lower Mancos Shale. The retreat of the shoreline that deposited these units was short-lived. The following transgression (T-2, Molenaar, 1983a) is represented by the Fite Ranch Sandstone Member of the Tres Hermanos Formation that intertongues with and is overlain by the Pescado Tongue of the Mancos Shale in the Zuni Basin and the D-Cross Tongue in the Acoma Basin and areas south and east of Socorro. The Gallup Sandstone, coal-bearing lower Dilco Coal Member, and fluvial Torrivio Sandstone Member (considered part of the Crevasse Canyon Formation by Molenaar et al., 1996) are part of the subsequent regression of the shoreline (R-2). The Borrego Pass Lentil of the Crevasse Canyon Formation represents a stillstand in the next transgressive (T-3) shoreline, and is overlain by the Mulatto Tongue of the Mancos Shale. The upper Mulatto Tongue, Dalton Sandstone, and Gibson Coal members of the Crevasse Canyon were deposited during the ensuing shoreline shift during

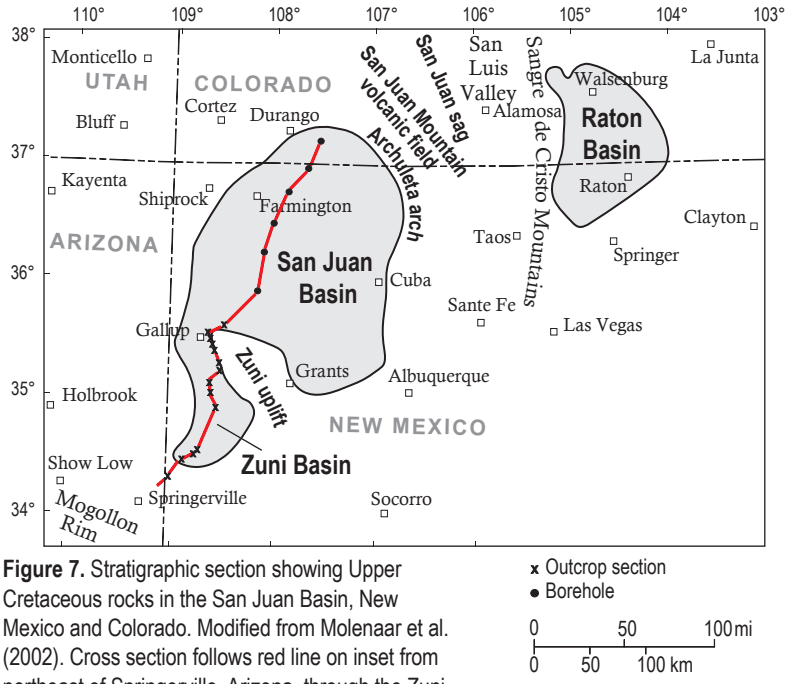


Figure 7. Stratigraphic section showing Upper Cretaceous rocks in the San Juan Basin, New Mexico and Colorado. Modified from Molenaar et al. (2002). Cross section follows red line on inset from northeast of Springerville, Arizona, through the Zuni and San Juan Basins in northwest New Mexico to just southeast of Durango, Colorado.

Southwest ←

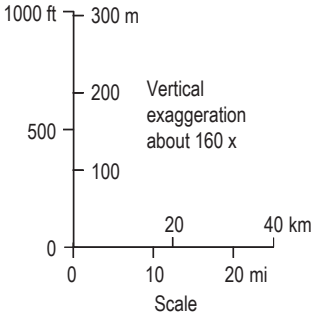
Facies colors for Cretaceous rocks

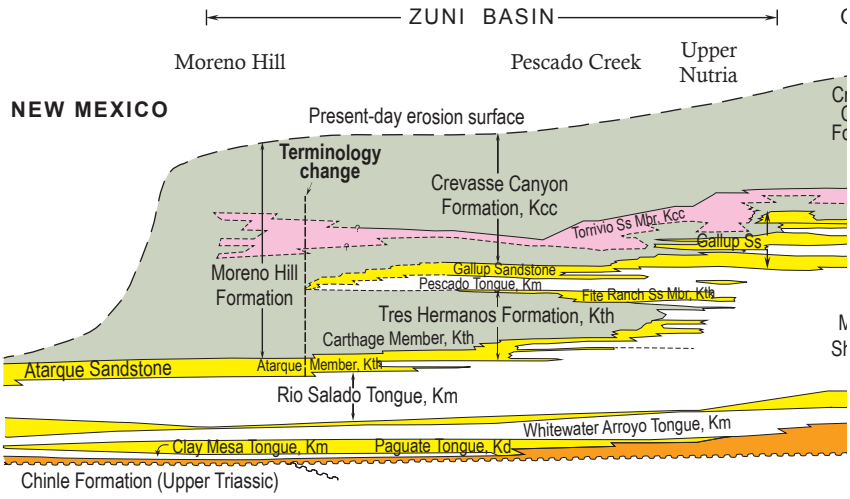
- Nomarine strata (various formations)
- Marine and coastal sandstone
- Dominantly marine shale siltstone
- Marine carbonate rocks
- Continental nearshore marine
- Fluvial sandstone

Abbreviation for stratigraphic units

Kk	Kirtland Shale
Kl	Lewis Shale
Kch	Cliff House Sandstone
Kpl	Point Lookout Sandstone
Km	Mancos Shale
Kcc	Crevasse Canyon Formation
Kth	Tres Hermanos Formation
Kd	Dakota Sandstone

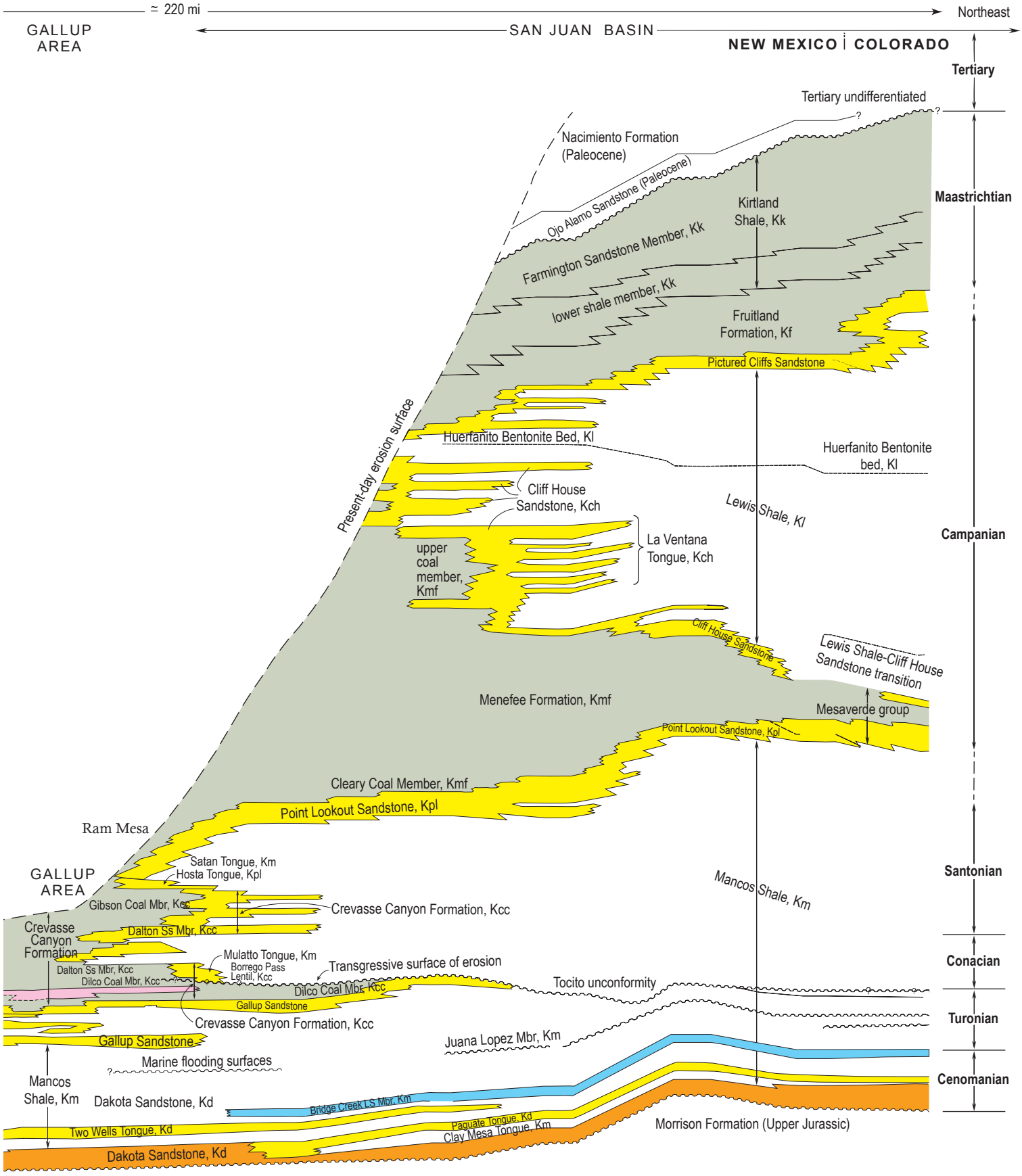
- Formation or member contact
- Contact that rises (uniformly or abruptly) in stratigraphic position—queried where uncertain
- Contact, position uncertain
- Unconformity—queried where uncertain





Santorian time (R-3). The Dilco Coal, Bartlett Barren, and Gibson Coal members outcrop in the Gallup and Crownpoint fields and in the Rio Puerco field and Mount Taylor area. The following major transgression of the sea (T-4) was relatively abrupt and, in some areas, the marine Mancos Shale directly overlies the paludal upper Gibson Coal Member (Molenaar, 1977). The Hosta Tongue of the Point Lookout Sandstone is part of this transgressive cycle and caps several mesas in the Crownpoint field.

The Satan Tongue of the Mancos Shale, the Point Lookout Sandstone, and the Cleary Coal Member of the Menefee were deposited during the following retreat of the shoreline in the Campanian (R-4). During this progradation across the San Juan Basin, the coastal-barrier Point Lookout Sandstone rose stratigraphically by 1,200 ft, and moved over a horizontal distance of 130 mi (Molenaar, 1977, p. 164). Exposures of the Point Lookout occur from northeast of Gallup to the northeast edge of the basin near Monero, New Mexico. The deposits of the upper Menefee Formation, the Cliff House Sandstone, and the lower Lewis Shale represent the final transgression of the shoreline (T-5) in the San Juan Basin. Within this overall transgressive sequence, there are minor regressions and major stillstands in the shoreline.


≃ 220 mi
Northeast
GALLUP AREA
SAN JUAN BASIN
NEW MEXICO | COLORADO
Tertiary
Tertiary undifferentiated
Nacimiento Formation (Paleocene)
Ojo Alamo Sandstone (Paleocene)
Kirtland Shale, Kk
Maastrichtian
Farmington Sandstone Member, Kk
lower shale member, Kk
Fruitland Formation, Kf
Pictured Cliffs Sandstone
Present-day erosion surface
Huerfanito Bentonite Bed, Kl
Huerfanito Bentonite bed, Kl
Cliff House Sandstone, Kch
Lewis Shale, Kl
Campanian
La Ventana Tongue, Kch
upper coal member, Kmf
Cliff House Sandstone
Lewis Shale-Cliff House Sandstone transition
Menefee Formation, Kmf
Mesaverde group
Point Lookout Sandstone, Kpl
Cleary Coal Member, Kmf
Point Lookout Sandstone, Kpl
Ram Mesa
GALLUP AREA
Satan Tongue, Km
Hosta Tongue, Kpl
Mancos Shale, Km
Santonian
Gibson Coal Mbr, Kcc
Crevasse Canyon Formation, Kcc
Crevasse Canyon Formation
Dalton Ss Mbr, Kcc
Mulatto Tongue, Km
Borrego Pass Lentil, Kcc
Transgressive surface of erosion
Dalton Ss Mbr, Kcc
Dilco Coal Mbr, Kcc
Conacian
Tocito unconformity
Dilco Coal Mbr, Kcc
Gallup Sandstone
Turonian
Crevasse Canyon Formation, Kcc
Gallup Sandstone
Juana Lopez Mbr, Km
Marine flooding surfaces
Cenomanian
Mancos Shale, Km
Dakota Sandstone, Kd
Bridge Creek LS Mbr, Km
Two Wells Tongue, Kd
Paguate Tongue, Kd
Clay Mesa Tongue, Km
Morrison Formation (Upper Jurassic)
Dakota Sandstone, Kd

These stillstands deposited the La Ventana Tongue of the Cliff House Sandstone on the southeast side of the San Juan Basin. The La Ventana Tongue intertongues shoreward with the upper coal member of the Menefee Formation (Beaumont and Hoffman, 1992).

The marine upper Lewis Shale, coastal Pictured Cliffs Sandstone, coal-bearing Fruitland Formation, and nonmarine Kirtland Formation were deposited during the Campanian-Maastrictian Ages as part of the last retreat (R-5) of the epicontinental sea from the San Juan Basin. The retreat of the shoreline continued in the Raton Basin with the deposition of the Trinidad Sandstone. The deposition of the Trinidad Sandstone is the lithogenic equivalent of the Pictured Cliffs Sandstone. The overlying nonmarine Vermejo Formation is equivalent to the Fruitland Formation.

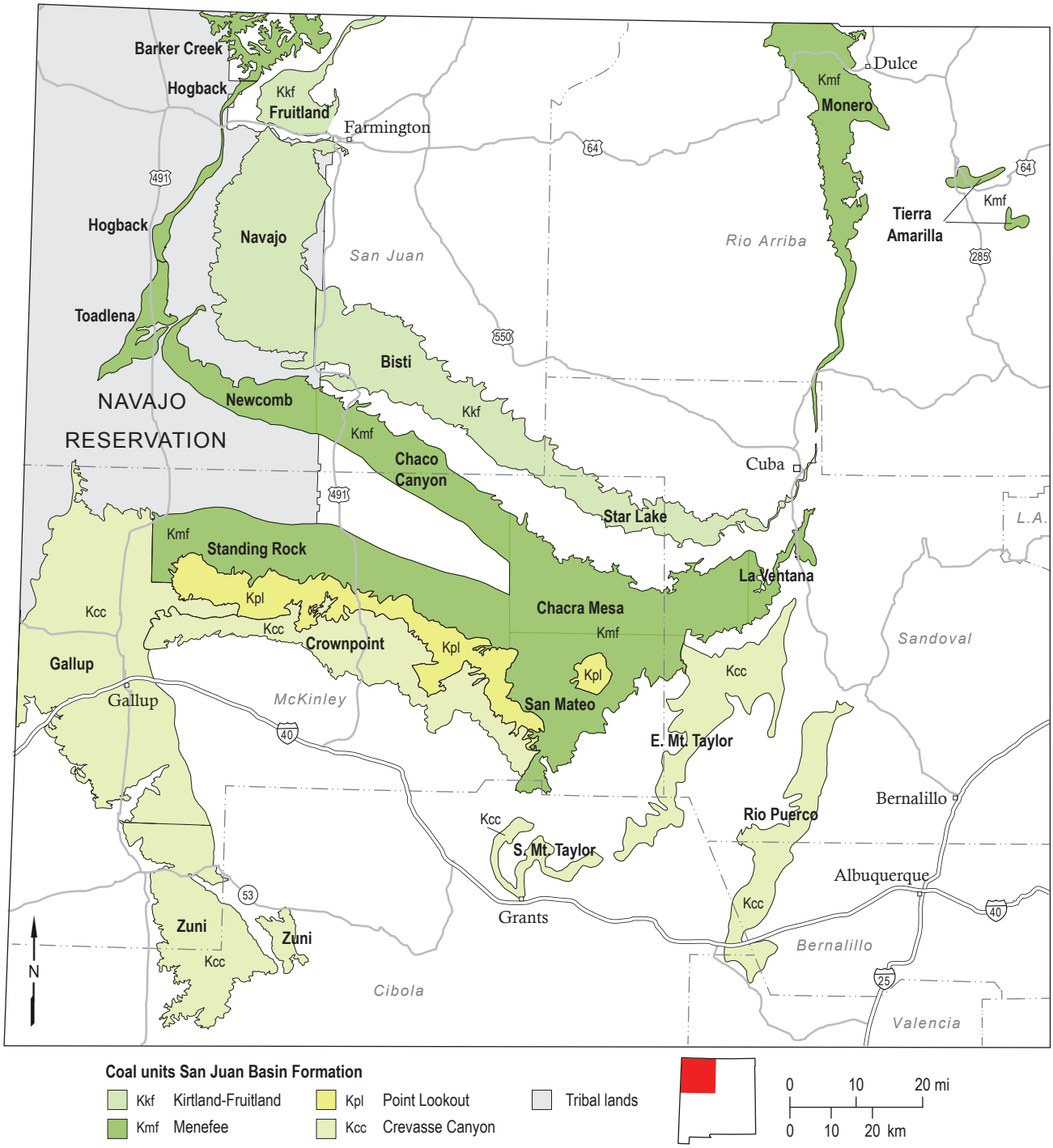


Figure 8. San Juan Basin coal fields. Modified from McLemore, et al. (2005).

The retreat of the epicontinental seaway from the Western Interior in the Maastrictian Age marked a change in the tectonic style from the folding and thrusting of the Sevier Orogeny to localized uplifts and partitioning of basins of the Laramide Orogeny (Roberts and Kirshcbaum, 1995). The formation of intermontane basins created several effects including 1) internal drainage and 2) a change from coastal sequences to fluvial sequences being deposited. Changing to fluvial depositional environments result in peat development changing from low-lying mires to raised mires. The Raton Formation, which is the youngest major coal-bearing sequence in New Mexico in the Raton Basin, developed in a fluvial environment. The Raton Formation is of Late Cretaceous–Paleocene Periods and contains the K-Pg boundary, formerly known as the K-T boundary. The K-Pg boundary is a clay layer rich in iridium, indicative of a massive asteroid impact with Earth that occurred about 65.5 million years ago. This impact is believed to have brought about the mass extinction of dinosaurs and represents the end of the Cretaceous Period.

Coal-Bearing Sequences and Fields

The major coal-bearing formations in the San Juan Basin include the Crevasse Canyon, the Menefee, and the Fruitland Formations. The Late Cretaceous Vermejo and lower Paleocene Raton Formations are major coal-bearing sequences in the Raton Basin.

Individual coal beds within the upper Cretaceous units of the San Juan Basin are highly lenticular and their minable thicknesses rarely extend laterally for more than 6 mi. Thus, a complete discussion of individual coal beds is impossible. Descriptions of coal beds, therefore, are done by referring to the coal-bearing members and coal-bearing formations in an individual field or area. The San Juan Basin is subdivided into coal fields or coal areas (Fig. 8), which are defined by formation and public land survey boundaries (Shomaker et al., 1971).

San Juan Basin coal fields by formation.

Fruitland Formation fields	Menefee Formation fields	Crevasse Canyon Formation fields
Fruitland	Barker Creek	Gallup
Navajo	Hogback	Zuni
Bisti	Toadlena	Crownpoint
Star Lake	Newcomb	East Mount Taylor
	Chaco Canyon	South Mount Taylor
	Chacra Mesa	Rio Puerco
	Standing Rock	
	San Mateo	
	La Ventana	
	Monero	
	Tierra Amarilla	

These fields were delineated by Shomaker et al. (1971) to facilitate a discussion of the surface-minable, low-sulfur coal within the basin. The field designations by Shomaker et al. (1971) are used in the following discussions. Shomaker et al. (1971) concentrated on the main part of the San Juan Basin and did not deal with the outliers of the basin or the small coal fields in New Mexico, nor did they discuss the Raton Basin. Many of these outliers, the Salt Lake and Datil Mountains fields in particular (Fig. 3), have coal-bearing formations that are of an older age than the Crevasse Canyon. The following discussions are presented in order of the age of the coal units that are present within a field.

Mutual's Black Star Mine railroad loading dock, near Gallup, New Mexico, McKinley County, October 26, 1942. *Photo courtesy of R. H. Allport, New Mexico Bureau of Geology and Mineral Resources, Historic Photograph Archives, Socorro, NM 87801.*

VI. SAN JUAN BASIN AND OUTLIERS

Description of Fields by Coal-Bearing Unit

Crevasse Canyon Formation

The Crevasse Canyon Formation contains two coal-bearing sequences: the Dilco Coal Member and the Gibson Coal Member. Both of these coal-bearing sequences developed in nearshore environments during retreats of the shoreline. In the Gallup area, the Dilco Coal Member is above the non-marine, fluvial Torrivio Sandstone Member of the Gallup Sandstone. In other areas, such as the southeast San Juan Basin and Carthage area, the top of the Gallup Sandstone is defined as the highest regressive shoreface sandstone and the non-marine Dilco Coal Member overlies the Gallup Sandstone (Molenaar, 1983b). The Dilco Coal Member was deposited during a time of major reversal of the shoreline, from a predominantly transgressive to predominantly regressive sequence during the late Turonian to early Conacian Ages. The Bartlett Barren Member overlies the Dilco and consists of fluvial deposits with very thin coals. The Gibson Coal Member is at the top of the Crevasse Canyon, deposited during the third major regression (Santonian Age) in the San Juan Basin shoreward of the marine Point Lookout Sandstone. The Gibson and Dilco coal members of the Crevasse Canyon crop out along the southern edge of the San Juan Basin.

Gallup field—The Gallup field is on the southwestern edge of the San Juan Basin, extending southward into a shallow, northward-plunging syncline called the Gallup sag (Fig. 9). The eastern edge of this field is defined by the steeply dipping Cretaceous Crevasse Canyon, Gallup Sandstone, Mancos Shale, and Dakota Sandstone exposures along the Nutria monocline. The western edge of the field is delineated by the Defiance uplift. Between the Nutria monocline and the Defiance uplift, the attitudes of the coal-bearing sequence are influenced by the Torrivio and Gallup anticlines (Fig. 9) and the intervening syncline, called the Gallup sag. The arbitrary southern limit of the Gallup field is the township line between T12N and T11N (Fig. 9).

North of the town of Gallup, the Paleogene strata of the Chuska Mountains cover the Upper Cretaceous coal-bearing beds. The Mesaverde Group (Shomaker et al., 1971, p. 39) coal-bearing units in the Gallup field include the Gallup Sandstone, the Dilco Coal Member of the Crevasse Canyon Formation, and the undivided Cleary Coal and Gibson Coal Members of the Menefee and Crevasse Canyon Formations (Cleary–Gibson Coal Members). The landward pinchout of the Point Lookout Sandstone is northeast

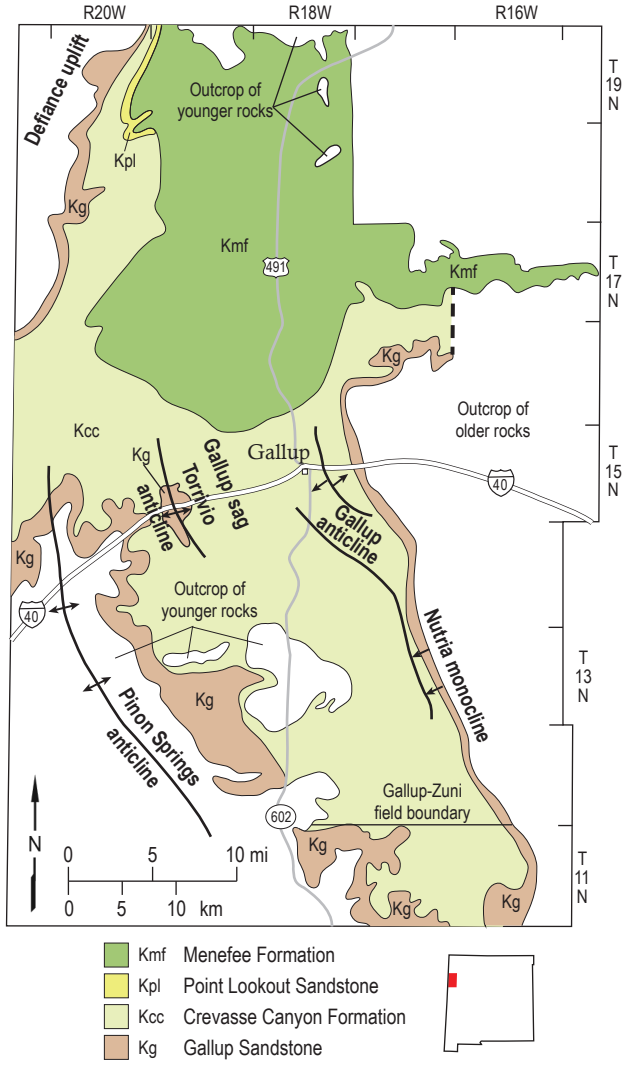


Figure 9. Map of Gallup field, Crevasse Canyon and Menefee Formation. Modified from Shomaker, et al. (1971).

of the Gallup field; consequently, no lithologic division exists between the Menefee and Crevasse Canyon Formations (see Fig. 7) near the town of Gallup. Thus, the coal-bearing Cleary-Gibson Coal Members form a thick, coal-bearing sequence shoreward of this pinchout. This thick coal-bearing sequence plays an important role in the long history of coal mining in the Gallup field.

Coal in the Gallup field, which was originally described as within the Gallup Sandstone, is of limited extent (Sears, 1925). The coal has been mined underground, but no surface minable resources appear to be economic. Sears (1925) recognized that the coal was lying below the "pink sandstone" (Sears, 1925, p. 17). The pink sandstone is the arkosic Torrivio Sandstone Member of the Crevasse Canyon as defined by Nummedal and Molenaar (1995). Estimated coal resources for these coal seams in the Gallup field below the Torrivio Sandstone (probably lower Dilco coals) are 6.5 million short tons within 250 ft of the surface. The basal Dilco Coal Member of the Crevasse Canyon Formation contains five thick coal beds. The Black Diamond coal bed is the most extensive coal (Sears, 1925). The Cleary-Gibson Coal Members also contains four commercial coal zones; one seam is locally 12 ft thick, but the average thickness is 4.5 ft. Drill hole data from Tabet (1981) indicate that the Cleary-Gibson coals thin in the southern Gallup field (average thickness 1.5 ft) and the number of seams decrease. All of the coal beds within these units are lenticular and only a few show more than 2 miles of lateral continuity.

Both the Dilco and Cleary-Gibson coals range in apparent rank, from high-volatile C bituminous to subbituminous A. The Dilco coals have a higher moist, mineral-matter free calorific value (MMFBtu; see Table 1) because of the lower moisture content of these coals. These are low sulfur (0.76% Dilco, 0.53% Cleary-Gibson), low to moderate ash (9.08% Dilco, 9.32% Cleary-Gibson) coals. These are some of the best quality coals in the San Juan Basin.

Underground mines in the Gallup area removed considerable blocks of coal from the 1880s to the 1950s. From 1882–1961, 33.3 million short tons of coal were mined from the Gallup coal field (New Mexico Territorial and State Mine Inspector, 1882–1962). The Cleary-Gibson remaining demonstrated coal resources are 449 million short tons to a depth of 200 ft, and 328 million short tons of this resource are within 150 ft of the surface. In 1989, Pittsburg and Midway estimated 170 million short tons of recoverable reserves for the McKinley mine area (Pittsburg and Midway brochure, 1989). From 1962 to the closing of the McKinley mine, production totaled 178 million short tons of coal, which essentially removed all recoverable reserves. The demonstrated coal resources (≤ 200 ft) of the Dilco Coal Member are 161 million short tons with an average coal thickness of 4.2 ft.

Underground mining in the Gallup field began in the 1880s, following the construction of the mainline of the Atchison, Topeka, and Santa Fe Railway through Gallup. Peak production from the underground mines was about 825,000 short tons in 1920. Underground mining continued on a large scale until 1951, when diesel engines replaced coal-fired steam engines on the railroads. Increased use of diesel fuel decreased the market for coal. Large-scale strip mining began in mid-1961, when Pittsburg and Midway Coal Mining Co. opened its McKinley mine. The McKinley mine reached a maximum production rate of 8.3 million short tons per year in 1994, and averaged 5 million tons per year. McKinley mine supplied coal to the following Arizona power plants: Cholla (Arizona Public Service) in Joseph City, AZ, Coronado (Salt River Project) in St. Johns, AZ, Apache (Arizona Electric Coop) in Cochise, AZ, and Irvington Station (Tucson Electric) in Tucson, AZ. With the closing of McKinley mine, many of these generating stations now get coal from the Lee Ranch and El Segundo mines northwest of Grants, NM. Two other small surface mines operated in the Gallup area in the past, but these mines have closed and have undergone reclamation.

Crownpoint field—The Crownpoint field is the largest coal field (930 mi^2) in the San Juan Basin. The Crownpoint field encompasses the Crevasse Canyon Formation exposures that are northeast of the Gallup field to the west edge of the San Mateo field (Fig. 8). The southern edge of the Crownpoint field is influenced by the Zuni uplift, and faulting is widespread along the southeast border (Fig. 5). The Dilco and Gibson Coal Members of the Crevasse Canyon Formation are the coal-bearing units.

In the Crownpoint field, the Dilco coal beds are thin and lenticular (Sears, 1936; Dillinger, 1990). The Gibson Coal Member contains the only coal considered economic in the Crownpoint field. These coals average 3.6 ft with a maximum thickness of 15.5 ft. Estimated surface-minable demonstrated resources (≤200 ft deep) are 663 million short tons. Underground demonstrated resources (200–1,000 ft) are 430 million short tons. Gibson coals are subbituminous B to subbituminous A. The beds are highly lenticular, and in most of the field, the coals are

overlain by the thick, massive Hosta Sandstone in the mesa and canyon terrain on the southwestern rim of the San Juan Basin. Gibson Coal Member coals have moderate ash (11.95% weighted average, 13 samples) and moderate sulfur (1.44%).

The first mine to open in the Crownpoint field was the Crownpoint mine that operated from 1918–1951. The Crownpoint mine supplied coal to the Indian schools and the Bureau of Indian Affairs (BIA) facilities in the town of Crownpoint. Eight mines operated sporadically from the 1920s to the 1950s and four prospects were opened during this time. United Electric obtained coal leases in the 1960s for the Crownpoint area and did exploration drilling (Nickelson, 1988). Although several leases were acquired, there has not been any further development due to the marginal economic potential for the coals in this area and the transportation problems from this part of the basin.

South Mount Taylor and East Mount Taylor fields—The Gibson Coal and Dilco Coal Members of the Crevasse Canyon Formation crop out on the flanks and in the foothill mesas of Mount Taylor and Mesa Chivato (Fig. 10). These outcrops constitute the South and East Mount Taylor coal fields (Fig. 8). In most places, the thick Tertiary volcanic sequence of Mount Taylor overlies the minable Gibson Coal and prevents surface mining, except in some small areas in the South Mount Taylor field in the Rinconada Canyon area (Fig. 10), which is northeast of Grants. These minable Gibson Coal Member coal beds range from 2.5–7 ft in thickness, but are highly lenticular and have minimal demonstrated resources (≤200 ft deep) of 14 million short tons. The resource estimates of the Dilco Coal Member coals in the South Mount Taylor field are slightly greater than 5 million short tons (Dillinger, 1989). The Dilco Coal Member intertongues northeastward with marine strata and thus contains essentially no coal seams in the East Mount Taylor field (Fig. 8). The few analyses of coal beds in these fields have an as received (testing done on sample as received in the lab, moisture level may or may not be representative of the total moisture content of the coal in the ground) heating value of about 11,200 Btu/lb, a sulfur content of 0.6%, and an ash yield of about 6%. In the past, small drifts (horizontal entry at coal outcrop) have been opened to mine the

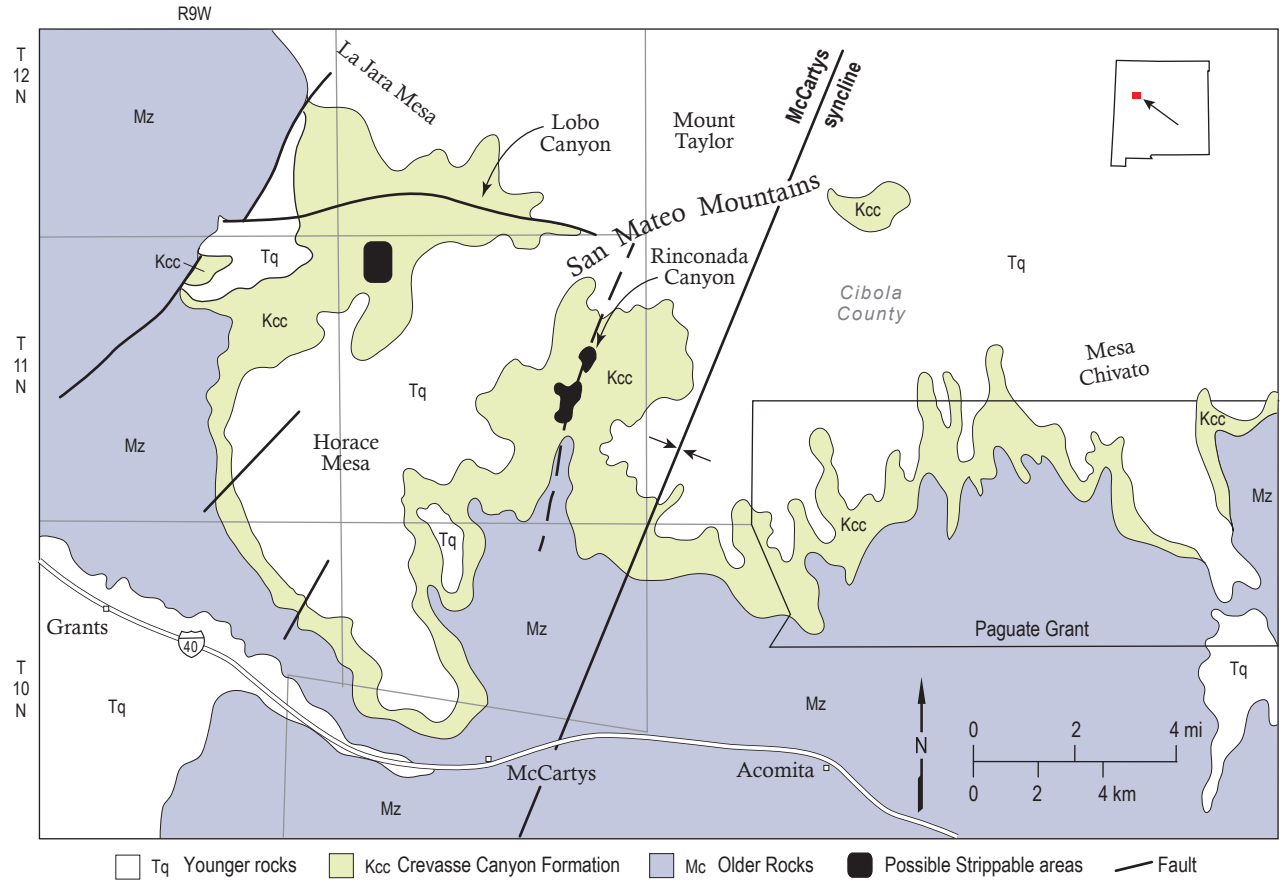


Figure 10. Map of South Mount Taylor, Crevasse Canyon area. Modified from Shomaker et al. (1971).

coal for local use. Three mines are known to have operated in the Lobo Canyon area (Fig. 10), northeast of Grants in the San Mateo Mountains.

Rio Puerco field—The Rio Puerco field is an irregular outcrop belt of Crevasse Canyon coal-bearing rocks in the Rio Puerco valley, an outlier of the San Juan Basin (Figs. 3, 8). The Rio Puerco field is about 15 mi east-southeast of the East Mount Taylor field (Fig. 8) and extends north-northeast for about 40 miles from Interstate 40 towards San Ysidro (Fig. 11). Coal occurs in both the Dilco Coal and Gibson Coal Members of the Crevasse Canyon Formation in the Rio Puerco field, but coals in the Dilco Coal Member are too thin to mine. The Gibson coal beds have an average thickness of 3.8 ft thick, although seams up to 5.6 ft have been mined for local use in the northern part of the field (Hunt, 1936). The field is within the Rio Puerco fault zone (Figs. 5, 11), a north-northeast-trending swarm of normal, en echelon faults active during Paleogene time with displacement to the southeast (Slack and Campbell, 1976). The coal-bearing outcrops are in narrow, steeply-dipping fault blocks, and the coal beds do not appear to be favorable for surface mining. In the eastern part of the field, sand masks the underlying bedrock, so it is difficult to estimate the potential for mining in this area. The demonstrated resources from the surface to a depth of 200 ft are estimated to be 25 million short tons.

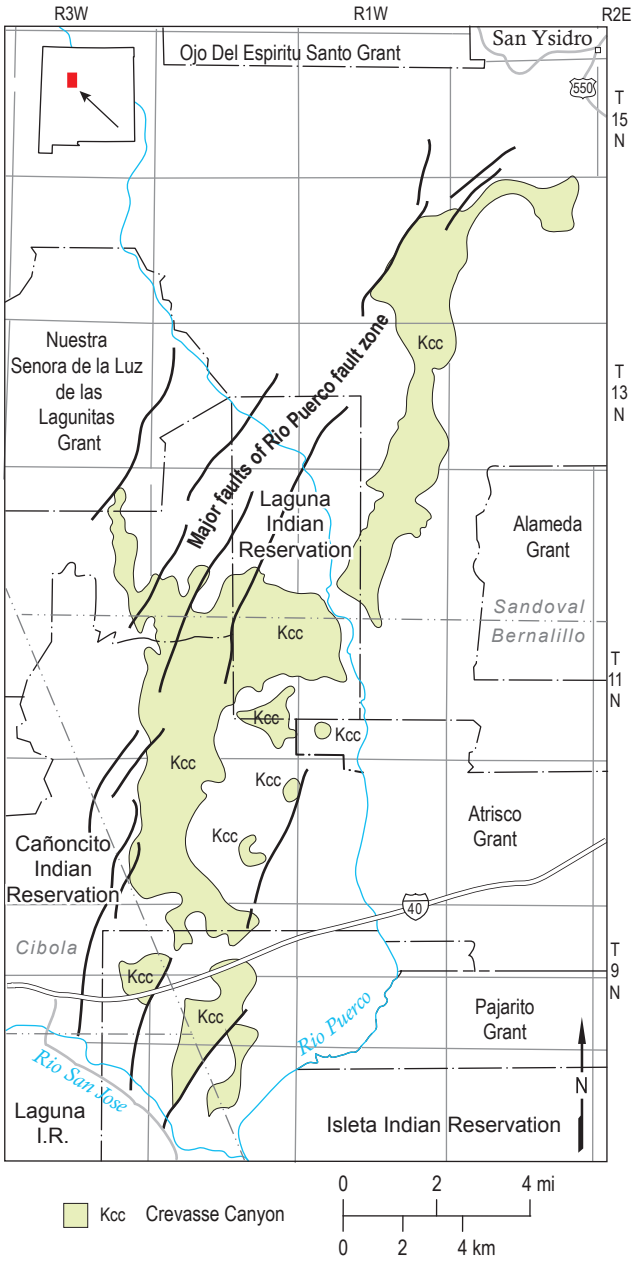


Figure 11. Map of Rio Puerco field, Crevasse Canyon Formation. Modified from Shomaker et al. (1971). Light green area shows outcrop area of Crevasse Canyon Formation.

The coal beds in the Rio Puerco field are of similar apparent rank (subbituminous A to high-volatile C bituminous) to those coals in the Mount Taylor areas. From the sparse analyses, these coal beds appear to be low-ash (8.35 % average), low- to moderate-sulfur (0.93% average) coals. Mining in the Rio Puerco field began in the 1920s and continued into the 1940s. Nickelson (Abandoned Mine Lands project, unpublished field notes, 1979) and Hunt (1936) reported eight small mines and prospects with a total production of 30,987 short tons.

Zuni field—The Zuni field is at the southern end of the Gallup sag (Figs. 5, 9). Coal-bearing Cretaceous rocks extend south of the Zuni Reservation (Fig. 12). Cenozoic volcanic rocks overlie these rock units that contain only thin coal beds. Coal-bearing strata gently dip east-northeast from the Pinon Springs anticline (Fig. 12) on the west side of the field, towards the north-northeast trending Allison–Ramah syncline (Fig. 12). The dip of the beds reverses on the east side of the Zuni field as the beds are influenced by the Nutria monocline, the southwest flank of the Zuni uplift (Fig. 5).

In the Zuni field, there is coal within the Tres Hermanos Formation, the lower Dilco (Ramah Member of Anderson and Sticker, 1996), and the Dilco Coal Member of the Crevasse Canyon (Fig.7; Sears, 1925; Anderson, 1987; Anderson and Stricker, 1987; Anderson and Stricker, 1996). The coal 'zones' within the Carthage Member of the Tres Hermanos are at the base and the top of this unit. The coal beds are thin (1.2–4.8 ft) and

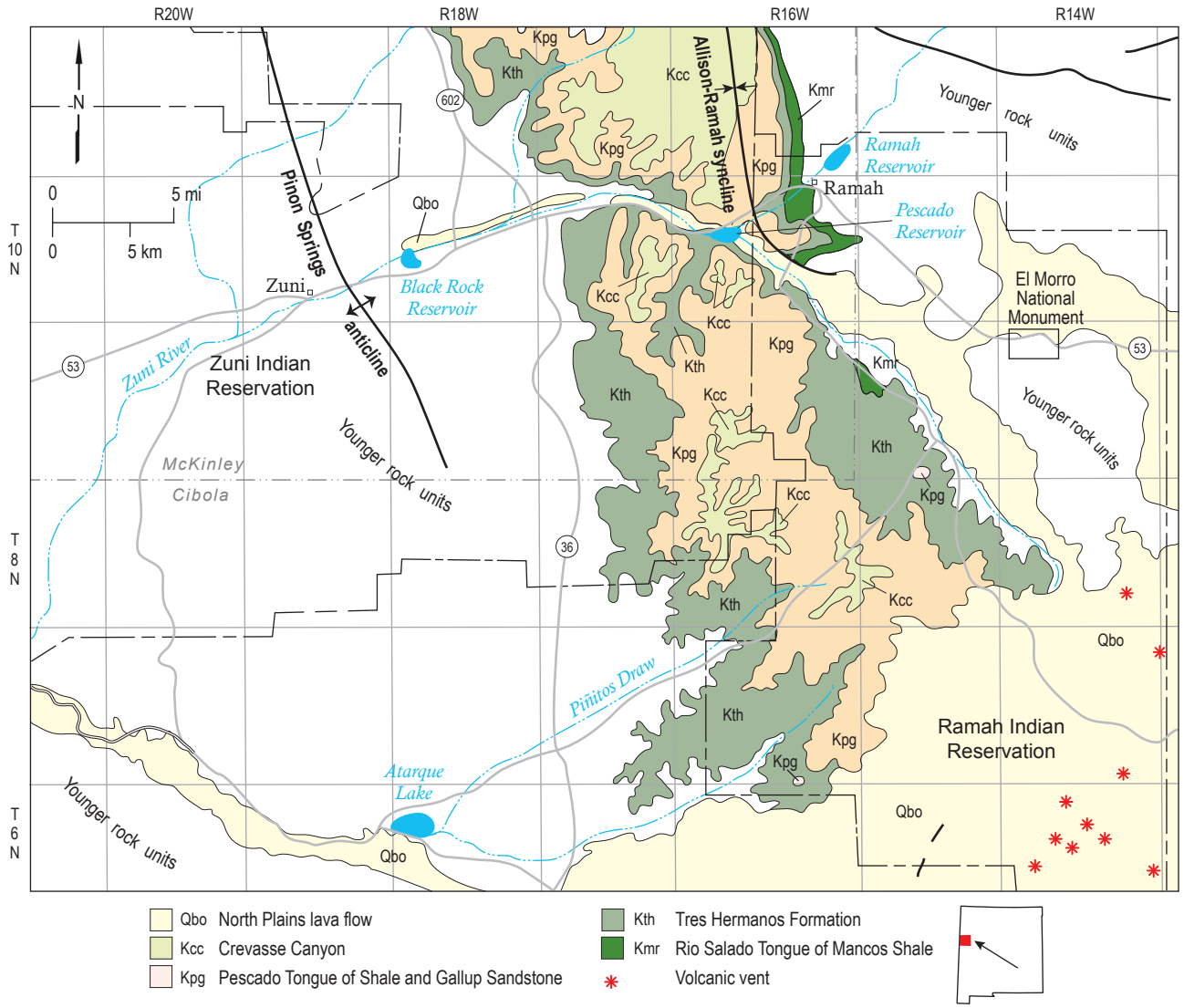


Figure 12. Map of the Zuni coal field. Modified from Anderson and Jones (1994).

lenticular (Anderson and Stricker, 1987). The basal coal zone directly overlies the Atarque Sandstone Member and represents back barrier mire deposits. The upper coal zone is about 25 ft below the base of the Fite Ranch Sandstone Member. These coals were deposited in mires that were developed on alluvial plains. Coal in the lower Dilco Coal Member is below the Torrivio Sandstone Member, a fluvial arkosic sandstone in the Crevasse Canyon Formation (see Hook, 2011, p. 80). This coal-bearing unit has coal up to 7 ft thick, but in general, the coal beds are thin and do not have great lateral extent. Sears (1925) recognized these coals as being within the upper Gallup Sandstone.

The Dilco Coal Member outcrops in the northern Zuni field, but coals in this unit are very lenticular. Demonstrated resources from available outcrop and sparse drilling data are only 23 million short tons for Dilco coals at depths less than 200 ft. Anderson (1987) estimated coal resources of approximately 49 million short tons in the southeastern corner of the Zuni field. Very few analyses of the coal beds in the lower Dilco Member exist and they have a quite a range of values. These are subbituminous A coals with moderate sulfur and ash content. Underground estimates of resources for lower Dilco coals are 11 million short tons.

Three mines operated in the Zuni field in the early to mid-1900s that supplied coal to the Zuni Reservation schools and administration buildings (Sears, 1925; Nickelson, 1988). In the 1970s, the Zuni tribe issued a few coal prospecting permits and several exploration holes were drilled, but no coal was mined.

Menefee Formation

The Menefee Formation contains two coal-bearing sequences deposited during the fourth major regression (Molenaar, 1983a) and subsequent retreat with stillstands in the shoreline. The Cleary Coal Member at the base of the Menefee was deposited during a retreating shoreline that overlies the coastal Point Lookout Sandstone. This deposition was followed by a sequence of nonmarine shale and siltstones that are barren of coal seams known as the Allison Member in the western part of the San Juan Basin. The upper part of the Menefee Formation intertongues with the La Ventana Tongue of the Cliff House Sandstone, which is an overall transgressive marine sandstone. The intertonguing indicates pauses in the retrogradation of the shoreline, allowing mires to develop and create some relatively thick coals within the upper coal member of the Menefee Formation.

Barker Creek—The Barker Creek field is the northwestern-most Menefee Formation field in the New Mexico portion of the San Juan Basin (Fig. 8). The Barker Creek field is defined by the Colorado-New Mexico boundary on the north and the township line between T30N and T31N to the south (Fig. 13). Exposures of the Pictured Cliffs Sandstone and Point Lookout Sandstone delineate the east and west boundaries, respectively. The Hogback monocline on the eastern side of the field (Fig. 13) greatly influences the dip (10–38°E-SE) of the bed, and several normal faults trending west-northwest are associated with this structure (O'Sullivan and Beaumont, 1957). Northwest of the Hogback monocline, the Menefee Formation is capped by Cliff House Sandstone, creating a dissected, steep-sided canyon and mesa topography.

Two Menefee coal zones (Shomaker et al., 1971) are present in the Barker Creek field. One coal zone is in the upper 250 ft, and the lower zone is within 100 ft of the Point Lookout contact (Hayes and Zapp, 1955). A total coal thickness reported by Hayes and Zapp (1955) was 19.2 ft in the upper zone and 17.3 ft in the lower zone. These measurements represent the composite thickness of multiple thin beds. Shomaker et al. (1971) reported that there were no exposed coal beds greater than 2.4 ft thick in the lower coal zone. Three available analyses indicate the Barker Creek coal beds are low-ash (7.03%), low-sulfur (0.9%), and have an apparent rank of high-volatile C bituminous.

Demonstrated resources for the upper coal member (within 200 ft of the surface) are estimated to be 48 million short tons. The lower coal zone demonstrated resources are 20 million short tons with a maximum overburden of 200 ft. The presence of overlying thick sandstones and the steep dip of the beds near the Hogback monocline would make surface mining difficult in the Barker Creek field. Underground (200–1,000 ft) demonstrated resources for the lower coal zone are 115 million short tons.

Hogback field—The relatively small Hogback field (140 mi^2) is defined by the continuation of the Menefee Formation outcrop on the west side of the San Juan Basin south of the Barker Creek field (Figs. 8, 13). The north and south boundaries are T30N, R15–16W to T26N, and R17–18W (Fig. 14).

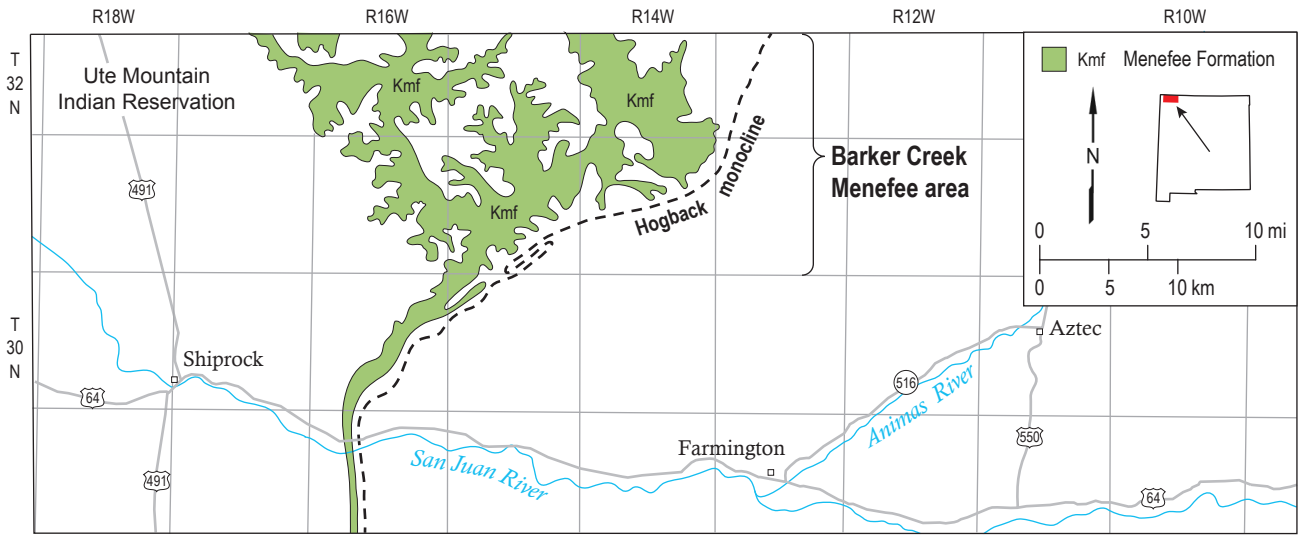


Figure 13. Map of Barker Creek Menefee area. Modified from Shomaker et al. (1971).

The Cliff House Sandstone and the Point Lookout Sandstone contacts with the Menefee Formation define the east and west boundaries, respectively. The east boundary is along the Hogback monocline (Fig. 14), which creates a sharp, steep slope. The Menefee beds dip as much as 38°E along the Hogback monocline structure and decrease to 10°E in the southern part of the field (O'Sullivan and Beaumont, 1957).

The Hogback field contains two Menefee coal zones. The lower zone is poorly developed except for the area near the San Juan River along the northern edge of the field. Coal beds in the lower zone range from a few inches to 11.3 ft (Lease, 1971a). The upper zone is just below the contact with the Cliff House Sandstone, and, in some cases, the upper zone intertongues with these overlying barrier beach sandstones. Total coal thickness ranges from 2.5–38.3 ft, with as many as 10 beds present in this interval (Lease, 1971a).

Few analyses are available from the Hogback field, but these coal beds have a moderate to high ash yield (15.68% weighted average, 3 samples) and low sulfur values (0.70%). The average apparent rank of the coal sampled is high-volatile C bituminous.

Past mining in the Hogback field was restricted to the area near Coal Mine Creek (T30N, R16W; Fig. 14). Hayes and Zapp (1955) mentioned 17 small mines, most operated by Native Americans (Navajo) on Reservation land. These early mines operated from the 1900s into the 1950s, with the last mine ceasing operation in 1976. Coal from the Hogback field mines was used for domestic purposes and at nearby Reservation schools. There are no currently active mines in this field.

Estimated resources within 200 ft of the surface are 45 million short tons for the Hogback field. Deep resources (200–1,000 ft deep) from sparse data are estimated to be at 21 million short tons. The high angle dips are prohibitive for surface mining (Lease, 1971a).

Toadlena field—The Toadlena field is defined by the Menefee Formation outcrops in T23–24N, R18–19W (Fig. 15), northeast of the Defiance monocline, and south of the Tocito Dome, in a small northern tributary of Captain Tom Wash (Fig. 15; Lease, 1971b). The strike of the beds is northeast, and the dip is 4–12 °SE (Lease, 1971b). Mesas capped by Point Lookout Sandstone are dissected by east-flowing streams (Lease, 1971b) that expose the coal-bearing Menefee Formation.

The coal beds are 1.5–2.5 ft thick in the upper Menefee Formation. Because thick sandstone overburden covers the coal, and the beds have a significant dip, no surface-minable resources have been calculated.

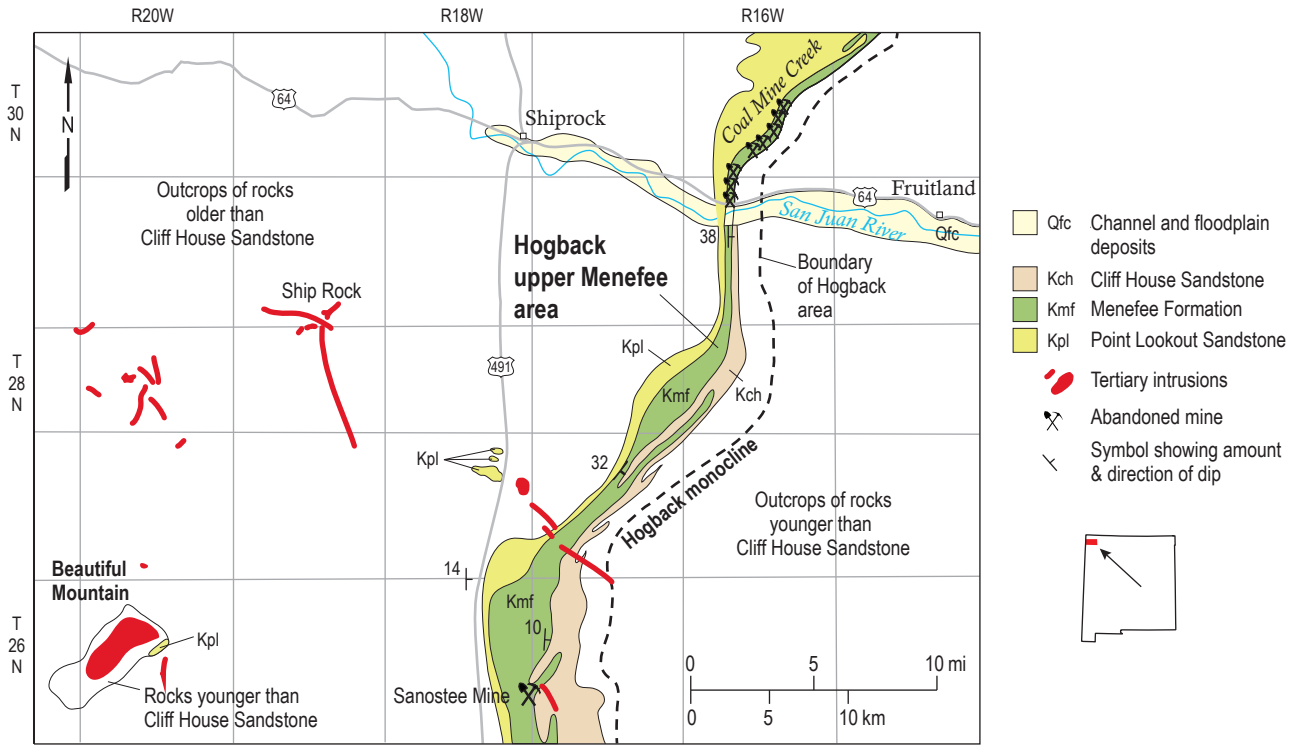


Figure 14. Map of Hogback upper Menefee area. Modified from Shomaker et al. (1971).

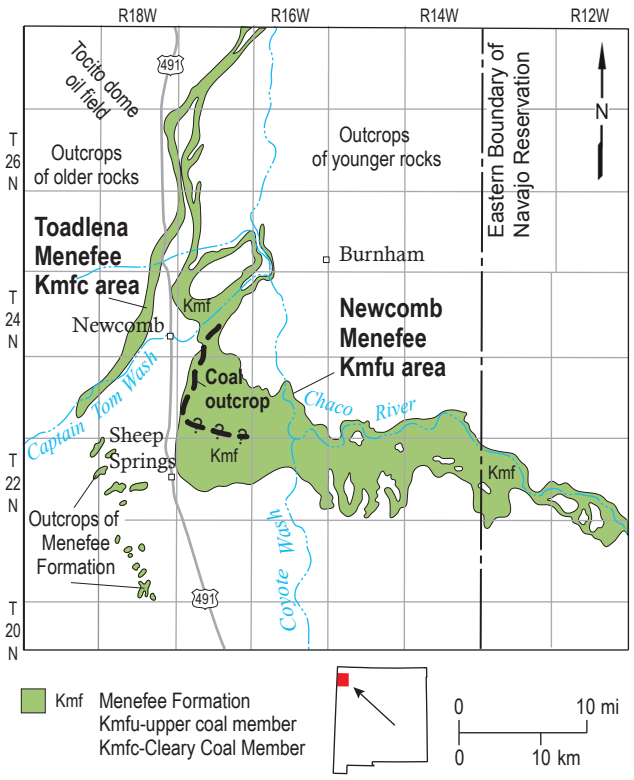


Figure 15. Map of Toadlena and Newcomb Menefee areas. Cleary Coal Member outcrops in Toadlena area; the upper coal member outcrops in the Newcomb coal area. Modified from Shomaker et al. (1971).

Newcomb field—The Newcomb field on the Navajo Reservation encompasses the southwestern edge of the upper Menefee outcrop (Fig. 8), where the strike of the beds changes from north-south to northwest-southeast (Fig. 15). The coal-bearing rocks in the Newcomb field are in the upper part of the Menefee Formation that contains numerous lenticular coal beds of irregular thickness.

These coals generally occur near the top of the upper Menefee Formation and are closely associated with the overlying Cliff House Sandstone. Thicknesses of coal beds at the surface are difficult to judge because, in most localities, the coal has been burned and the surrounding rock was baked to form masses of red clinker (Shomaker et al., 1971). In several places, coal beds do reach economic thicknesses of 4–8 ft and have reason able lateral continuity. The upper Menefee Formation coals in the Newcomb field have an apparent rank of subbituminous A or B, low sulfur values (<1%), and low to moderate ash yields (6.6%–13.0%). Resource estimates of surface-minable coal beneath less than 200 ft of overburden total at least 72 million short tons. Underground demonstrated resources to a depth of 1,000 ft are 54 million short tons. These figures are based on sparse data and more exploration drilling is needed to appraise the coal resources in the Newcomb field.

Chaco Canyon and Chacra Mesa fields—The Chaco Canyon and Chacra Mesa fields extend from the eastern boundary of the Navajo Reservation lands (Fig. 16) to the La Ventana field (Fig. 17; R3W) on the southeast edge of the basin (Fig. 8). The coal-bearing Menefee Formation along the south side of the San Juan Basin defines these two areas. The general strike of these beds is northwest-southeast and, because these fields are within the Chaco Slope geographic province (Fig. 5), the beds have gentle dips of 1–5°N-NE. The Cliff House Sandstone caps the prominent northeast-trending Chacra Mesa, defining the northern boundary of these fields (Figs. 16, 17).

The Chaco Canyon field contains only the upper coal member of the Menefee Formation. Much of this coal area encompasses northwest-trending valleys and mesas capped by Cliff House Sandstone that overlies and intertongues with the upper coal member. The Chacra Mesa field includes both the Cleary Coal and upper coal members of the Menefee Formation. Coal beds are highly lenticular in both the Chaco Canyon and Chacra Mesa fields. These coal beds average 3.4 ft in thickness. In the Chacra Mesa area the coal beds are often overlain by a very thick overburden of Cliff House Sandstone that inhibits surface mining (Speer, 1971).

Coal analyses of the upper coal member in the Chaco Canyon field indicate these are low-ash (7.88% weighted analyses, 4 samples), moderate-sulfur (1.38%) coals, with an apparent rank of subbituminous A. Work in the Chacra Mesa field (Hoffman et al., 1993) resulted in several analyses for the upper coal member and Cleary Coal Member coals in the Chacra Mesa field.

The upper coal member coal beds are higher in moisture (15.29% upper, 11.94 % Cleary) and sulfur (0.72% upper and 0.45% Cleary). The upper coals are lower in ash (9.69% upper, 11.05% Cleary) and calorific values (10,207 Btu/lb and 10,898 Btu/lb) than the Cleary Coal Member coals. Both groups of analyses indicate the coal is low in sulfur, and has a moderate ash yield. The upper coal and Cleary coal have an apparent rank of subbituminous A and high-volatile C bituminous, respectively.

Inactive small drifts and pits often operated by Navajos are the only evidence of mining in the Chacra Mesa and Chaco Canyon areas. The Blake mine in the Chaco Canyon field, mentioned by Bauer and Reeside (1921), was located on the north rim of

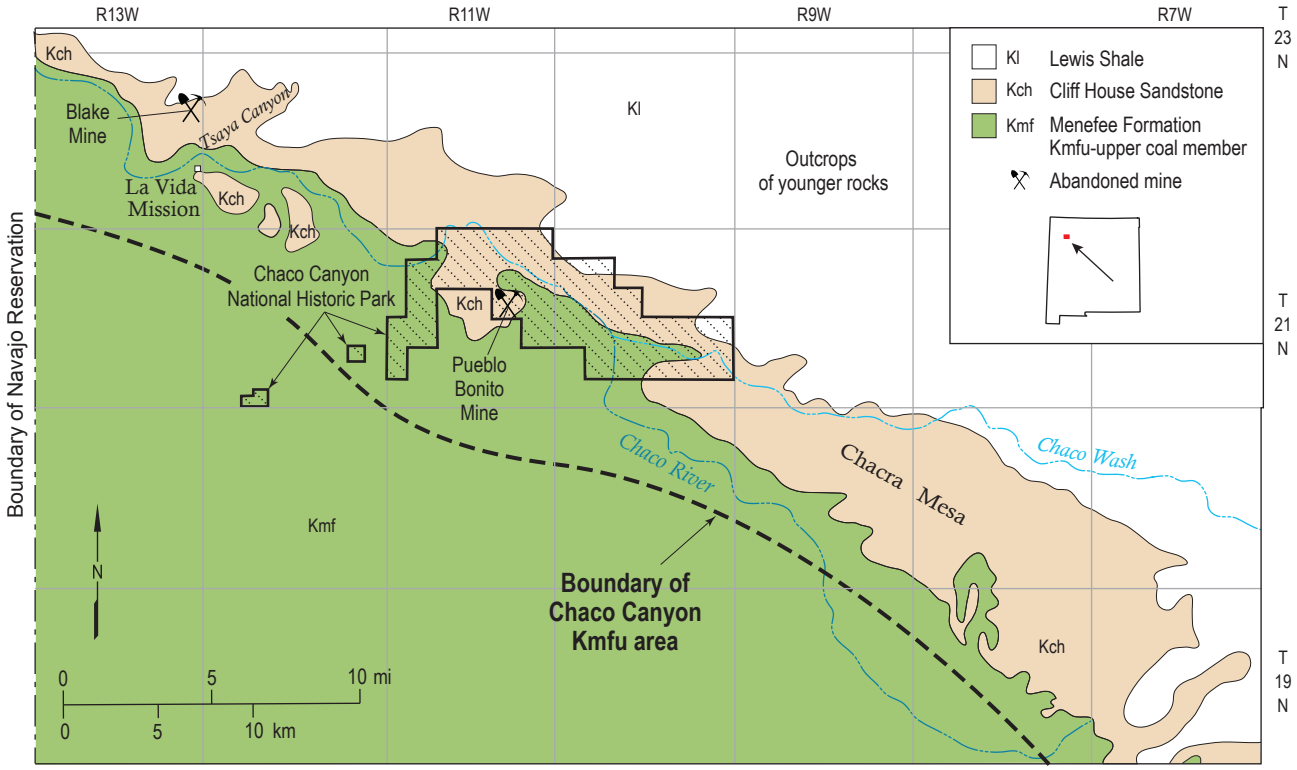


Figure 16. Map of Chaco Canyon upper Menefee area. Modified from Shomaker et al. (1971). The upper coal member of the Menefee is stratigraphically below the Cliff House Sandstone. The dashed line with the northern outcrop line of the Cliff House defines the Chaco Canyon upper coal member area.

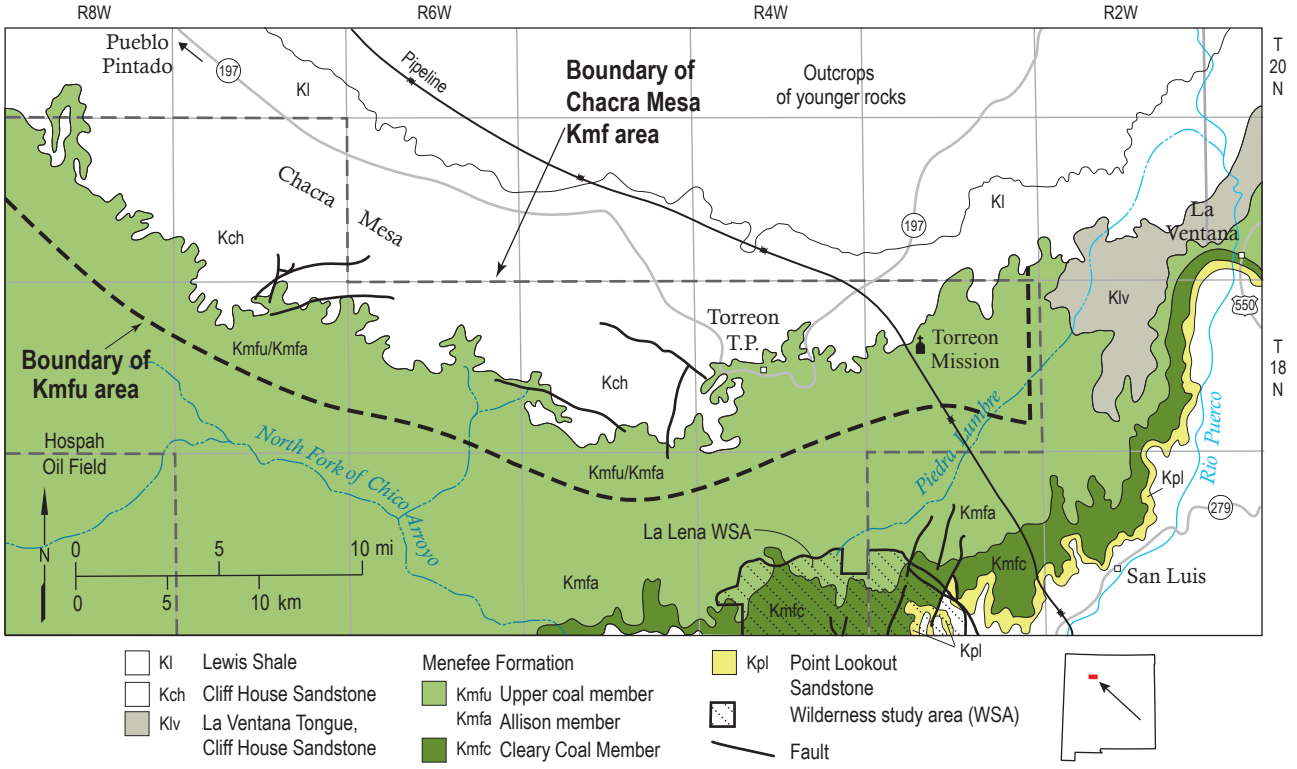


Figure 17. Map of Chacra Mesa Menefee area. Modified from Shomaker et al. (1971). Green area on map is Menefee Formation.

Tsaya Canyon (Fig. 16), and probably opened in one of the upper coal beds in the Menefee Formation. The Pueblo Bonito mine, operated in the early 1900s, was in the south wall of Chaco Canyon near the National Historic Park. The coal from both these mines was used at local trading posts and for domestic purposes (Nickelson, 1988).

Geologic investigations of the Menefee coal at depths greater than 500 ft (Shomaker and Whyte, 1977) have shown thick, extensive deposits in the Chacra Mesa area, with resources in the millions of short tons. Geologic investigations by the New Mexico Bureau of Geology and Mineral Resources, NMBGMR (Tabet and Frost, 1979; Hoffman et al., 1993), estimate demonstrated resources of 140 million short tons of coal within 200 ft of the surface in the Chacra Mesa field. Coal resources in this area within 150 ft of the surface are estimated from point-source data (drill holes, outcrops) to be 14 million short tons. Resource calculations are based on 3.5 ft average coal thickness. Demonstrated resources at depths less than 250 ft are at least 30 million short tons in the region north of La Vida Mission and northwest of Chaco Canyon National Historic Park (Fig. 16) where good quality coal beds are 5–6 ft thick (Shomaker et al., 1971). Estimates for the entire Chaco Canyon field are 46 million short tons of demonstrated resources within 200 ft of the surface. The upper coal member and Cleary Coal Member resources are 30 million short tons and 16 million short tons, respectively.

La Ventana field—The La Ventana field is on the southeastern edge of the San Juan Basin (Figs. 8, 18). The beds are gently dipping (2–5°N-NW) in the western part of the field. The eastern La Ventana field is close to the Nacimiento uplift (Fig. 18) where the dip of the 35–45 °SW beds increases to vertical. This area includes the Cleary Coal Member and the upper coal member of the Menefee Formation. Coal beds average 3–6 ft thick in both coal–bearing sequences, although some individual coal beds in the upper coal member attain a thickness of 10–12 ft.

The La Ventana field has significant resources in the Cleary Coal Member and upper part of the Menefee Formation. However, because of extreme dips on the east edge of the field and thick sandstone overburden associated with the upper coal member, only about 15 million short tons of the resources can be considered surface minable.

At least 130 million short tons of low-ash, moderate-sulfur demonstrated resources occur within 200 ft of the surface in the upper (56 million short tons) and Cleary (75 million short tons) coal members. The upper coal beds average 4.3 ft but individual beds can be up to 12 ft thick. The average coal within the Cleary Coal Member is 4 ft. The underground resources for the upper and Cleary Coal Members are 133 million short tons in the La Ventana field. Apparent rank of coal in both members of the Menefee is subbituminous A. The Cleary coal beds are higher in ash (11.06%, compared to 8.14%) and lower in sulfur (1.01% compared to 1.36%) than the upper coal member coals.

The La Ventana coal field had several periods of mining, beginning in the 1880s and continuing into the 1980s. With the exception of the Arroyo No. 1 mine, all the mines in this area have been

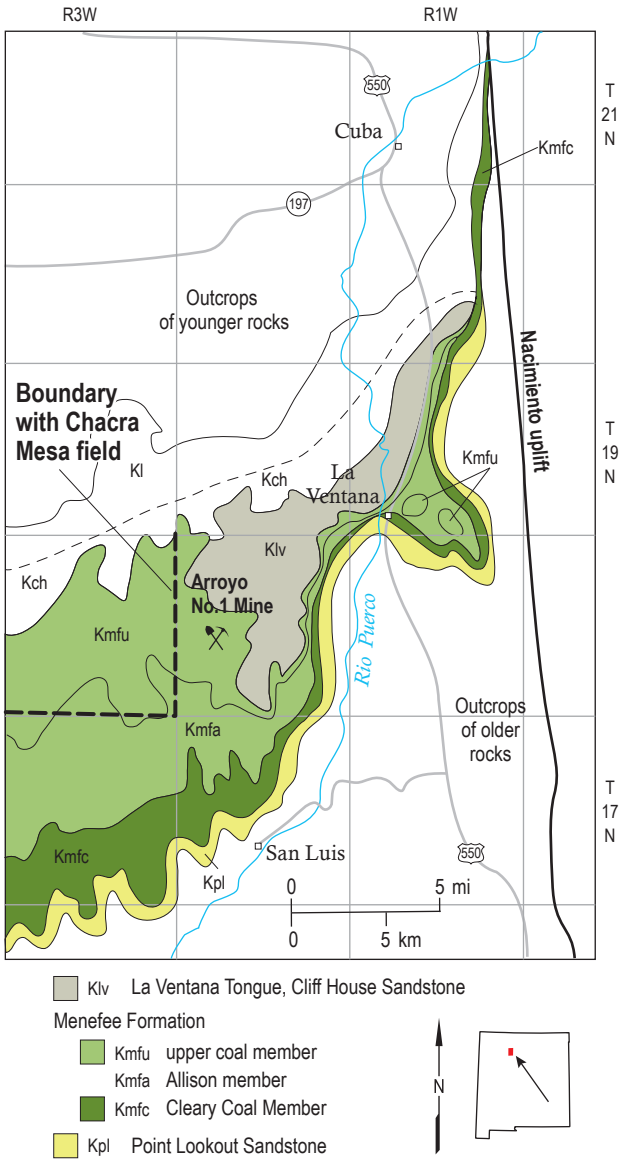


Figure 18. Map of La Ventana Menefee area. Modified from Shomaker et al. (1971). The upper coal member stratigraphically underlies and intertongues with the La Ventana Tongue of the Cliff House Sandstone.

underground. Early mining, from 1884–1900, was centered on the eastern edge of the field near the village of La Ventana (south of Cuba, NM, Fig. 18) and many of these mines provided fuel for the nearby metal mines in the Nacimiento Mountains. Interest in coal mining waned until the 1920s when a railroad from Bernalillo (Preface Fig. 1 and Fig. 5), just north of Albuquerque, to La Ventana was built. Washouts of the rail bed along the Rio Puerco were a problem for the railroad, and by 1931 the trains were no longer running to the mines near La Ventana, although a few mines continued to operate to meet local fuel needs. In 1964, Consolidation Coal ("Consol") became interested in the thick upper coal member seam, often referred to as the Padilla Seam, and obtained leases in the area north of the town of La Ventana. Consol sold their leases to Ideal Basic Industries who acquired a state permit for an underground mine to supply coal to their Tijeras Canyon cement plant (Fig. 3). Lack of rail transportation and economics hindered the development of this mine and Ideal Basic relinquished their leases. The most recent mining (1976–mid-1984) in the La Ventana field has been limited to a very small surface operation on half a state section, the Arroyo No. 1 mine, near the village of San Luis (Fig. 18) in the Cleary Coal Member.

San Mateo and Standing Rock fields—The San Mateo field is northwest of the Mesa Chivato, part of the Mount Taylor volcanic complex (Fig. 19) and south of the Chacra Mesa field (Fig. 8). It includes exposures of the Cleary Coal Member of the Menefee Formation. The San Mateo and San Miguel Creek Domes (Fig. 19), structural features in the southern San Mateo field, were topographically high areas during the deposition of the Cleary Coal Member and influenced the thickness of the coal beds, as well as the strike and dip of these beds (Beaumont, 1987). The coal-bearing units on the southwest side of the San Mateo field were also influenced by the Zuni uplift (Fig. 5). The Standing Rock field, northwest of the San Mateo field (Fig. 8), is within the Chaco Slope that dips gently north-northwest into the basin. The arbitrary boundary between the San Mateo and Standing Rock fields is the western border of R8W (see outline of fields, Fig. 19).

Coal beds in the Cleary Coal Member of the Menefee Formation outcrop in both the San Mateo and Standing Rock fields. Economic coal in the San Mateo field averages 4.8 ft thick, although coal as much as 14 ft thick occurs locally. Usually, these lenticular seams are within the first 100 ft above the Point Lookout Sandstone contact, indicative of a near shore environment. Demonstrated resources for the San Mateo field are estimated at more than 385 million short tons of coal within 200 ft of the surface. Underground resources are estimated to be more than 317 million short tons.

No major resources are evident from surface exposures in the Standing Rock field, but limited drill-hole data have shown on the order of 392 million short tons of surface-minable coal (within 200 ft) with an average thickness of 5 ft. Of this total demonstrated resource, 228 million short tons are within 150 ft of the surface. Both the Standing Rock and San Mateo fields have moderate ash yields (17.3% and 14.36%, respectively) and low to moderate sulfur values (1.06% and 0.93%, respectively). The apparent rank of these Cleary Coal Member coals is subbituminous A.

Mining in the Standing Rock field has been limited to small pits opened on outcrops of coal by Navajos for domestic use, but the San Mateo field has had significant mining beginning in the 1980s. Lee Ranch Coal Company, a division of Peabody Energy Corporation, operates the Lee Ranch mine in the south-central part of San Mateo field (Fig. 19). The Lee Ranch mine started operations in 1984 under ownership of Santa Fe Mining. During 1987, Santa Fe completed a land exchange with the BLM allowing the mine to go from a strictly truck-and-shovel operation to include a dragline that became operational in December 1990. This acquisition increased production from slightly more than 2.7 million short tons in 1990 to more than 4.1 million short tons in 1991. Coal shipments from the mine are under long-term contract to the Tri-State Generation and Transmission Escalante Generating Station in Prewitt, NM and the Tucson Electric Power Company's generating station in Springerville, AZ (Energy, Minerals and Natural Resources Department, 1994). In early 1993, Santa Fe entered into an agreement with Hansen Natural Resources Company, Inc., of which Peabody is a subsidiary, to trade its coal holdings, including the Lee Ranch mine, for some of Hansen's gold assets (Dillard, 1993). The trade was finalized in June 25, 1993. In March 1997, Hanson divested its coal properties to Peabody Group, renamed Peabody Energy Corporation in April 2001. In that same year, Lee Ranch Coal Company, subsidiary of Peabody Energy, submitted an application to develop the El Segundo mine, northwest of their Lee Ranch operation (Fig. 19). The permit was approved in 2005 by the Mining and Minerals Division and Lee Ranch opened El Segundo mine in 2008. The mine has a projected mine life of 30 years and is forecast to produce 102 million short tons of coal (EMNRD 2006 Annual Report).

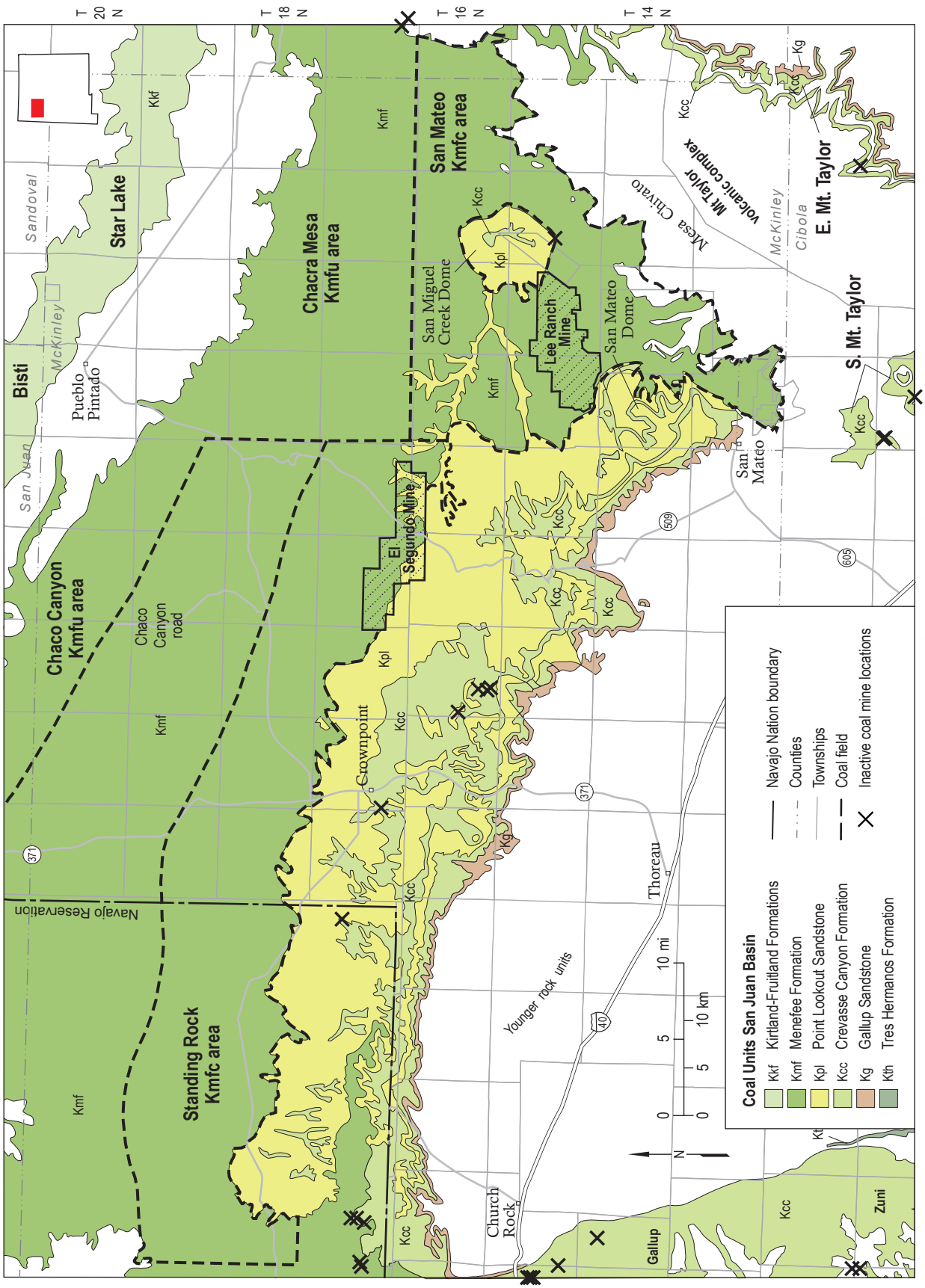


Figure 19. Geologic map of San Mateo and Standing Rock Cleary Menefee areas. Modified from Shomaker et al. (1971). The coal fields are outlined by dashed lines. Coal areas are designated by coal-bearing sequence.

Peabody lists this as one of the most productive mines in the Southwest because of the low overburden ratio (overburden thickness to coal thickness) with 182 million tons of coal reserves (Peabody Energy, 2012). Peabody's surface operations in the San Mateo field produce over 6 million tons annually and supply coal to generating stations in Arizona owned by Arizona Public Serves, Tucson Electric, Arizona Electric Power Cooperative and Catalyst Paper Company (Peabody Energy, 2012). In November 2015, Peabody agreed to sell El Segundo and Lee Ranch mines to Bowie Resource Partners LLC, based in Louisville, Kentucky. Purchase by Bowie Resources of these mines fell through and Peabody retains ownership. Coal mining at Lee Ranch was suspended in 2016 and all production to meet contracts is coming from El Segundo mine.

Monero field—The Monero field on the northeast side of the San Juan Basin is defined by outcrops of the Mesaverde Group that extend southward from the New Mexico–Colorado state line for about 26 mi (Figs. 8, 20). The coal-bearing rocks strike N–S in the Menefee and Fruitland Formations under influence of the Archuleta arch that separates the central San Juan Basin from the smaller Chama Basin to the east (Fig. 20). Most of the northern Monero field is influenced by small domes and southwest–trending synclines that are part of the Archuleta arch (Dane, 1948). The southern part of the field parallels the N30°W trend of the Gallina arch. Several faults in the Monero field are parallel to the eastern edge of the basin, and contemporaneous with the folding that took place along the eastern San Juan Basin during the Laramide tectonic activity (Dane, 1948). High angle or normal faults are widespread with displacement of less than 100 ft (Dane, 1948), generally to the west. The dips of the coal beds are variable because of the complex structure. Outcrops of the Menefee and Fruitland Formations are limited to the steep canyon walls of the fault-block mesas. Only the Menefee Formation coal at shallow depths has limited economic significance in this field. The Menefee Formation thins to the northeast, near the New Mexico–Colorado border, and is replaced by marine sandstones of the Point Lookout Sandstone or Cliff House Sandstone. The coals are mainly in the central and southern parts of the field.

Substantial shallow coal is present in the central Monero field on the backslopes of cuesta fault blocks (blocks that have a gentle slope on the backslope and a steep angle on the frontslope), although very little drill data are available to delineate this resource. Preliminary estimates of demonstrated resources to a depth of 200 ft are 8 million short tons. Beds as much as 7.3 ft thick have been mined, but the average coal thickness is 3.5 ft. Deeper coal resources are estimated at 32 million short tons, but dips greater than 5° and faulting make underground mining difficult. These moderate sulfur (1.85%, weighted average, 14 samples), moderate ash (10.16%) coal beds are of high-volatile bituminous B to A in apparent rank. Some of the seams have coking qualities (Averitt, 1966), but these resources have not been determined.

Coal was mined from the 1890s in underground mines near Monero and Lumberton, principally for the Denver and Rio Grande Western Railroad, and the lumber railroads. Local domestic use and the Jicarilla Reservation School at Dulce made up the remaining markets for coal from this area. Coal mines operated in the Monero area from 1899 until 1970, producing 1.6 million short tons.

Tierra Amarilla field—This small field is an outlier of the coal-bearing Menefee Formation, and is located about 12 mi east of the edge of the San Juan Basin, southeast of Tierra Amarilla (Figs. 8, 20). The field is on the eastern flank of the Chama Basin (Fig. 20) and the lowest part of this basin is marked by the Chama syncline (Fig. 20) that cuts through the western part of the coal area. Exposures of the Mesaverde Group, including the Cliff House Sandstone, Menefee Formation, and Point Lookout Sandstone dip to the west, forming a hogback along the boundary between the Chama and San Juan basins (Fig. 20). Most of the coal seams in these Menefee Formation exposures are thin, lenticular, and overlain by excessive overburden, including massive sandstones of the Cliff House that prevents surface mining. Three to four of the upper Menefee coal beds exposed in the western part of the Tierra Amarilla field reach a maximum thickness of 1.6 ft (Landis and Dane, 1969). The lower coal zone contains three coal beds. The upper bed is the most persistent and reaches a maximum thickness of 4.1 ft in places. Samples from the Dandee mine (Fig. 20) indicate that the coal is of subbituminous A (apparent rank) and contain 1.0%–1.1% sulfur, about 8% ash yield, and averages about 10,000 Btu/lb (Landis and Dane, 1969). The primary coal resources are in the western part of this field. Landis and Dane (1969) estimated resources of 1.8 million short tons for this area and 4.5 million short tons for the entire Tierra Amarilla field.

Very little mining has taken place in the Tierra Amarilla field except for local use. Landis and Dane (1969) located four small mines in this area. The Dandee mine operated from 1944 until 1954, and the

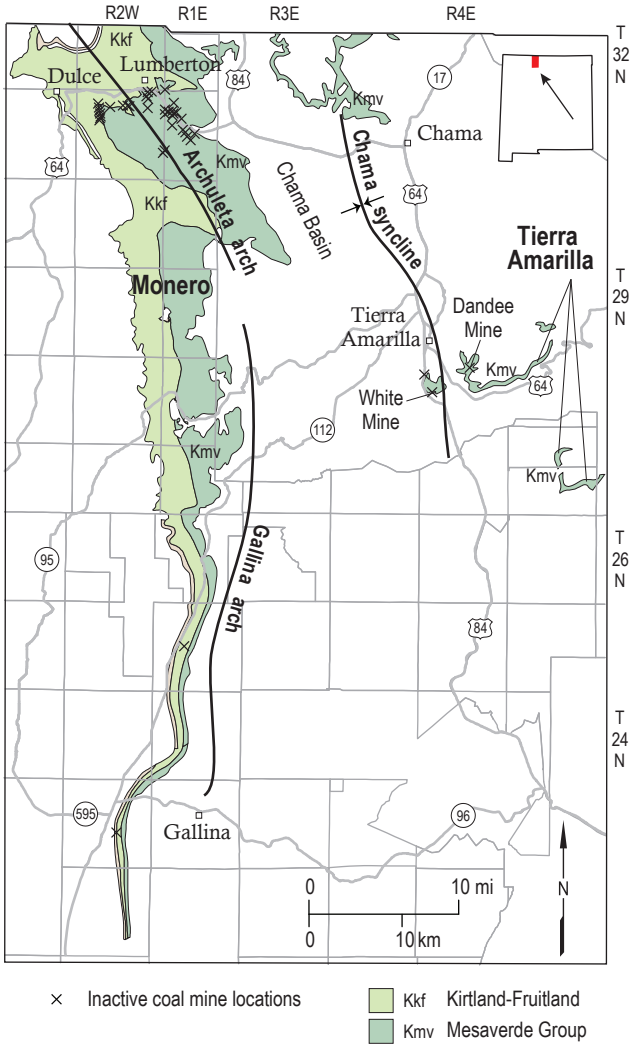


Figure 20. Geologic map of Monero and Tierra Amarilla fields. Modified from McLemore et al. (2005). The Fruitland Formation outcrops in the Monero area, however most coal mining occurred in the Menefee Formation.

White mine opened in 1935 and operated for several years (Landis and Dane, 1969; Nickelson, 1988). Production from these mines was limited and used for domestic purposes such as heating and cooking.

Fruitland Formation

The Fruitland Formation represents the last development of a coal-bearing sequence in the San Juan Basin during the Late Cretaceous (Maastrichtian) time. Outcrops of this formation extend from the Colorado border on the west side of the basin, south-southeast to south of Cuba, New Mexico. The east side of the basin has a thin outcrop of Fruitland, but this area has an abbreviated section with little coal. In the Monero area, there is some Fruitland coal, but it is not extensive. The Fruitland Formation outcrop in the San Juan Basin is divided into four fields: the Fruitland, Navajo, Bisti, and Star Lake. Many of the thicker coals are at the base of the Fruitland Formation, overlying the shoreface sandstones of the Pictured Cliffs Sandstone. These coals developed in mires transitional between low lying and raised peat environments (Roberts and McCabe, 1992). The high ash yield, numerous partings, and relationship with coeval shoreline sandstones support this idea. The rank of the Fruitland coal decreases from north to south and has been influenced by the San Juan volcanic complex north of the San Juan Basin in the area denoted San Juan uplift in Figure 5. Ash content in some of the Fruitland coals can be very high, indicative of large amounts of sediment being brought into the mires by flooding. The Fruitland coals are a tremendous source of coalbed methane, particularly in the northern part of the San Juan Basin extending into Colorado.

***Fruitland field*—**The Fruitland field includes the Late Cretaceous Fruitland Formation exposures from the San Juan River (Fig. 21) north to the New Mexico-Colorado state line, trending N-NE for about 25 mi (Fig. 21). The overlying Kirtland Formation is similar in lithology but lacks significant coal beds. Therefore, the contact between the Fruitland and Kirtland Formations is chosen arbitrarily at the uppermost significant coal bed. The Fruitland Formation is relatively flat, lying (3–5°E) in the southern part of this field. The angle of dip increases from 18–30°SE at the Hogback monocline on the western edge of the northern Fruitland field (Fig. 21).

Several thick minable coal seams occur in the Fruitland Formation within this field, averaging about 16 ft thick, and generally occur near the base of the formation. One seam is nearly 50 ft thick near the Colorado border. These coal beds are high in ash content (18% weighted average, 105 samples) and have low sulfur values (0.8% weighted average, 103 samples). The apparent rank of the Fruitland field coal is high-volatile bituminous C and B.

Small coal mines in the Fruitland field were opened in the 1890s and early 1900s to supply fuel for domestic use (Nickelson, 1988, p. 126). Very little large-scale mining took place in the Fruitland field before 1958. At that time, exploration projects resulted in some of the present-day large surface mining operations. Most of the surface-minable resources of the Fruitland field are within the lease areas of the San Juan and La Plata mines seen in Figure 21. San Juan Coal Co., a subsidiary of BHP Billiton operated the surface mines at these two locations.

The Fruitland coal area between the San Juan and La Plata mines is on the Ute Mountain Reservation. Public Service Company of New Mexico delineated 10–14 million short tons of surface-minable coal through drilling on the Ute Mountain property. The coal beds in this area have steep dips, owing to their proximity to the Hogback monocline seen in Figure 21 (Shomaker and Holt, 1973). At the northern end of the Fruitland field, the La Plata mine produced coal from three thick zones.

Demonstrated resources of surface-minable coal beneath overburden of less than 200 ft in the Fruitland field are approximately 550 million short tons. The resources within 150 ft of the surface are estimated at 545 million short tons, with an average coal thickness of 7.4 ft. Most of these surface-minable resources are in the southern part of the field on the San Juan mine property that supplies coal to the San Juan generating station, operated by Public Service Company of New Mexico. San Juan Coal's La Plata mine, located just south of the New Mexico–Colorado boundary, supplied coal to the San Juan power plant from 1986–2002 (Fig. 21). Underground resources (200–1,000 ft) are 861 million short tons in the Fruitland field. San Juan Coal Company started an underground longwall mine at the south end of their San Juan permit area in 2001. The underground operation replaced coal production from their San Juan surface operation when the coal could no longer be economically mined by surface methods. The La Plata mine increased production during the development of the San Juan underground operation to meet contract requirements. La Plata mine stopped production in 2002, when the San Juan underground mine had reached full production capacity. Westmoreland Coal acquired the San Juan mine from BHP Billiton and took over operations Feb. 1, 2016.

Navajo field—The Navajo field is south of the Fruitland field, within the Navajo Reservation, a distance of approximately 35 mi from the San Juan River, south to Hunters Wash (T23N), and east to the boundary of the Navajo Reservation (Figs. 8, 21). The predominant dip of the Fruitland beds is less than 5°E–NE. There is little or no significant faulting in the Navajo field. Tributaries of the Chaco River run east west and dissect this area. The northern part of the field is predominantly badlands topography and the southern part has low, sandstone capped mesas and rolling hills. Numerous coal beds in the Fruitland Formation occur near the base of the Fruitland Formation, with up to eight minable seams in the southern part of the field (Shomaker et al., 1971).

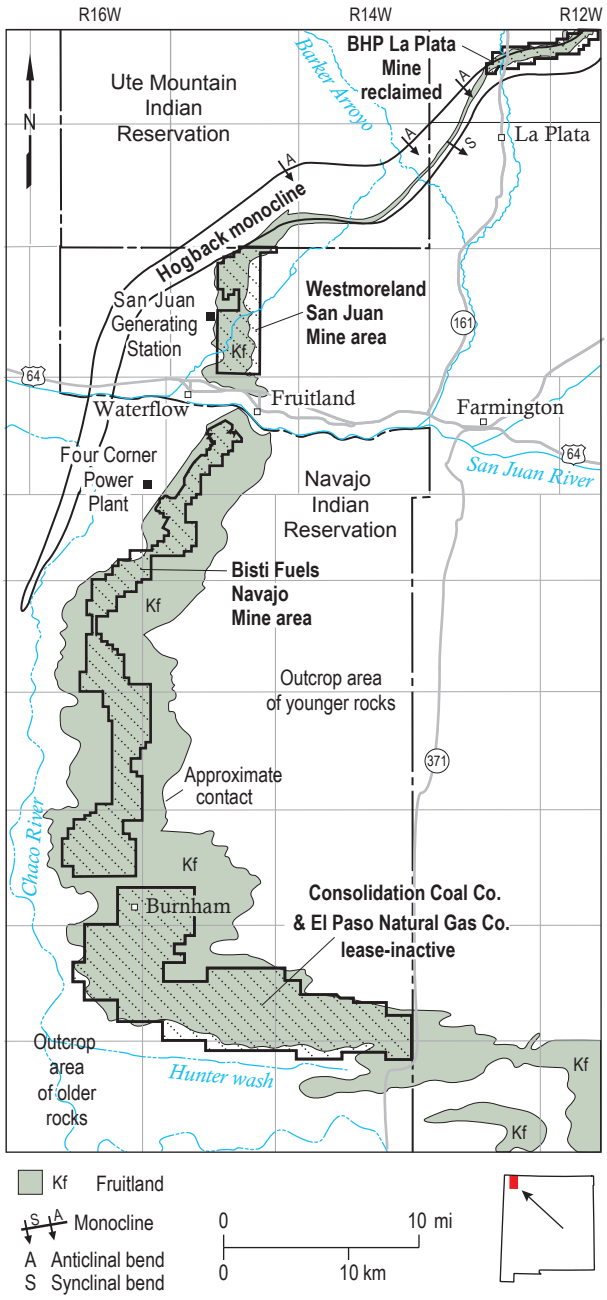


Figure 21. Map of the Fruitland and Navajo field. Modified from Shomaker et al. (1971). Hachure polygons are coal mine lease areas within the Fruitland outcrop area.

Oscillations of the Late Cretaceous shoreline, with minor stillstands, created the relatively thick coal beds, en echelon to the north, with increasingly older beds southward (Shomaker et al., 1971, p. 108).

Coal in the Navajo field has an apparent rank of subbituminous A to high-volatile C bituminous, with a slight decrease in quality southward, owing to an increase in ash yield, lower calorific values, and greater moisture content. The lower calorific values

and greater moisture content are indicative of a lower degree of coalification. Average ash for the Navajo field coals is 19.29% (weighted average, 39 samples), with average sulfur content of 0.79% (37 samples).

Before 1953, there was very little mining, except for small, temporary pits opened by the local Navajos for home heating fuel in the Navajo field. Utah Construction and Mining became interested in this area in the early 1950s, and obtained a permit to mine from the Navajo Nation in 1957. In 1958, the company obtained a permit for water use. Arizona Public Service Co. became interested and negotiated with the Navajo Tribe to build a generating station. The Four Corners generating station became operational with three units in 1963. By 1970, two additional units had been built and Utah Construction reached full production at the Navajo mine (Nickelson, 1988). In 1986, BHP Minerals, Inc. acquired Utah International (Fig. 21). BHP Minerals, Inc. hold the leases for the northern two thirds of the Navajo field. BHP merged with Billiton in May 2001, becoming BHP Billiton. The Navajo Nation purchased the Navajo mine from BHP in 2013. The Navajo Nation Council voted to form a limited liability company to buy the coal mine on April 29, 2013. Through this company, Navajo Transitional Energy Company (NTEC), the Navajo Nation signed a mine management agreement on October 31, 2013. As part of the agreement, Arizona Public Service (APS), majority owner of the Four Corners Power Plant, acquired Southern California Edison's portions of units 4 and 5 in late December 2013. A new coal supply agreement was made between APC and NTEC. BHP continued to operate the Navajo mine for NTEC until the end of 2016. Bisti Fuels Company, LLC, a subsidiary of Norh American Coal Corporation currently operates Navajo Mine on behalf of NTEC.

In the late 1950s, El Paso Natural Gas Co. ("El Paso") was interested in developing a coal gasification plant using coal from the southern Navajo field. A gasification plant converts hydrocarbon feedstock, in this case coal, into gaseous components, including synthetic natural gas, by applying heat under pressure in the presence of steam. El Paso acquired a prospecting permit in 1959 from the Navajo Nation and exploration drilling began on the 85,760 acres south of the Utah Construction lease (Fig. 21). In 1963, El Paso had negotiated a lease with the Navajo Nation for 22,640 acres for a minimum of ten years. The lease had several stipulations, including a pilot plant for coal gasification. El Paso could not meet the requirements in the allotted time, so the lease expired. After several renegotiations, El Paso and Consolidation Coal (Consol) acquired a ten-year lease in 1968. At this time, Consol reevaluated the resources in the southern Navajo field. Consol estimated about 0.7 billion short tons of surface minable coal in this area. El Paso began plans for the building of a four–unit gasification plant. By 1977, an Environmental Impact Statement was completed, and a mining permit obtained, but the Navajo Nation had not approved the plan. To comply with terms of the renegotiated lease (August 1976), the Conpaso (Consolidated Coal and El Paso Natural Gas) Burnham mine was developed (Fig. 21). This mine produced a total of 600,000 tons of coal from 1980–1984. The Burnham mine was idled in 1985 and Consolidated Coal relinquished its lease in 1991. For this operation to be economically feasible, the mine needed a railroad spur built across Navajo Reservation land to the main rail line (Nickelson, 1988). The other alternative would be a generating station built adjacent to the mine.

Demonstrated surface-minable coal resources in the Navajo field, to depths of 200 ft, are about 1.34 billion short tons, with an average bed thickness of 5.6 ft. Resources within 150 ft of the surface are 1.1 billion short tons. Limited data is available for coal at depths of 200–1,000 ft demonstrated resources are 185 million short tons for underground mining.

Bisti field—The Bisti field includes the Fruitland Formation exposures that trend southeast, from the eastern boundary of the Navajo Nation, more or less parallel to the Late Cretaceous shoreline (Fig. 8). The Bisti field is about 35 mi long, and is arbitrarily separated at the boundary between R9W and R8W from the Star Lake field (Figs. 22, 23). The Bisti field is within the Chaco slope physiographic area (Fig. 5), resulting in gentle dips of 3–5°N-NE. The Fruitland Formation and overlying Kirtland Formation have lithologies that erode into badlands topography. Overburden in the Bisti field is largely shale and fine–grained friable sandstone, with no significant faulting and/or high angle dips, therefore surface mining is relatively straightforward.

Coal beds in the Bisti field average 6 ft, but can be up to 30 ft thick. The thicker, more continuous coal beds in the Bisti field are stratigraphically in the middle of the Fruitland Formation coal-bearing sequence (Hoffman et al., 1993), rather than at the base of this unit. These low-sulfur, high-ash Fruitland Formation coal beds have an apparent rank of subbituminous A. The quality of the Bisti coal beds is very similar to those in the Navajo field, except for lower sulfur

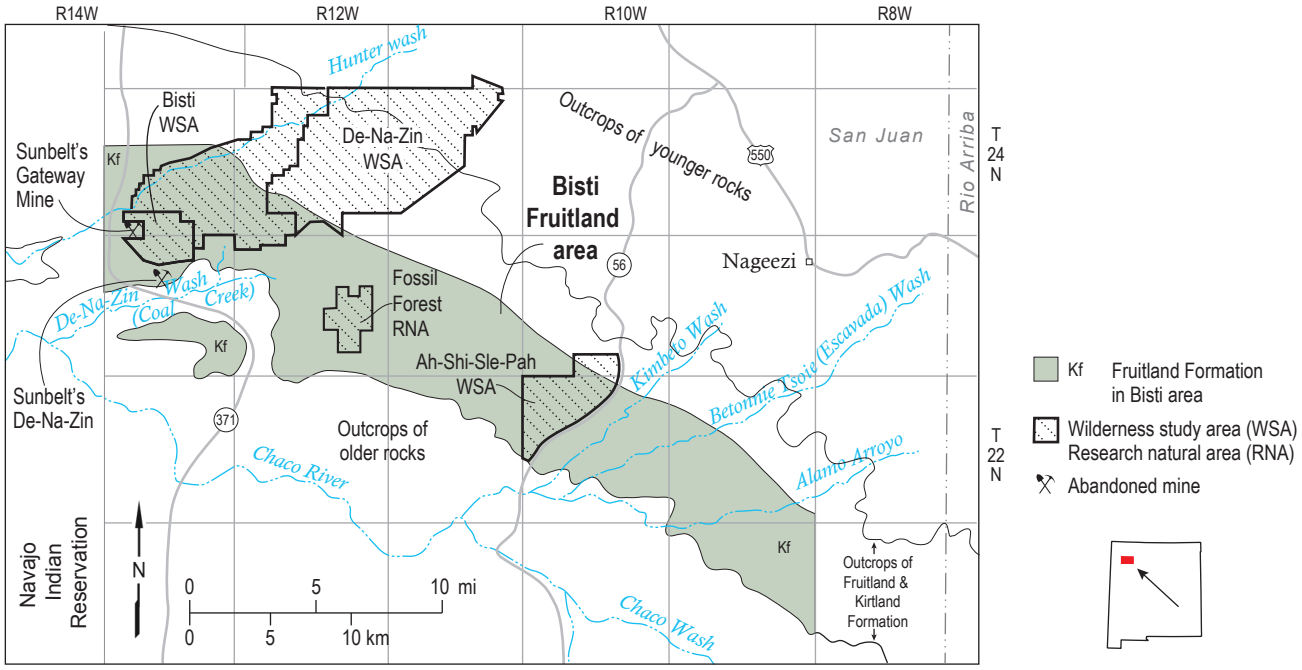


Figure 22. Bisti area showing inactive mines and wilderness areas within the Fruitland Formation outcrop. Modified from Hoffman and Jones (1998).

(0.52% weighted average, 44 samples) and calorific values (8,744 Btu/lb, weighted average, 44 samples).

The Bisti field represents the largest underdeveloped surface-minable coal resource in the San Juan Basin. The De-Na-Zin and Gateway mines, owned by Sunbelt Mining Company, were located in the northwest part of the Bisti area (Fig. 22). Because transportation is a major economic hindrance in this area, both mines were closed in December of 1988. Although a railroad was proposed to provide access to the Star Lake and Bisti areas, this endeavor is no longer viable because of right-of-way problems related to multiple land owners and the present economics of coal mining.

The Bisti and De-Na-Zin Wilderness areas (Fig. 22) are within the Bisti field and include 3,946 and 19,700 acres of public land, respectively. In 1996, the area linking the Bisti and De-Na-Zin Wilderness areas officially became a wilderness area. The wilderness areas are federally managed by the U.S. Department of the Interior's Bureau of Land Management office in Farmington, and have been withdrawn from mineral entry, therefore these areas cannot be considered part of the economic Bisti field coal resource. The wilderness area contains Fruitland Formation and Kirtland Shale outcrops that erode into badlands topography, resulting in spectacular geomorphic features.

Preliminary estimates based on widely spaced drilling and on outcrop data, indicate about 872 million short tons of surface-minable coal resources (≥2.5 ft thick; ≤200 ft deep) exist in the Bisti field. Demonstrated resource estimates for coal, within 150 ft of the surface, are 544 million short tons. Underground (200–1,000 ft) demonstrated resources are 1.17 billion short tons. A coal availability study (Hoffman and Jones, 1998) in the Bisti field that included most of the wilderness area within the Fruitland surface minable coal removed 334 million short tons from the total demonstrated resources. This tonnage is about 25 percent of the total near surface demonstrated resources for western third of the Bisti field.

Star Lake field—The Star Lake field extends E–SE from the Bisti field for 55 mi, and is defined by the outcrops of the Fruitland Formation (Figs. 8, 23). The Fruitland Formation has a greater sandstone component in the Star Lake field and pinches out at the eastern edge of the area, southeast of the town of Cuba (Fig. 23). Hunt (1984) believed that the lithology and overall thinning of the Fruitland in this part of the San Juan Basin was caused by differential subsidence during deposition. The beds dip less than 5°N-NW into the basin and some normal faulting has occurred within Star Lake field.

Fruitland Formation coals in the Star Lake field are thin, lenticular, and rarely exceed 10 ft. Analyses from cores suggest the coal has an apparent rank of subbituminous A to high-volatile bituminous C. These coal beds have a greater average

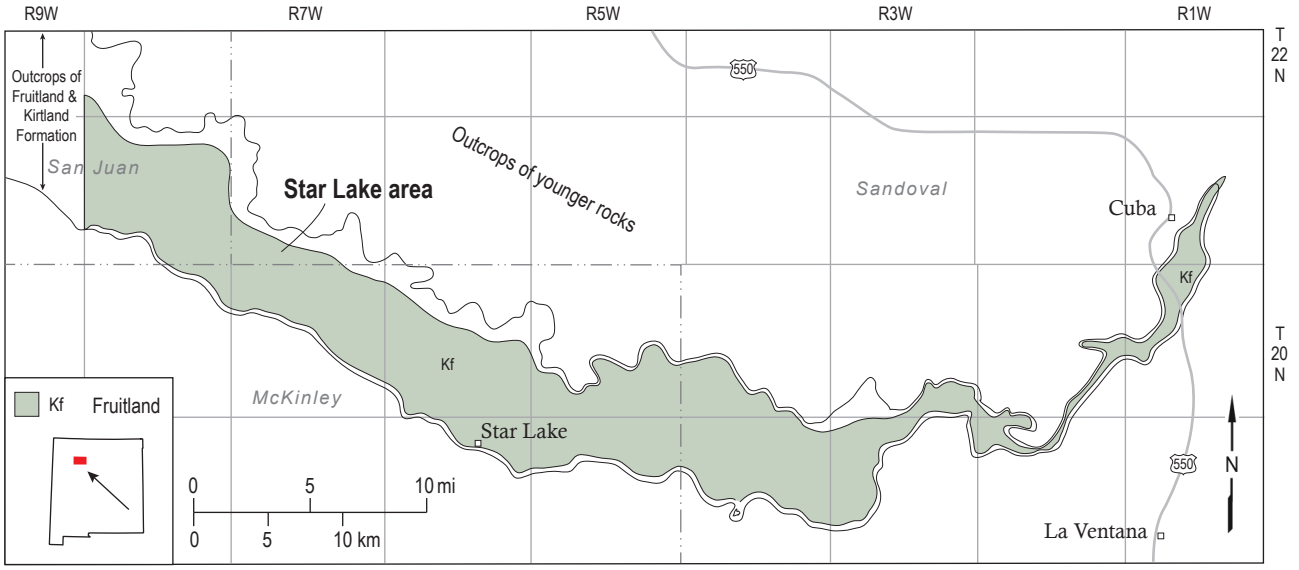


Figure 23. Map of Fruitland Formation in the Star Lake area. Modified from Shomaker et al. (1971).

ash yield (22.42% weighted average, 52 samples) and lower sulfur values (0.55% weighted average, 52 samples) than any of the other Fruitland Formation fields.

The first mining in the Star Lake field was by Navajos to obtain home–heating fuel. This area was included in the early coal investigations by the U.S. Geological Survey in the 1930s (Dane, 1936), but exploration activities did not begin until the 1960s. Exploration led to limited leasing of federal coal in the late 1960s. Thermal Energy and Peabody Coal did exploration drilling in the early 1970s on leases in T19-20N, R6W. A mine plan was developed for this area that was to be operated by Chaco Energy, a subsidiary of Texas Utilities that signed an agreement with Thermal and Peabody to purchase the leases and mine the coal. Coal from the Star Lake mine was to be shipped by rail to Texas. A 65-mile rail spur would be needed to connect to the main line (Speer et al., 1977). The mine plan was submitted to the State, but no mining ever occurred. There are no producing mines and no active Federal coal leases in this field. Lack of economic transportation is a major problem in developing this area for coal resources.

Conservative estimates of the demonstrated surface-minable coal resources for the Star Lake area with (≤200 ft deep) is 946 million short tons. The demonstrated resource estimates for coal, within 150 ft of the surface, are 624 million short tons. The average thickness of an economic coal bed is 6.6 ft. Peabody Coal has announced resources of 162 million short tons, to depths of 150 ft, for their Star Lake mine property, leased by Chaco Energy Co. Demonstrated resources for coal, at depths of 200–1,000 ft, are 327 million short tons.

VII. SMALLER COAL FIELDS

Tres Hermanos Formation, Moreno Hill Formation, Dilco Coal Member of the Crevasse Canyon Formation

The Moreno Hill and Tres Hermanos Formations (Turonian Age) were deposited during the first major retreat of the shoreline in northwestern New Mexico. The Tres Hermanos is a regressive-transgressive wedge of nearshore marine and non-marine deposits, intertonguing with the lower or middle Mancos Shale, in west-central New Mexico and the Zuni Basin (Fig. 5; Hook et al., 1983). The Moreno Hill Formation is, in part, the landward equivalent of this wedge, beyond the pinchout of the Pescado Tongue of the Mancos Shale (Fig. 7). These units outcrop in the southwestern San Juan Basin, in outliers of the basin, as well as some of the smaller coal fields within the Rio Grande Rift (Fig. 5) region. Coals within these units are marginal quality, but there has been mining in the past, along the coal outcrops. In the Salt Lake field in west-central New Mexico, the Moreno Hill Formation coals were the target of drilling and exploration activity in the 1980s and 1990s.

Salt Lake field—The Salt Lake field is an outlier of the San Juan Basin, which covers 750 mi^2 in west–central New Mexico, southwest of the Zuni field (Figs. 3, 8). The Salt Lake field is separated by the Atarque monocline (Fig. 24), that trends southeast from near Ojo Caliente, and by a tongue of the Bandera lava flows (Qb on Fig. 24). The coal-bearing Moreno Hill Formation, named by McLellan et al. (1983), is laterally equivalent to the Tres Hermanos, Gallup Sandstone, and Crevasse Canyon Formation in the southwestern San Juan Basin (Fig.7; Hook et al., 1983).

Outcrops of the Moreno Hill Formation form a westfacing arcuate belt centered on the Zuni Salt Lake (Fig. 24). Coal-bearing units within the field are predominantly flat lying with dips up to 3–5° to the southeast that have undergone minor displacement along faults, and show minor flexures in different parts of the field because of Tertiary volcanism (Campbell, 1989).

The Moreno Hill Formation is 520 ft thick at the type section and consists of three informal units of continental origin, overlying the marine Atarque Sandstone (Figs. 7, 25). The lower, coal-bearing unit is, in part, equivalent to the Carthage and Fite Ranch Sandstone Members of the Tres Hermanos Formation (Anderson and Stricker, 1987). This member consists of channel sandstones and crevasse splays that grade laterally into siltstone, mudstone, and coal. The middle member represents a braided stream environment with coalescing channel sands, consisting of medium- to coarse-grained quartzose sandstones, and is laterally equivalent to the fluvial Torrivio Sandstone Member (Fig. 7) in the Gallup area (Campbell, 1981). The upper member of the Moreno Hill has a similar lithologic sequence to the lower member, although this unit has a greater percentage of silty sandstone, siltstone, and claystone. There is one coal zone, informally called the Twilight coal zone, within this member that is equivalent to coals within the lowermost Dilco Coal Member of the Crevasse Canyon Formation (Fig. 7). This is the uppermost of the four coal zones recognized in the Moreno Hill Formation.

The thickest coals in the Moreno Hill Formation are within 50–180 ft of the top of the Atarque Sandstone, within the lower member (Fig. 25). The Antelope coal zone is near the base of the lower member, and the Cerro Prieto coal zone is about 150 ft below the middle member. The Antelope zone coals are a few feet above the marine Atarque Sandstone (Fig. 25) and represent back barrier swamp deposits (Anderson and Stricker, 1987) and the coals in the Cerro Prieto zone are upper coastal plain deposits. The coals higher in the section (Rabbit zone) are commonly associated with siltstone, and the
entire sequence becomes more siltstone and sandstone-dominated upward, indicating a greater influx of sediment (Fig. 25). The Rabbit zone coals are fluvial in origin (Campbell, 1989). Comparison of the Cerro Prieto and Rabbit zone total coal isopachs (Campbell, 1989) show a change from a northwest trend to a northeast trend, indicating a change from coastal plain mires, which tend to parallel the

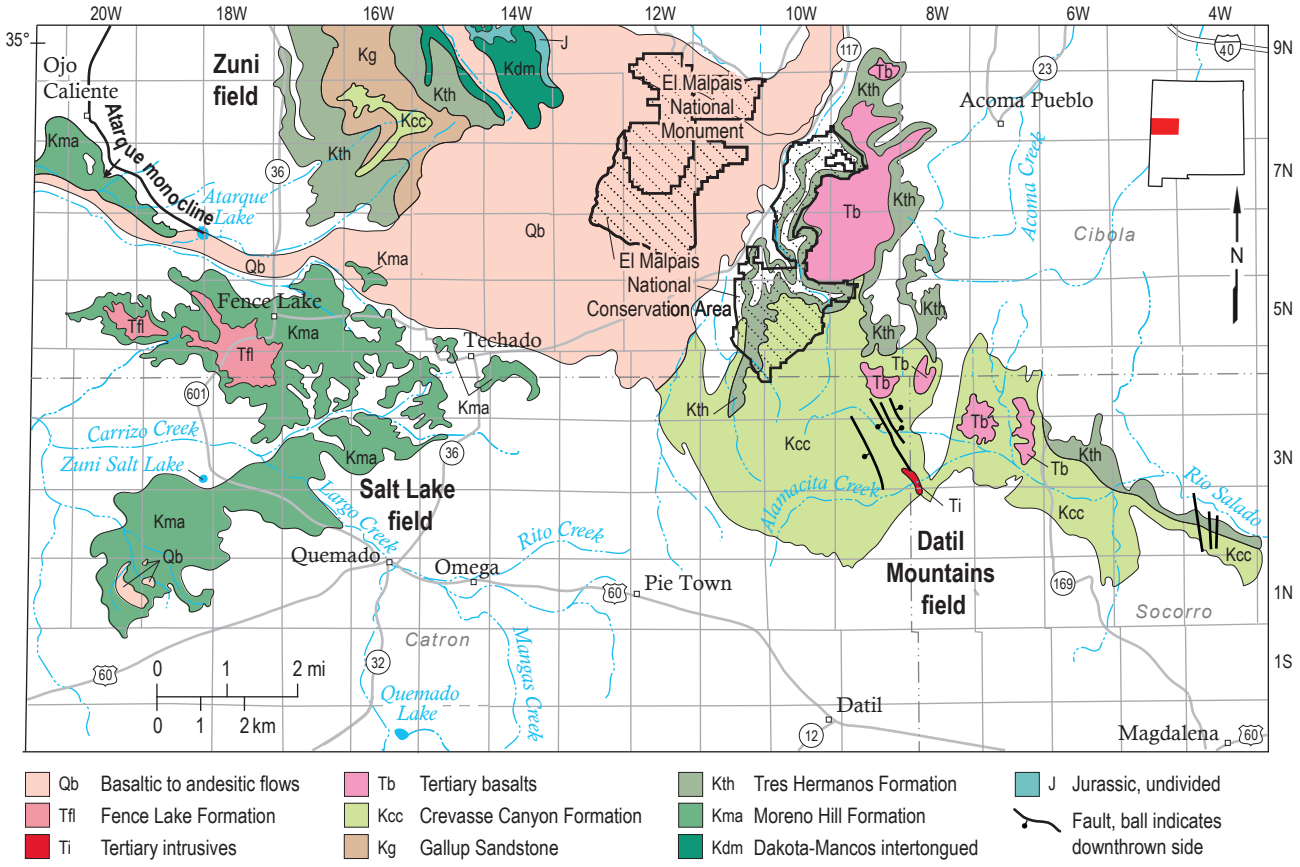


Figure 24. Map of Zuni, Salt Lake and Datil Mountains field. Modified from Hoffman, 1996. Bandera flow (Qb) dividing the Zuni and Salt Lake field is shown.

shoreline, to fluvial-dominated mires that parallel stream drainage patterns. Anderson and Stricker (1987) also noted the trend of the Cerro Prieto coal isopach by Campbell (1989) and the relatively thick coals in this zone. They related this factor to the proximity (6–8 mi) of the landward pinchout of the laterally equivalent Fite Ranch Sandstone Member of the Tres Hermanos Formation to the northeast. It is common for thicker coals to have developed landward of marine sandstone pinchouts that represent reversals in the shoreline migration. Nearly stable conditions are created in coastal mires during these periods of reversal. On a smaller scale, the Cerro Prieto coal zone is similar to the younger Cleary-Gibson coal members of the Menefee-Crevasse Canyon formations undivided in the Gallup area (Fig. 7), southwest of the Point Lookout Sandstone pinchout.

Recent resource evaluations indicate 323 million short tons of demonstrated coal resources of surface-minable coal beneath overburden of less than 200 ft (Campbell, 1981, 1989; Roybal and Campbell, 1981; NMBGMR coal database) with seams averaging 5 ft and up to 14 ft thick. Coal in the Moreno Hill Formation is moderate–ash (17.07% weighted average, 58 samples), low–sulfur (0.69%), with an apparent rank of subbituminous A.

Exploration and lease sales in the 1980s and 1990s created interest in the Salt Lake field. In July 1981, a state lease sale was announced for coal in the Salt Lake area. Salt River Project Agricultural Improvement and Power District, a public entity (SRP, Phoenix, AZ) obtained several of the coal leases and conducted drilling programs in 1982 and 1984 on these leases. In 1983, SRP acquired the Santa Fe Minerals coal leases from the 1981 state lease sale. SRP also acquired state leases from Northwestern Resources in 1986. In March of 1985, John T. Boyd (Denver office) did a reserve study for SRP. In May 1985, a mine plan was submitted to the state's Mining and Minerals Division. A mining permit was issued in November of 1986 for the Fence Lake No.1 mine.

Mining began in January 1987; mining and reclamation was completed in July 1987. The Fence Lake #1 operation mined coal specifically for a test burn at SRP's Coronado Generating Station (Greenberg, 1987) to determine the suitability of the coal. Initial

requirements for this burn were 80,000 short tons, but final production was 100,000 short tons. The mine was closed on completion of tests at Coronado.

In 1988, SRP conducted drilling to apply for a Federal coal lease on lands surrounding their State leases. The Federal lease sale was announced in the spring of 1991 by the BLM with a deadline for bids at the end of July. SRP had the winning bid ($2.4 million) and signed the first federal coal lease agreement in New Mexico in 12 years, on September 25, 1991. This acquisition brought SRP lease acreage in the Salt Lake area to 18,000 acres, with reserves of 120 million short tons. The New Mexico Energy, Minerals and Natural Resources Department, Mining and Minerals Division issued a mine permit to SRP in July, 1996; however, the permit was appealed. The permit was upheld by the New Mexico Coal Surface Mining Commission, and renewed in 2001. Delays in approval and economic factors led SRP to withdraw the permit in May, 2004, and no mining activity occurred under this permit.

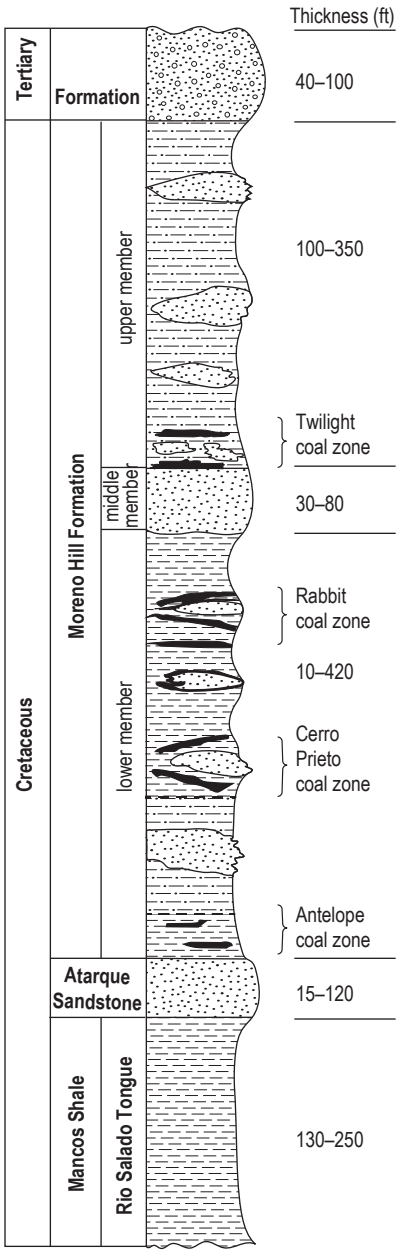


Figure 25. Generalized stratigraphic column of the Moreno Hill Formation with coal zones for the Salt Lake coal field. Modified from Hoffman (1994).

Datil Mountains field—The Datil Mountains area is at the junction of Socorro, Catron, and Cibola Counties (Fig. 24), in west-central New Mexico, and is an outlier of the San Juan Basin (Fig. 3). The field lies on the southeastern edge of the Colorado Plateau, between the Zuni and Lucero uplift (Fig. 5), in a synclinal extension of the San Juan Basin, referred to as the Acoma sag (Fig. 5). The Datil Mountains field encompasses 760 mi^2 of rugged terrain accessible only by secondary roads.

Exposures of the Tres Hermanos and Crevasse Canyon Formations delineate this field (Fig. 24). These coal-bearing units crop out in the northern part of the field and are influenced by several intrusions of Tertiary age. To the south, thick volcanic tuffs and flows overlie the coal-bearing units; broad-scale faulting and folding complicates the structure of the area. Coals are thin (<1.2 ft) and lenticular in the Carthage Member of the Tres Hermanos Formation. Coal beds in most of this field are less than 3 ft thick, although local lenses are as much as 7 ft thick in the Dilco Coal Member of the Crevasse Canyon Formation. These coals lack lateral continuity. Geologic mapping in the Datil Mountains field (Frost, et al., 1979; Osburn, 1982), combined with other available data at the NMBGMR, suggest that the demonstrated resources (≤ 200 ft deep) are approximately 47 million short tons; 31 million short tons of coal are within 150 ft of the surface. The average thickness of the coal beds is 3 ft. Coal seams in the Datil Mountains field have a moderate ash yield (12.84%, weighted average 10 samples), low sulfur value (0.72%), and apparent rank of subbituminous A.

Frost et al. (1979) reported four abandoned mines in the Datil Mountains field. Very few details are available for these mines, except for their locations. The El Cerro mine intermittently operated from 1917 until 1940, and produced approximately 788 short tons of coal. The Hot Spots mine reportedly produced 85 short tons of coal between 1927 and 1931 Nickelson (Abandoned Mine Lands project, unpublished field notes, 1979).

Carthage field—The Carthage coal field, in east-central Socorro County, is on the northwest edge of Jornada del Muerto, an extensive syncline-graben on the east flank of the Rio Grande Rift (Figs. 3, 26). The Carthage field contains the principal reference section, defined as the primary location of reference where the type section was never designated or is inaccessible, for the Tres Hermanos Formation. The type section, defined as where the unit was named and defined, for the Fite Ranch Sandstone, and Carthage members of the Tres Hermanos Formation is in this field. The coals are very thin in the Carthage Member and are of limited extent. Two coal seams, ranging from 4–7 ft thick, are within the Dilco Coal Member of the Crevasse Canyon Formation (Hook et al., 1983). These coals are within 25 ft of the top of the Gallup Sandstone. Only the lower Carthage seam, a local name for a coal seam in the Dilco Coal Member, has been mined; it is excellent coking coal of high-volatile C bituminous apparent rank.

Most of the easily mined coal has been removed; remaining resources may be as much as 30 million short tons. The few analyses available for this field (8 weighted averages) are dubious because of the low moisture content. The low moisture (3.58%) indicates these samples may have dried before analyses were done, which result in elevated Btu/lb values. These coals have moderate ash content (10.86%) and low sulfur (0.84%).

The Carthage field encompasses approximately 10 mi^2, broken into a series of small fault blocks, containing coal-bearing units that make mining difficult and expensive. These fault blocks played havoc with early mining, as coal seams would suddenly end, and the miners would have to give up their workings and try to locate the seam. U.S. Army troops stationed at nearby Fort Craig began mining in this field in 1862. This was the earliest recorded "large-scale" mining in New Mexico, supplying coal to Forts Craig, Seldon, Bayard, and Stanton for smithing (Hoffman and Hereford, 2009). In the late 1800s and early 1900s, the Carthage field supplied coke and coking coal to many smelters in southwestern New Mexico and northern Mexico (Hoffman and Hereford, 2009). Between 1950 and 1975, only one small underground mine operated intermittently, providing coal for local heating, including the public schools in Socorro (F. Kottlowski, pers. comm. 1993). Cactus Industries permitted the Tres Hermanos mine, a surface operation, in 1980. Once development began at the mine, the company realized the reserves had been overestimated and operations ceased in 1981(Martinez, 1981).

Jornada del Muerto field—From 5 to 25 mi east and northeast of the Carthage field in central New Mexico (Figs. 3, 26) coal-bearing rocks underlie the northwest edge of the Jornada del Muerto. Although the Tres Hermanos Formation is present in this field, the principle coal-bearing unit here is equivalent to the Dilco Coal Member of the Crevasse Canyon Formation (Hook et al., 1983). Where exposed,

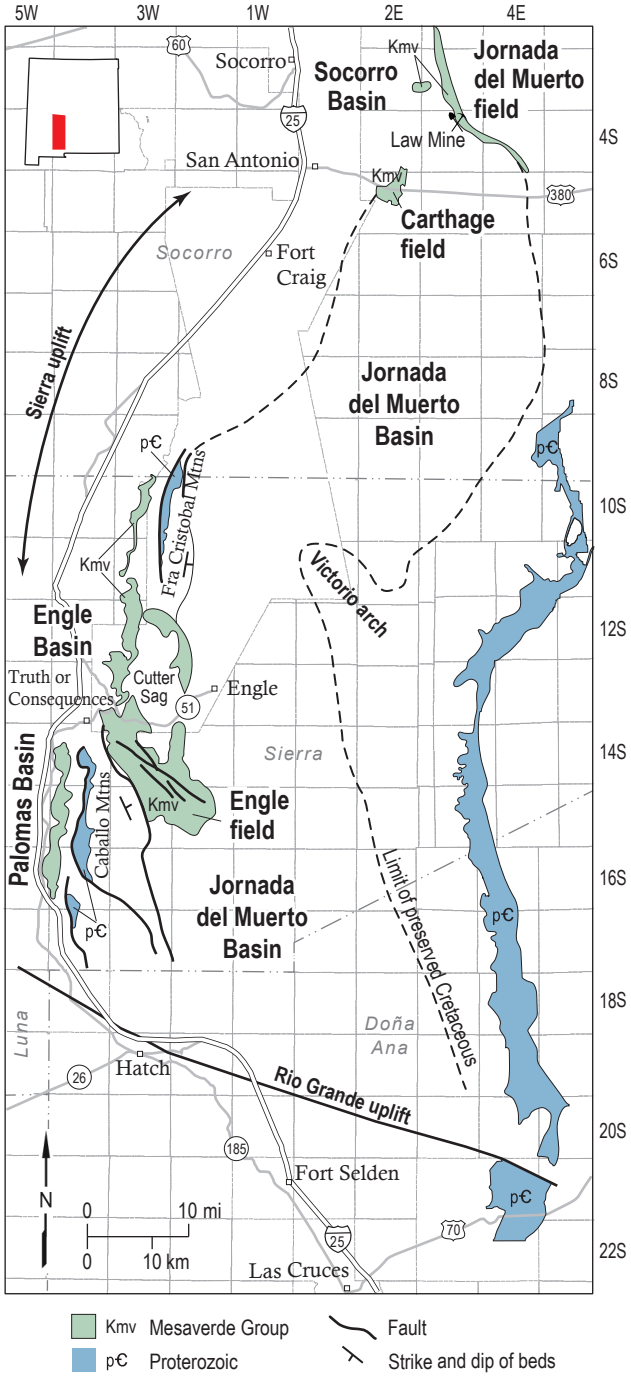


Figure 26. Map of small coal fields in Socorro and Sierra Counties. Modified from Hoffman (1996) and Ewing (2012).

coal beds are generally within 100 ft of the top of the Gallup Sandstone (Tabet, 1979). In this remote area of the state, the Cretaceous units extend for at least 10 mi in a narrow southeast to northwest band. Wind-blown sands conceal much of the bedrock. The few outcrops of coal are similar to that mined in the Carthage field, but maximum coal thickness is only 3 ft. This area is within the Rio Grande Rift region, and steep dips and faulting make exploration and mining difficult.

Two small mines operated in the past in the Jornada del Muerto field. One of these, the Law mine, produced from a 4 ft coal bed (Tabet, 1979). This mine closed in 1927 because the displacement of the coal bed by faulting made it difficult to follow the coal by underground mining methods available at the time.

Engle Field—The Engle area is about 50 mi south of the Carthage field (Fig. 26). It lies on the west edge of the Jornada del Muerto syncline, on the alluvial fans east of the Caballo Mountains. Prospect pits have opened thin lenses of coal, and drill holes have penetrated several coal beds, but the apparent maximum thickness of coal seams is 4 ft. Wallin (1983) recognized the coal-bearing sequence as part of the lower Crevasse Canyon Formation, overlying the Gallup Sandstone. Sparse drilling indicates 8.6 million short tons of estimated resources from 150 to 250 ft below the surface. Deep coal resource estimates (250–1000 ft deep) are 6.1 million short tons. Only one analysis is available for this field and has a high ash (20.10%) and low sulfur (0.40%) content.

Kelley and Silver (1952) described a mine in Sec. 12 T14S R4W (Fig. 26), in a 15-inch seam. Tabet (1979) felt this mine was probably the same one mentioned in the Territorial Mine Inspectors report of 1909, operated by the Southwest Lead and Coal Company to supply nearby metal mines. Two other mines are reported for the Engle area, although very little information is available for these operations. A few wildcat holes were drilled in the 1940s and the 1970s, but little coal was intercepted.

Sierra Blanca field—Coal-bearing strata in the Sierra Blanca field on the northeast margin of the Tularosa Basin crop out near Capitan, Fort Stanton, White Oaks, Three Rivers, and Carrizozo in Lincoln County (Figs. 3, 27). These outcrops form a broken semicircle on the west, north, and east sides of Sierra Blanca. The Sierra Blanca field is part of a southeast-trending synclinal basin that has been complicated by igneous intrusions and subsequent faulting.

Coal beds in the Sierra Blanca field are difficult to mine because the coal-bearing units are broken by many faults and are intruded by numerous igneous dikes and sills associated with the Sierra Blanca igneous complex. Outcrops of Cretaceous rocks in this field are limited and highly faulted. Good exposure of the complete section is lacking, making it difficult to map individual units. Cobban (1986) determined through ammonite zonation that the Cretaceous sequence in this field is similar to that found in the Carthage area. The Cretaceous section includes the lower Mancos Shale, Tres Hermanos Formation, D–Cross Tongue of the Mancos Shale, the Gallup Sandstone, and the Crevasse Canyon Formation. The minable coals are in the Crevasse Canyon Formation, although not much of the coal can be surface mined because of dips greater than 5° and excessive overburden. Average coal thickness is 4 ft and estimated resources within 150–250 ft of the surface are 42 million short tons.

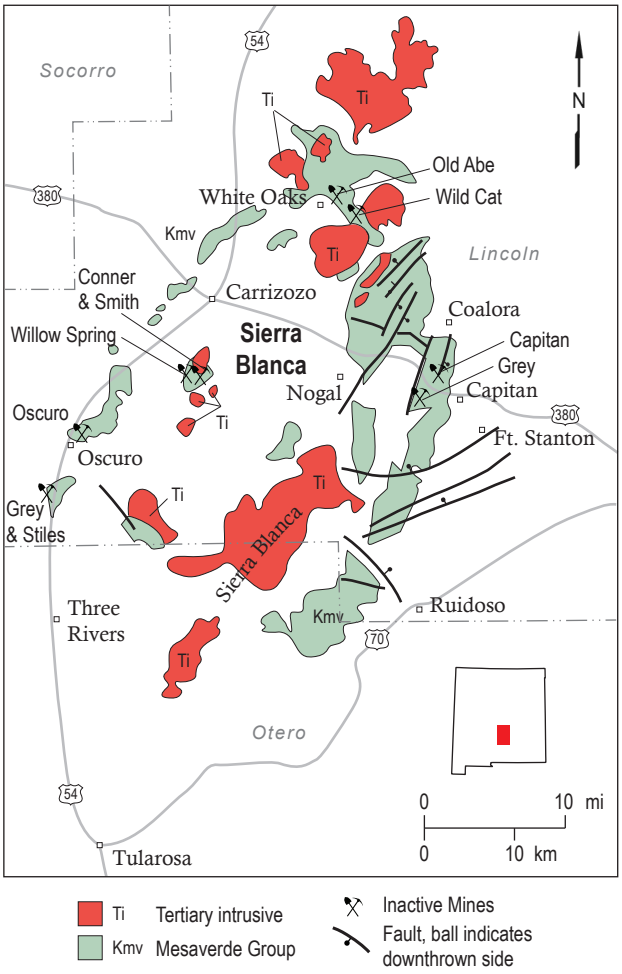


Figure 27. Map of Sierra Blanca coal area. Modified from Hoffman (2002).

Most of the seams in this field are of high-volatile C bituminous apparent rank, and some of the coal near Carrizozo appears to have coking qualities. There are an unusually large number of sandstone "rolls," lenses of sandstone that replace parts of the seams, which make mining expensive and extremely difficult. The averages of 15 as-received weighted-analyses indicate coals are moderate ash (13.51%) and moderate sulfur (0.75%) coals (Hoffman, 2002).

Early coal mining was concentrated in the White Oaks and Capitan areas of the Sierra Blanca field (Figs. 3, 27). The earliest mines opened in the 1880s, near White Oaks, northeast of Carrizozo. The Old Abe coal mine opened in 1898 and continued to operate until 1927. It supplied coal to the gold mine of the same name, and later to the village of White Oaks. The Wild Cat mine, also in the White Oaks area, operated from 1914 until 1958, furnishing coal to the local power plant that served White Oaks, Carrizozo, and Nogal (Fig. 27). Coal mining in the Capitan area started in the 1880s, when the army opened a mine to meet the needs of nearby Fort Stanton (Fig. 27).

In 1899, a rail spur of the El Paso and Northeastern Railroad (EP&NE) was laid from Carrizozo to a site called Salado, later to be known as Coalora, north of the town of Capitan (Fig. 27). The New Mexico Fuel Company opened coal mines in this area and shipped coal to smelters in Arizona from 1899–1905. During this time, the EP&NE railroad extended its line to Santa Rosa west of Albuquerque (Fig. 3), with a spur to Dawson, southwest of the town of Raton (Fig. 3) where a better and larger source of coal could be mined. The rail spur to Coalora was abandoned in 1905, and many of the company houses in the area were moved to Dawson (Slagle, 1991). Coal in the Capitan area continued to be produced on a small scale for domestic purposes into the 1930s. Small coal mines opened for short periods of time near Oscura and Three Rivers, on the west side of Sierra Blanca.

Recent exploration focused on the coal-bearing sequence northwest of Carrizozo. Interest in this area during the late 1970s–1980s was influenced by two factors, the quality of the coal and the proximity of the Southern Pacific rail line. In 2006, Grupos Cementos de Chihuahua (GCC), owners of the cement plant east of Albuquerque in Tijeras Canyon, were developing a mining permit application for an area northwest of Carrizozo. GCC collected data and met with the Mescalero Tribal representatives, but this permit was never completed. GCC acquired an established coal mine at Hesperus, CO (King Coal mine) which had been supplying the coal to the Tijeras cement plant (Fig. 3).

Menefee Formation

Cerrillos field—The Cerrillos field is in the broken foothill country, northwest of the Ortiz Mountains, and south of the Galisteo Creek (Figs. 3, 28), which is traversed by the main line of the Atchison, Topeka, and Santa Fe Railway (Fig. 3). The field is on the west flank of the Galisteo Basin, a complex syncline. The 1,000-ft thick coal-bearing Mesaverde Group is broken by many faults and intruded by swarms of dikes. This sequence is interrupted by two thick igneous sills and overlain by the Galisteo Formation. Near these thick igneous sheets, the coal has been metamorphosed to semianthracite and anthracite.

Major coal beds, probably within the Menefee Formation, are up to 6 ft thick, and have yielded considerable tonnages of anthracite and bituminous coal. From the base upward, the five main coal seams are the Miller Gulch, Waldo Gulch, Cook and White, White Ash, and Ortiz Arroyo or 'B' seams (Fig. 29, Lee, 1913; Beaumont, 1979). Some of the bituminous beds are medium coking coals. Anthracite is restricted to the White Ash seam where it is in contact with, or in close proximity to, the intrusive sills, and to the 'B' seam, immediately overlying the intrusive body.

Resources estimated by Read et al. (1950) are 46.5 million short tons of bituminous coal and 11.4 million short tons of anthracite in the Cerrillos field. Beaumont (1979) believed 5.2 million short tons is a more realistic resource figure for this field because Read et al.'s (1950) parameters of calculation are unrealistic; a 1.1-ft thick coal is too thin to be economical and 3,000 ft is an impractical depth for mining in this area.

Although some of the coal is of anthracite rank, where seams have been intruded by igneous sills, most of the Cerrillos coal beds are moderate-ash, moderate-sulfur coals that have an apparent rank of high volatile B to A bituminous. The weighted–average analyses (as–received, 15 samples) for the Cerrillos field indicate these are low-moisture (3.3%), medium-ash (11.69%), and medium-sulfur (1.14%) coals.

The Miller Gulch bed was mined in the late 1880s to early 1890s, before the railroad spur was completed to Madrid (Fig. 29). Upon completion of the railroad spur, several mines produced coal from the White Ash bed (Fig. 29) north and south of Madrid from 1882–1962. The bituminous and anthracite coal of this bed furnished a large percentage of the Cerrillos field total production. Several mines were also opened in the Cook and White bed in Madrid Gulch (Fig. 29). One of the largest mines

in this bed, the Cook and White, opened in 1889 and continued production until 1906. An explosion caused by methane gas led to the closure of this mine. On the east side of Miller Gulch, the 'B' seam overlies the Madrid sill. The irregular surface of the sill resulted in the variable thickness of this coal bed, and the heat of the intrusion turned the coal to natural coke in some areas (Beaumont, 1979). Several mines were opened in the 3–4 ft thick anthracite Ortiz Arroyo bed in the early 1900s.

Total production for the years 1882–1890 and 1898–1962 was 5.5 million short tons of bituminous and anthracite coal. As much as 45,000 short tons of anthracite were mined annually from the Cerrillos field during 1888–1957 and shipped to users throughout the central and western parts of the United States.

Hagan field—The Hagan field is northeast of Albuquerque (Fig. 3, Fig. 28), on the northeast flank of the Sandia Mountains. This field is within a dissected valley between the Sandia and Ortiz mountains, known as the Hagan embayment (Fig. 28). Campbell (1907) called this coal area the Una Del Gato field, for a settlement south of Hagan (Fig. 28), although he included in his description the mines near the town of Hagan that had previously been named the Hagan coal field by Keyes (1904). Campbell (1907) thought the coal-bearing sequence was probably equivalent to that in the Cerrillos field, to the northwest, although the beds could not be traced because of the thick overlying Quaternary alluvium.

Several high-volatile C bituminous coal seams, from 0.5–5 ft thick, are within the Menefee Formation (Black, 1979). The coal-bearing Menefee dips 25–35°E–NE, and is cut by numerous faults (Black, 1979). Thin, lenticular coal beds, steep dips, and faulting make these coals uneconomic for mining. Read et al. (1950) estimated resources of 17.3 million short tons of medium ash, low sulfur coal.

Several small underground mines opened in 1902, and another group of small mines operated from 1927–1939 near Hagan (NM Territorial Mine

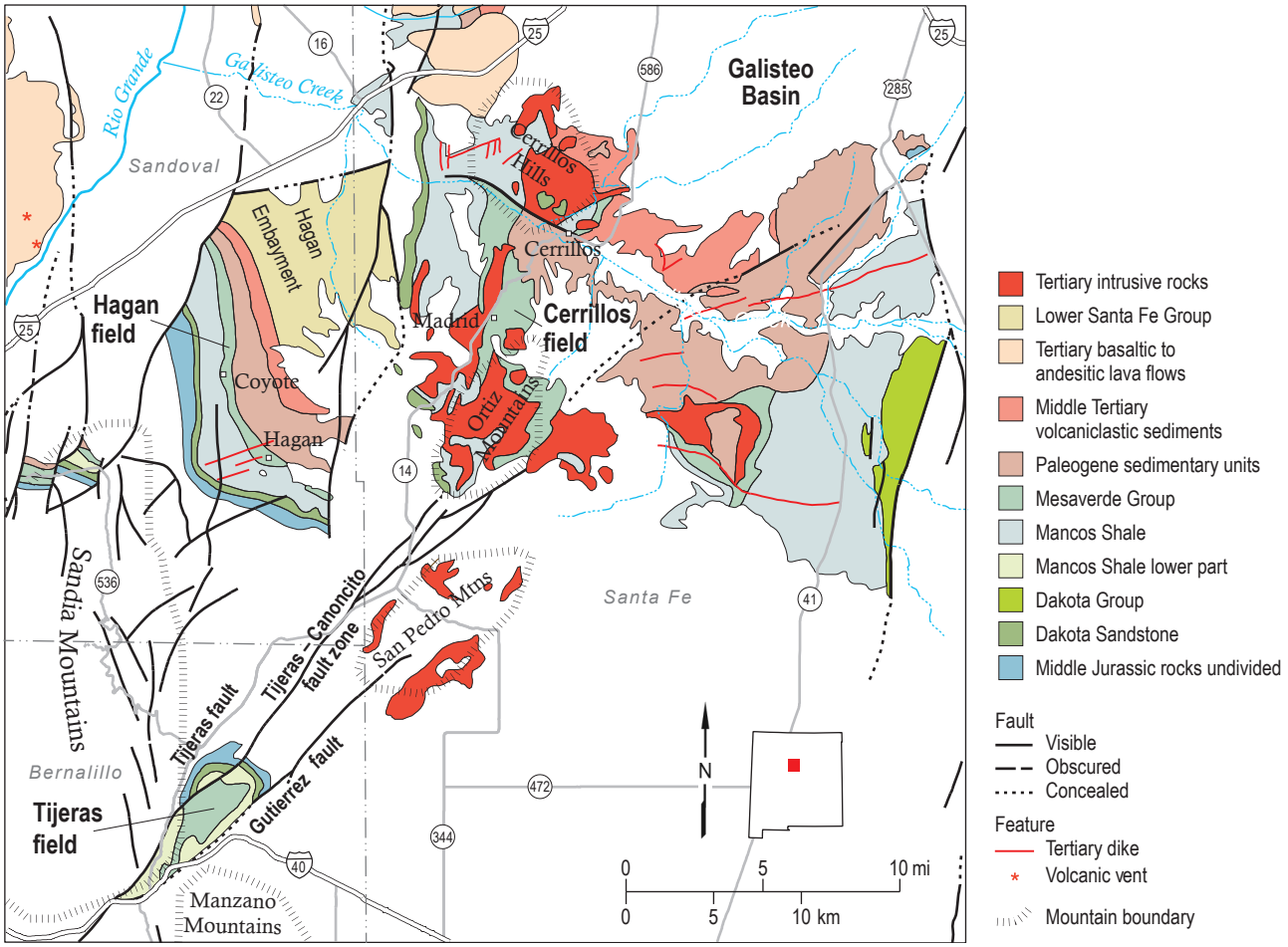


Figure 28. Map of small coal fields (Tijeras, Hagan, Cerrillos) in Bernalillo and Santa Fe Counties. Modified from Hoffman (1996).

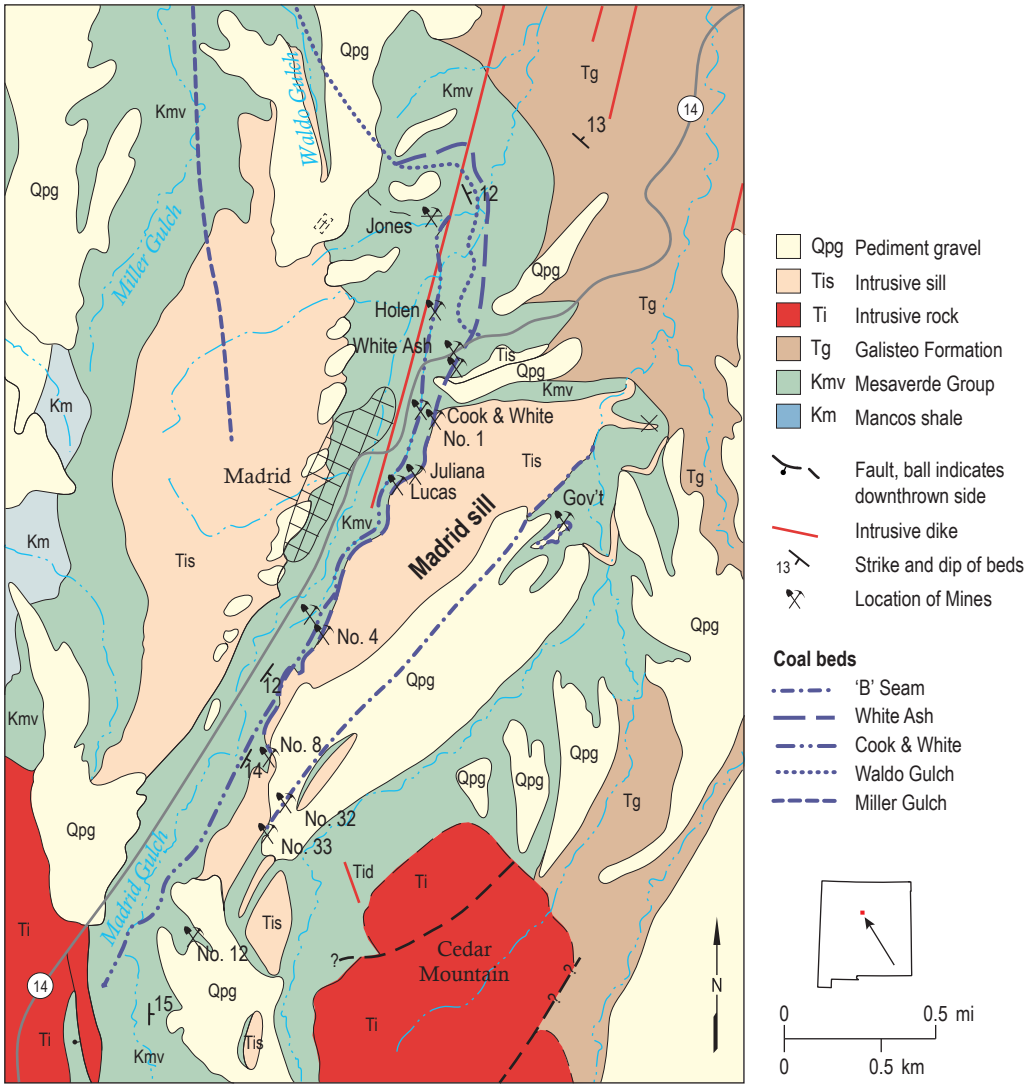


Figure 29. Generalized geologic map of Madrid area with coal beds, Santa Fe County. Modified from Beaumont (1979). Town of Madrid shown as cross-hatched area.

Inspectors, 1902–1912; NM State Mine Inspectors, 1912–1940). In 1904, a few small mines were opened near Coyote (Fig. 28) in some of the northernmost exposures of the Menefee Formation within the Hagan embayment.

Tijeras field—The Tijeras field is east of Albuquerque, on the eastern slope of the Sandia Mountains (Fig. 28). Mesaverde Group coal-bearing rocks occur in a small down-dropped fault block, defined on the east by the Tijeras fault, and on the west by the Gutierrez fault (Fig. 28). The coal-bearing strata occupy the center of a syncline, 5 mi long by 2 mi wide (Lucas et al., 1999). These beds dip steeply on the edge of the syncline, near the faults zones, but flatten towards the center. Most of the Mesaverde section here has been removed by erosion and only a third of its total thickness remains (Kelley and Northrop, 1975). Several thin bituminous coal beds crop out, but only a few short tons were mined for domestic use in the late 1890s to early 1900s (NM Territorial Mine Inspectors, 1882–1911). Mining was difficult, as the coal beds tend to be badly fractured and relatively thin (Lee, 1912). Read et al. (1950) estimated resources of 1.6 million short tons for the Tijeras field.

VIII. RATON BASIN, RATON FIELD

The Raton field covers 900 mi^2 in northeastern New Mexico and is part of a large asymmetrical, arcuate basin, formed during the Laramide orogenic event on the eastern edge of the Rocky Mountains (Baltz, 1965). The basin is bounded on the southeast by the Sierra Grande arch and on the northeast by the Apishapa arch, in New Mexico and Colorado, respectively, and on the west by the Sangre de Cristo Mountains (Fig. 30; Pillmore, 1991). The Canadian and Vermejo Rivers (Fig. 30) have created a highly dissected plateau, with many northwest-trending canyons, that provide easy access to the coal beds. Coal in this area has been mined underground by driving nearly horizontal drifts from the canyon walls. Only a few localities have overburden thin enough to allow surface mining, although there are considerable resources underlying this overburden. The east limb of the Raton Basin dips gently (1–5°) northwest and generally lacks significant faulting (Wanek, 1963). Vermejo Park (Fig. 30) is a prominent anticlinal structure in the northwest Raton coal field, with

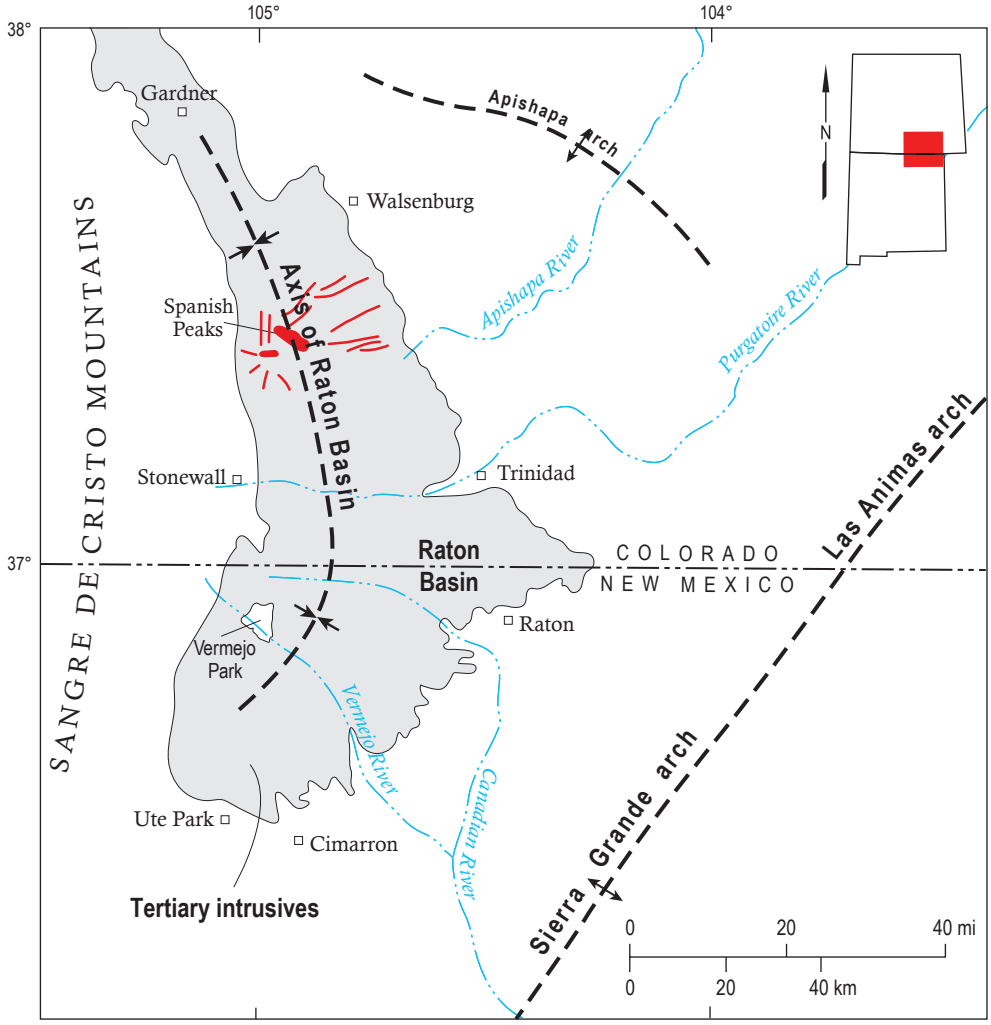


Figure 30. Structural features of the Raton Basin in Colorado and New Mexico from Pillmore (1991). Area of Raton Basin shown in grey, Spanish Peaks dikes shown in red; axis of basin is dashed line with arrows.

2,500 ft of structural relief across 3.85 mi. This structure is attributed to a buried intrusive body as delineated by drill records (Pillmore, 1976).

Vermejo Formation and Raton Formation

The Vermejo and Raton Formations are the coal-bearing units of the Raton Basin (Fig. 31). A regressive deltaic and interdeltaic barrier-bar deposit (Pillmore and Flores, 1987), the Trinidad Sandstone, underlies the Vermejo Formation and is considered equivalent to the Pictured Cliffs Sandstone in the San Juan Basin. The Late Cretaceous Vermejo Formation conformably overlies, and in places, intertongues with the Trinidad Sandstone. The lower Vermejo Formation is a transitional sequence, which contains extensive coal beds, including the Raton coal bed at the base of the Vermejo Formation, deposited in back-barrier brackish mires and lower coastal-plain distributary channels (Fig. 32). Most of the thick, laterally extensive coal beds are back-barrier in origin and are aligned subparallel to the N-NE Late Cretaceous shoreline in this region (Pillmore, 1991). Coal in the upper Vermejo Formation accumulated in poorly drained mires on the upper coastal plains (Pillmore and Flores, 1987). In the northeastern Raton Basin, the Vermejo thins and in places, is unconformably overlain by the Raton Formation. Pillmore and Flores (1987) divided the Raton Formation into three units; the lower coal zone, the barren series zone, and the upper coal zone as shown in Figure 32. The lower coal zone includes all of the Late Cretaceous age rocks of the formation; the K-Pg boundary (formerly known as the K-T boundary) is at the top of this unit. This zone includes a basal conglomeratic sandstone that grades upward into overbank floodplain deposits of interbedded mudstone, siltstone, carbonaceous shale and thin coal (Pillmore, 1991). Northeast of the town of Raton, a 6-ft coal bed, named the Sugarite bed, is at the top of the lower coal zone. Near the top of this bed, in a kaolinitic iridium-enriched parting, the K-Pg boundary is recognized (Pillmore and Flores, 1987). The overlying barren series consists of channel sandstones and minor floodplain coal beds. The upper coal zone contains floodplain deposits, with several economically significant coal beds of 10 ft or greater in thickness that developed in raised mires. Pillmore (1976, 1991) describes seven coal beds in detail within the upper coal zone, in the central and eastern parts of the Raton coal field. The Raton Formation coarsens and interfingers to the west with the wholly continental Poison Canyon Formation (Fig. 32).

Resources estimated by Pillmore (1969), for the northern part of the field, are 700 million short tons of coking coal; Wanek's (1963) estimate for the entire field is 1.5 billion short tons. Using a minimum of 1.2 ft of coal for resource estimates and including inferred resources, Read et al. (1950) estimated 4.7 billion short tons in the Raton field. Pillmore (1991) estimated 1.5 billion short tons of demonstrated (greater than 2.5 ft thick) coal resources in this field, with about 8 billion short tons of inferred resources. The Vermejo Formation has demonstrated resources (greater than 2.5 ft) of 971 million short tons and the Raton Formation has 513 million short tons of demonstrated resources. The inferred resources are mainly in thinner beds, distributed throughout the Raton field (Pillmore, 1991, p. 49).

The Vermejo and Raton Formations coals contain low-sulfur and moderate ash (14.49%, 12.88%, respectively). Most of these coal seams have an apparent rank of high-volatile A to B bituminous, and many are coking coals. The rank of these coals has been elevated because of the proximity of the Spanish Peaks in southern Colorado (Fig. 30), and latest Oligocene-earliest Miocene dike complex in southernmost Colorado. These coals are some of the highest quality coals in New Mexico.

Several minable coal beds occur in the Upper Cretaceous Vermejo Formation and the Upper Cretaceous and Paleocene Raton Formation (Wanek, 1963; Pillmore, 1969, 1976). The most valuable and extensive coal seams are: 1) the Raton coal bed, near the base of the Vermejo Formation; 2) the Vermejo coal bed, near the top of the Vermejo Formation; and 3) a series of seams in the upper part of the Raton Formation, the Tin Pan, Yankee, Left Fork, Cottonwood Canyon, Ancho Canyon, York Canyon, and Chimney Divide beds (Pillmore, 1976, 1991). The York Canyon bed, which is 6–13 ft thick, was mined at the Pittsburg & Midway York Canyon No. 1 and the Cimarron mine, both underground operations.

Coal was discovered in the Raton area in the 1820s and has been mined in the Raton field since the 1870s. From the 1870s to the mid-1960s, the majority of the coal mined was from the Raton coal bed or equivalent beds at the base of the Vermejo Formation in the underground mines in the subdistricts of Koehler, Van Houten, Brilliant, and Dawson (Fig. 31). These early mines were along the eastern edge of the field, at the mouths of canyons (Fig. 32). From 1898–1965, 63.7 million short tons of coal were produced from Raton coal field mines. A significant part of the coal produced during the late 1800s through the early 1900s from these early operations was coked and shipped to smelters in the Southwest and the eastern U.S. Coke was shipped from the Dawson mines owned by a subsidiary of Phelps Dodge, called Stag Canyon Coal, to the company's Arizona smelters.

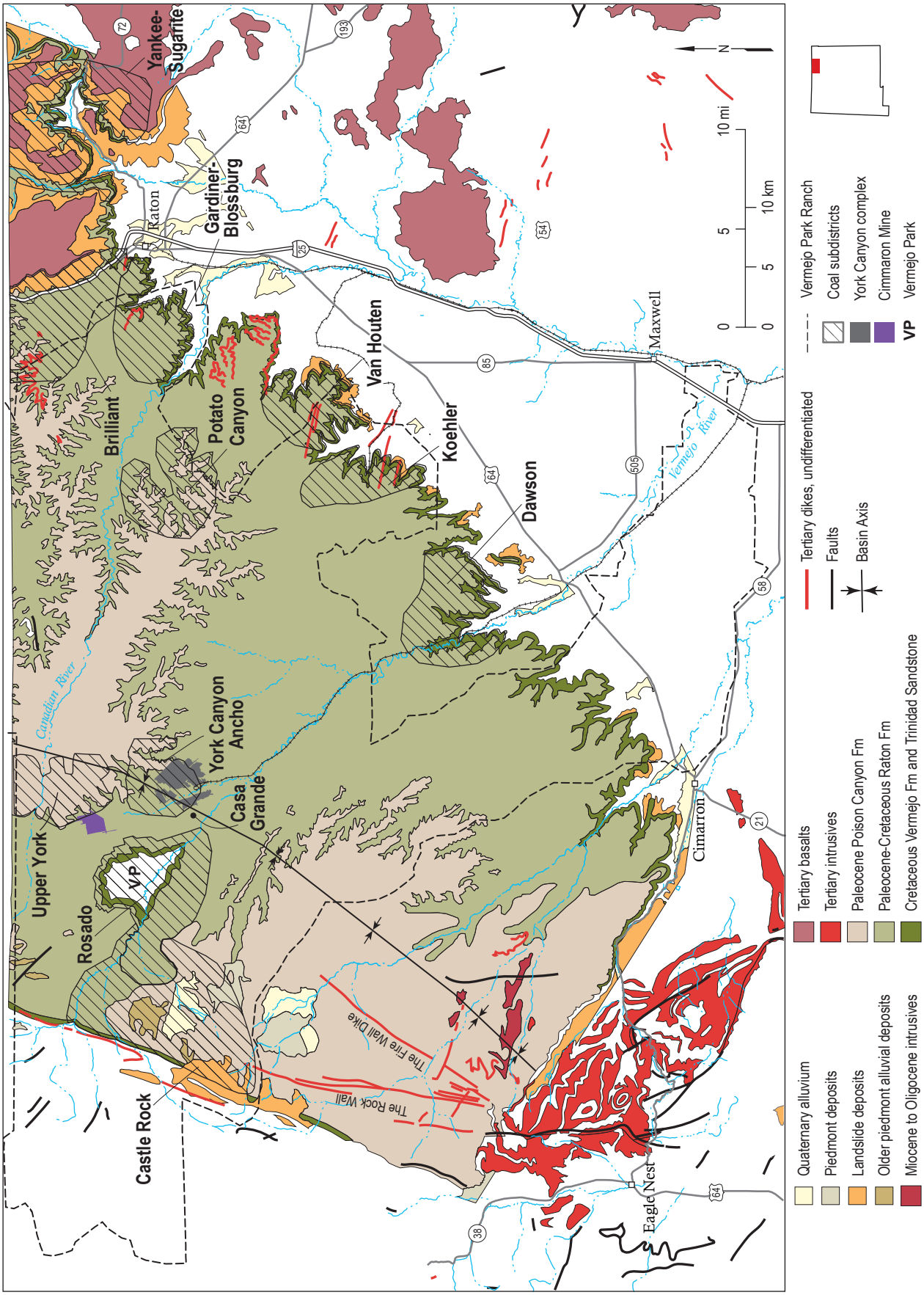


Figure 31. Generalized geologic map of Raton coal field, New Mexico with mining districts (Pillmore, 1991). Geology from New Mexico Bureau of Geology (2003).

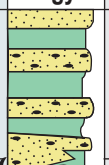
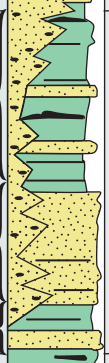
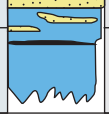
Age		Formation Name	General Description	Litho-logy	approx. Thickness (feet)
Cenozoic	Paleocene	Poison Canyon	**Sandstone**—Coarse to conglomeratic beds 13–50 feet thick, interbeds of soft, yellow-weathering clayey sandstone. Thickens to the west at expense of underlying Raton Formation.		500+
		Raton	Formation intertongues with Poison Canyon Formation to the west **Upper Coal Zone**—Very fine grained sandstone, siltstone, and musstone with carbonaceous shale and thick coal beds. **Barren Series**—Mostly very fine to fine-grained sandstone with minor mudstone, siltstone with carbonaceous shale and thin coal beds **Lower Coal Zone**—Same as upper coal zone; coal beds mostly thin and discontinuous. Conglomeratic sandstone at base; locally absent.		0(?)–2,100 ← K-Pg boundary
Mesozoic	Upper Cretaceous	Vermejo	**Sandstone**—Fine to medium grained with mudstone, carbonaceous shale, and extensive, thick coal beds. Local sills		0–380
		Trinidad Sandstone	**Sandstone**—Fine to medium grained; contains casts of Ophiomorpha		0–300
		Pierre Shale	**Shale**—Silty in upper 300 ft. Grades upward to fine-grained sandstone. Contains limestone concretions.		1800–1900

Figure 32. Generalized stratigraphic column Raton Basin from Flores and Bader (1999), Pillmore and Flores (1987), and Flores (1987). The K-Pg boundary formerly known as the K-T boundary.

In 1955, Kaiser Steel of Fontana, California acquired 530,000 acres from St. Louis Rocky Mountain Pacific and took over the underground mine at Koehler. Kaiser conducted an extensive exploration program of their acquisition and determined the York Canyon region, east of Casa Grande, along the Left Fork of the York Canyon, a tributary valley of the Vermejo River (Fig. 31), had the greatest potential for development. Kaiser began underground operations in 1996, using modern methods of continuous miners and longwall mining east of Road Canyon at their York Canyon mine (Fig. 31). Kaiser opened a surface operation in 1977 in the York Canyon area, southeast of Vermejo Park. Kaiser controlled the majority of the coal leases in the northern Raton field until February 1989 when they sold all of their coal reserves within 623,000 acres, including the York Canyon and Cimarron mine facilities, to Pittsburg and Midway Coal Mining Co., a subsidiary of Chevron Corporation. Pennzoil purchased the surface and oil and gas rights for this acreage. Pittsburg and Midway submitted a mine plan in 1993 for a new operation, the Ancho surface mine, which is in the same area as their other operations. The Ancho mine closed in 2002 because of the expense of surface mining in this area. Currently, there are no active coal mines in the New Mexico portion of the Raton Basin. There was one underground coal mine near Trinidad, Colorado, mining coal up to July 2012, but has been idle since that time. This area is now a major producer of coalbed methane, primarily from the Vermejo Formation coals at depths greater than 1,000 ft. El Paso has production wells within the Vermejo Park Ranch (Fig. 31).

IX. CONCLUSION

Coal has played an important role in New Mexico's history. Coal was needed by the early forts and settlements for heating and blacksmithing. The proximity of coal deposits played an import role in railroad construction in the New Mexico Territory after the Civil War. Many towns in New Mexico developed around the coal mining camps supplying the railroads and smelters in the Southwest. Many of these coal camps are now ghost towns, but others developed into thriving communities such as Gallup and Raton. These communities still have a diverse population that reflects the nationalities of miners that came to work in the coal mines.

With the advent of electricity and the lack of large bodies of water to supply hydroelectric power in New Mexico, coal became the fuel of choice for many power generating stations in the state. Today almost two-thirds of the state's electricity is generated from coal combustion. With new regulations (2014), set by the Environmental Protection Agency for carbon dioxide emissions, many of the coal-fired generating stations in New Mexico are shutting down coal-fired units and looking for alternative energy sources for electrical generation (Hoffman, 2014a). The switch to alternative energy sources (natural gas, nuclear, solar, wind) has had an impact on the coal industry in New Mexico. Decreases in coal production will impact the state's economy with a loss of revenue from employment and severance taxes. Because coal is such a large source of electrical generation in New Mexico and the U.S., it will continue to be a part of the equation until other generating sources and their infrastructure can be developed. According to the EIA (2014), New Mexico has 26% of the nation's coalbed methane proven reserves, second only to Colorado in the United States. Both the San Juan and Raton basins have coalbed methane reserves and development. Depending on the oil and gas prices, coalbed methane may be the future of coal development in New Mexico.

AUTHOR

Gretchen K. Hoffman
gretchen.hoffman@nmt.edu

Gretchen Hoffman is the principal senior coal geologist- emeritus- at the New Mexico Bureau of Geology and Mineral Resources. Ms. Hoffman has an M.S. in Geology from the University of Arizona, Tucson. With over 35 years at the Bureau, she has done field mapping in west-central New Mexico, managed a drilling/coring program three years for a coal quality study in the San Juan Basin, and completed several coal resource evaluations in the San Juan and Raton basins. Recent work includes georeferencing old coal mine maps in New Mexico's major coal basins and creating a coal mine database with location and mining statics for the inactive coal mines.

Ms. Hoffman's primary research has been on coal and coal-related industrial minerals within the state. She has authored or co-authored over 100 peer-reviewed publications, and 30 talks at professional meetings mainly on evaluation of New Mexico's coal resources, humate and fly ash/pozzolan resources and applications, and use of coal clinker as an aggregate. Ms. Hoffman authored the chapter on Pozzolans and Supplementary Cementitious Materials, co-authored the Soil Amendments chapter in the seventh edition of Industrial Minerals and Rocks (IMAR7) with George Austin, and was the database manager for this book.

Ms. Hoffman managed the Bureau's Perlite testing lab from 2009–2015, analyzing about 500 samples from several different companies. As an invited speaker, Gretchen presented a talk on the perlite lab to the Perlite Institute in September 2014 in Park City, Utah.

Ms. Hoffman served on the editorial board for the Bureau's general interest periodical Lite Geology for over 20 years and has contributed articles including the lead article for Lite Geology's Fall 2014 issue: New Mexico's coal and electricity industries and the Clean Air Act As part of the Bureau's outreach program, Gretchen has taught topographic map reading at several teacher workshops.

Gretchen has been active in American Association of Petroleum Geologists, serving as the Energy and Minerals Division (EMD) education committee chair from 1991–1994, and is a recipient of EMD's Distinguished Service Award. Ms. Hoffman has served as program chair and co-led field trips for the Geological Society of America Coal Division. She is a past president and honorary member of the New Mexico Geological Society. The Industrial Minerals Division of SME awarded Gretchen the Distinguished Service award in 2009 for her work on the IMAR7 publication.

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REFERENCES

Preface

Energy Information Administration, 2015, Energy production estimates in physical units, 2013, 2015, online at http://www.eia.gov/state/seds/sep_prod/pdf/P1.pdf.

McLemore, V., Caledon, M., and Barker, J., 2008, Industrial Minerals, a Staple in the Economy of New Mexico: Colorado Geological Survey, Resource Series 46, p. 11–156.

Harrer, C.M., 1965, Iron, *in* New Mexico Mineral and water resources of New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 87, p. 176–183.

Howard, E.V., 1967, Metalliferous occurrences in New Mexico: Phase 1, state resources development plan: State Planning Office, Santa Fe, 270 p.

IIED (International Institute for Environment and Development), 2002, Mining Minerals Sustainable Development Breaking new ground: International Institute for Environment and Development, http://pubs.iied.org/9084IIED.html.

Kelley, V.C., 1949, Geology and economics of New Mexico iron ore deposits: University of New Mexico, Publications in Geology, no. 2, 246 p.

Mack, G.H., 1997, The geology of southern New Mexico: University of New Mexico Press, Albuquerque, NM, 176 p.

Mack, G.H. and Giles, K.A., eds., 2004, The Geology of New Mexico—A Geologic History: New Mexico Geological Society Special Publication 11, 474 p.

McLemore, V.T., 2017, Mining Districts and Prospect Areas in New Mexico: New Mexico Bureau of Geology and Mineral Resources, Resource Map 24, 1 sheet, booklet, 65 p.

New Mexico Energy, Minerals and Natural Resources Department, 1986–2016, Annual Resources Report: New Mexico Energy, Minerals and Natural Resources Department, Santa Fe, various paginated, http://www.emnrd.state.nm.us/ADMIN/publications.html.

Price, L.G., 2010, ed., The Geology of Northern New Mexico's Parks, Monuments and Public Lands: New Mexico Bureau of Geology and Mineral Resources, Socorro, 380 p.

Wagner, L.A., 2002, Materials in the Economy— Material Flows, Scarcity, and the Environment: U.S. Geological Survey Circular1221, 34 p. http://pubs.usgs.gov/circ/2002/c1221/

U.S. Bureau of Mines (USBM), 1927–1990, Minerals Yearbook: Washington, D.C., U.S. Government Printing Office, variously paginated.

U.S. Geological Survey (USGS), 1902–1927, Mineral resources of the United States (1901–1923): Washington, D.C., U.S. Government Printing Office, variously paginated.

U.S. Geological Survey (USGS), 1965, Mineral and water resources of New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 87, 437 p.

Memoir 50B | Special Publication 13B

Allen, John E., Baldwin, B., and Hill, J., 1954, Selected stratigraphic sections in the Menefee and Crevasse Canyon Formations, *in* Allen, J.E., Balk, R., eds., Mineral resources of Fort Defiance and Tohatchi quadrangles, Arizona and New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 36, p. 157–164.

American Society for Testing and Materials, 1981, Annual book of ASTM standards; part 26, gaseous fuels, coal and coke; atmosphere analyses: Philadelphia, Pennsylvania, p. 181–399.

Anderson, O.J., 1987, Geology and coal resources of Atarque Lake 1:50,000 quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources Geologic Map 61, 2 sheets.

Anderson, Orin J., and Jones, Glen E., 1994, Geologic map of New Mexico, 1:500,000, New Mexico Bureau Mines Mineral Resources Open-File Report, 408, p. 1–43.

Anderson, O.J., and Stricker, G.D., 1987, Stratigraphy and coal occurrences of the Tres Hermanos Formation and Gallup Sandstone (Upper Cretaceous), Zuni Basin, west–central New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 121, p. 59–63.

Anderson, O.J., and Stricker, G.D., 1996, Ramah Member of the Crevasse Canyon Formation—a new stratigraphic unit in the Zuni Basin, west-central New Mexico: New Mexico Geology, v. 18, no. 1, p. 6–12.

Averitt, P., 1966, Coking-coal deposits of the western United States: U.S. Geological Survey Bulletin 1222-G, p. 32–36.

Baltz, E.H., 1965, Stratigraphy and history of Raton Basin and notes on the San Luis Basin, Colorado–New Mexico: American Association of Petroleum Geologists Bulletin, v. 49, p. 2041–2075.

Bauer, C.M., and Reeside, J.B., 1921, Coal in the middle and eastern parts of San Juan County, New Mexico; in Contributions to Economic Geology: U. S. Geological Survey Bulletin 716, p. 155–237.

Beaumont, E.C., 1973, Stratigraphic distribution of coal in San Juan Basin; in Strippable low–sulfur coal resources of the San Juan Basin in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Memoir 25, p. 15–30.

Beaumont, E.C., 1979, Geology of the Cerrillos coal field, Santa Fe County, New Mexico, *in* Ingersoll, R.V., Woodward, L.A., James, H.L., eds., Santa Fe Country: New Mexico Geological Society, 30th Annual Field Conference, Guidebook, p. 269–274.

Beaumont, E.C., 1987, Geology and mining activity in the Lee Ranch area, McKinley County, New Mexico, in coal deposits and facies changes along the southwestern margin of the Late Cretaceous seaway, west–central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 121, p. 37–40.

Beaumont, E.C., Dane, C.H., and Sears, J.D., 1956, Revised nomenclature of the Mesaverde Group in San Juan Basin, New Mexico: American Association of Petroleum Geologists Bulletin, v. 40, no. 9, p. 2149–2162.

Beaumont, E.C., and Hoffman, G.K., 1992, Interrelationships between the upper coal member of the Menefee Formation, the La Ventana Tongue, and the Lewis Shale in the southeastern San Juan Basin, New Mexico, *in* Lucas, S.G., Kues, B.S., Williamson, T.E., Hunt, A.P., eds., San Juan Basin IV: New Mexico Geological Society, 43rd Annual Field Conference Guidebook, p. 207–216.

Black, B.A., 1979, Structure and stratigraphy of the Hagan embayment: A new look, *in* Ingersoll, R.V., Woodward, L.A., James, H.L., eds., Santa Fe Country: New Mexico Geological Society, 30th Annual Field Conference, Guidebook, p. 101–105.

Campbell, F.W., 1981, Geology and Coal resources of Cerro Prieto and the Dyke Quadrangles: New Mexico Bureau of Mines and Mineral Resources Open–File Report 144, 68 p, 2 maps, scale 1:24,000.

Campbell, F.W., 1989, Geology and coal resources of the Fence Lake 1:50,000 quadrangle, Catron and Cibola Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources GM-62, 2 sheets.

Campbell, M.R., 1907, The Una Del Gato coal field, Sandoval County, New Mexico, in Contributions to economic geology, 1906, Part II: U. S. Geological Survey Bulletin 316, p. 427–430.

Cobban, W.A., 1986, Upper Cretaceous molluscan record from Lincoln County, New Mexico, *in* Ahlen, J.L. and Hanson, M.E., eds., Southwest section of American Association of Petroleum Geologists: Transactions and guidebook of 1986 convention Ruidoso, New Mexico p. 77–89.

Craigg, S.D., 2001, Geologic framework of the San Juan structural basin of New Mexico, Colorado, Arizona, and Utah with emphasis on Triassic through Tertiary rocks: U.S. Geological Survey Professional Paper, 1420, p. 1–70.

Dane, C.H., 1936, Geology and fuel resources of the southern part of the San Juan Basin, New Mexico, Part 3—La Ventana–Chacra Mesa coal field: U.S. Geological Survey Bulletin 860–C, 80 p.

Dane, C.H., 1948, Geologic map of a part of the eastern side of the San Juan Basin, Rio Arriba County, New Mexico: U. S. Geological Survey Oil and Gas Investigations Preliminary Map 78.

Dane, C. H., and Bachman, G.O., 1965, Geologic map of New Mexico, U.S. Geological Survey, scale 1:500,000.

Dillard, G., 1993, Santa Fe Pacific and Hanson swap gold and coal assets: Pay Dirt p. 13B–14B.

Dillinger, J.K., 1989, Coal resources maps of the Grants 30'x 60' quadrangle, west–central New Mexico: U. S. Geological Survey Coal Investigations Map C–188–B, 3 sheets, 1:100,000 scale.

Dillinger, J.K., 1990, Geology and contour maps of the Gallup 30'x 60' quadrangle: U. S. Geological Survey Investigations Series I-2009, 2 sheets, 1:100,000 scale.

Energy Information Administration (EIA), 1993, The Changing Structure of the U.S. Coal Industry: An Update, Energy: Energy Information Administration Report v. 0513(93), p. 27–28.

Energy Information Administration (EIA), 1996, US Coal Reserves: A Review and Update, Figure 1, Coal Bearing Areas of the United States, August, 1996, http://netl.doe.gov/File%20Library/Research/Coal/major%20demonstrations/publications/M96013817.pdf (accessed November 23, 2015).

Energy Information Administration (EIA), 2011, Annual Energy Review, Table 4.8, Coal Demonstrated Reserve Base, January 1, 2011, http://www,eia,gov/totalenergy/data/annual/pdf/sec4_17.pdf (accessed April 18, 2013).

Energy Information Administration (EIA), Rankings: Coal Production, 2015 (thousands short tons), https://www.eia.gov/state/rankings/?sid=NM#series/48 (accessed April 24, 2017).

Energy Information Administration (EIA), 2016, Frequently Asked Questions: What is U.S. Electricity generation by energy source?, https://www.eia.gov/tools/faqs/faq.php?id=427&t=3 (accessed April 24, 2017).

Energy Information Administration (EIA), 2014, State Profile and Energy Estimates: New Mexico: http://www.eia.gov/state/?sid=NM (accessed December 21, 2015).

Energy, Minerals and Natural Resources Department, 1994, Coal, *in* Annual Resources Report 1994, p. 35–47. http://www.emnrd.state.nm.us/mmd/Publications/documents/1994EMNRDAnnualReport.PDF (accessed March 26, 2015).

Energy, Minerals and Natural Resources Department, 2006, Annual Report, http://www.emnrd.state.nm.us/ADMIN/documents/EMNRD2006.pdf (accessed March 26, 2015).

Energy, Minerals and Natural Resources Department, 2016, p. 51.

Ewing, T.E., 2012, Geology and hydrocarbon resource potential of Cretaceous strata in the Jornada del Muerto, Sierra and Socorro Counties, New Mexico, *in* Lucas, S.G., McLemore, V.T., Lueth, V.W., Spielmann, J.A., Krainer, K., eds., Geology of the Warm Springs region, New Mexico Geological Society, 63rd Annual Field Conference, Guidebook, p. 569–580.

Flores, R.M., 1987, Sedimentology of upper Cretaceous and Tertiary siliclastics and coals in the Raton Basin, New Mexico, in Lucas, S.G., and Hunt, A.P., eds., Northeastern New Mexico: New Mexico Geological Society, 38th Annual Field Conference, Guidebook, p. 255–264.

Flores, R.M. and Bader, L.R., 1999, A summary of Tertiary coal resources of the Raton Basin, Colorado and New Mexico in 1999 Resource assessment of selected Tertiary coal beds and zones in the Northern Rocky Mountains and Great Plains Region: U.S. Geological Survey Professional Paper 1625-A, chapter SR.

Frost, S.J., Tabet, D.E., and Campbell, F.W., 1979, Coal exploratory drilling in the Datil Mountain coal field: New Mexico

Bureau of Mines and Mineral Resources Open-File Report 111, 48 p.

Gore, A.J.P., 1983, Introduction, *in* Gore, A.J.P., eds., Ecosystems of the world; 4A, Mires: Swamp, bog, fen, and moor, general studies: Amsterdam, Elsevier Scientific Publishing Company, p. 1–34.

Greenberg, M.A., 1987, Large-scale combustion test of Fence Lake coal at the Coronado Generating Station, *in* Roybal, G.H., Anderson, O.J, and Beaumont, E.C., compilers, Coal deposits and facies changes along the southwestern margin of the Late Cretaceous seaway, west-central New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 121, p. 79–83.

Hatton, K.S., 1988–1994, Coal, in Annual Reports: New Mexico Energy, Minerals and Natural Resources Department.

Hayes, P.T., and Zapp, A.D., 1955, Geology and fuel resources of the upper Cretaceous rocks of the Barker Dome–Fruitland area, San Juan County, New Mexico: U.S. Geological Survey Oil and Gas Investigations Map 144, 1:62,500 scale.

Hoffman, G.K., 1994, Coal geology of the lower Moreno Hill Formation, Salt Lake Field, west-central New Mexico, *in* Chamberlin, R.M., Kues, B.S., Cather, S.M., Barker, J.B., McIntosh, W.C., eds., Mogollon Slope, west-central New Mexico: New Mexico Geological Society, 45th Annual Field Conference, Guidebook p. 283–289.

Hoffman, G. K., 1996, Coal resources of New Mexico, New Mexico Bureau of Mines and Mineral Resources, Resource Map, v. 20, 22 p., 1 sheet, scale 1:1,000,000.

Hoffman, G.K., 2002, Sierra Blanca coal field, Lincoln and Otero counties, New Mexico, in Lueth, V.W., Giles, K.A., Lucas, S.G., Kues, B.S., Myers, R., Ulmer-Scholle, D.S., eds., Geology of White Sands, New Mexico: Geological Society, 53rd Field Conference, Guidebook p. 21–24.

Hoffman, G.K., 2014a, New Mexico's coal and electricity industries and the Clean Air Act, Lite Geology, v. 36, p. 2–7.

Hoffman, G.K., 2014b, Carbon dioxide emissions: New guidelines and economic challenges: Lite Geology, v. 36, p. 9.

Hoffman, G.K., 2016, Coal, *in* McLemore, V.T., Timmons, S., and Wilks, M., eds., Energy and mineral resources of New Mexico: New Mexico Bureau of Geology and Mineral Resources Memoir 50B, and New Mexico Geological Society Special Publication 13B, 80 p.

Hoffman, G.K., Campbell, F.W., and Beaumont, E.C., 1993, Quality assessment of strippable coals in northwestern New Mexico: Fruitland, Menefee, and Crevasse Canyon Formation coals in San Juan Basin and Moreno Hill Formation coals in Salt Lake field: New Mexico Bureau of Mines and Mineral Resources Bulletin 141, 84 p.

Hoffman, G.K., and Hereford, J.P., 2009, Mining History of the Carthage coal field, Socorro County, New Mexico, *in* Lueth, V.W., Lucas, S.G., Chamberlin, R.M., eds., Geology of the Chupadera Mesa, New Mexico: Geological Society, 60th Annual Field Conference, Guidebook, p. 407–413.

Hoffman, G.K., Jones, G.E., 1998, Availability of coal resources in the Fruitland Formation, San Juan Basin, northwest New Mexico, New Mexico Bureau of Geology and Mineral Resources Open-File Report 438, p. 5.

Hoffman, G.K., O'Hara, J., and Lucas Kamat, S.A, 2009, Coal Geology of New Mexico, *in* 2010 Keystone Coal Industry Manual, Johnson, P., publisher, p. 517–527.

Hook, S.C., 2011, The Late Cretaceous oyster Cameleolopha bellaplicata (Shumard 1860), guide fossil to middle Turonian strata in New Mexico, New Mexico Geology, v. 33, no. 3, p. 67–96.

Hook, S.C., Molenaar, C.M., and Cobban, W.A., 1983, Stratigraphy and revision of nomenclature of upper Cenomanian to Turonian (upper Cretaceous) rocks of west–central New Mexico; in Contributions to mid–Cretaceous paleontology and stratigraphy of New Mexico—Part II: New Mexico Bureau of Mines and Mineral Resources Circular 185, p. 7–28.

Hunt, A.P., 1984, Stratigraphy, sedimentology, taphonomy, and magnetostratigraphy of the Fossil Forest area, San Juan County New Mexico [M.S. Thesis]: Socorro, New Mexico Institute of Mining and Technology, 338 p.

Hunt, C.B., 1936, Geology and fuel resources of the southern part of the San Juan Basin, New Mexico, Part 2—The Mount Taylor coal field: U.S. Geological Survey Bulletin 860–B, 49 p.

Kelley, V.C., and Northrop, S.A., 1975, Geology of the Sandia Mountains and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 29, 136 p.

Kelley, V.C., and Silver, C., 1952, Geology of the Caballo Mountains, Sierra County, New Mexico: University of New Mexico Publications in Geology no. 4, 286 p.

Keyes, C.R., 1904, The Hagan coal field: The Engineering and Mining Journal, v. 78, p. 670–671.

Kottlowski, F.E., 1963, Pennsylvanian rocks; *in* Spiegel, Z., and Baldwin, B., eds., Geology and water resources, Santa Fe area, New Mexico: U.S. Geological Survey Water–Supply Paper 1525, p. 28–32.

Kottlowski, F.E., 1971, Zuni Mesaverde area; *in* Shomaker, J.W., Beaumont, E.C., and Kottlowski, F.E., eds., Strippable low–sulfur coal resources of the San Juan Basin in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Memoir 25, p. 75–80.

Landis, E.R., and Dane, C.H., 1969, The Tierra Amarilla coal field Rio Arriba County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 100, 11 p.

Lease, R.C., 1971a, Hogback upper Menefee area, *in* Shomaker, J.W., Beaumont, E.C., and Kottlowski, F.E., eds., Strippable low–sulfur coal resources of the San Juan Basin in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Memoir 25, p. 47.

Lease, R.C., 1971b, Toadlena upper Menefee area, *in* Shomaker, J.W., Beaumont, E.C., and Kottlowski, F. E., Strippable low–sulfur coal resources of the San Juan Basin in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Memoir 25, p. 47.

Lee, W.T., 1912, The Tijeras coal field, Bernalillo County, New Mexico, *in* Contributions to Economic Geology 1910, Part II—mineral fuels: Coal and lignite, U.S. Geological Survey Bulletin, v. 00471, p. 575–578.

Lee, W.T., 1913, The Cerrillos coal field, Santa Fe County, New Mexico, in Campbell, A., Marius, R., eds., Contributions to economic geology 1911, Part II, Mineral fuels: U.S. Geological Survey Bulletin, v. 00531-J, p. 285–312.

Lucas, S.G., Read, A., Karlstrom, K.E., Estep, J.W., Kues, B.S., Anderson, O.J., Smith, G.A., and Pazzaglia, F.J., 1999, Second-day trip 1 road log: From Albuquerque to Tijeras, Cedar Crest, and Sandia Crest, *in* Pazzaglia, F.J., Lucas, S.G., Austin, G.S., eds., Albuquerque Country: New Mexico Geological Society, 50th Annual Field Conference, Guidebook, p. 27–46.

Maksimovic, S.D., and Mowry, G.L., 1993, Basic geological and analytical properties of selected coal seams for coal interface detection: U.S. Bureau of Mines, Information Circular 1993, p. 5–10.

Martinez, L.B., 1981, Coal in Arnold, E.C. and Hill, J.M., comps. New Mexico's energy resources 1981: annual report of the Bureau of Geology *in* the Mining and Minerals Division of New Mexico Energy and Minerals Department, Santa Fe, New Mexico, p. 43–44.

McCabe, P.J., 1991, Tectonic controls on coal accumulation: *in* Coal; formation, occurrence and related properties: symposium Bulletin de la Societe Geologique de France, Huitieme Series 162, no. 2, p. 277–282.

McCabe, P.J., and Parrish, J.T., 1992, Tectonic and climatic controls on the distribution and quality of Cretaceous coals: *in* McCabe, P.J., and Parrish, J.T., eds., Controls on the distribution and quality of Cretaceous coals: Geological Society of America Special Paper 267, p. 1–15.

McLellan, M.W., Haschke, L.R., Robinson L.N., Carter, M.D., and Medlin, A.L., 1983, Middle Turonian and younger Cretaceous rocks, northern Salt Lake coal field, Cibola and Catron Counties, New Mexico, *in* Hook, S.C., compiler, Contributions to mid–Cretaceous paleontology and stratigraphy of New Mexico—part II: New Mexico Bureau of Mines and Mineral Resources Circular 185, p. 41–47.

McLemore, V.T., Hoffman, G.K., Mansell, M., Jones, G.R., Krueger, C.B., Wilks, M., 2005, Mining districts in New Mexico, New Mexico Bureau of Geology and Mineral Resources Open-File Report, 494, p., CD-ROM.

Molenaar, C.M., 1977, Stratigraphy and depositional history of Upper Cretaceous rocks of the San Juan Basin Area, New Mexico and Colorado, with a note on economic resources, *in* Fassett, J.F., James, H.L., eds., San Juan Basin III (northwestern New Mexico): New Mexico Geological Society, 28th Annual Field Conference, Guidebook, p. 159–166.

Molenaar, C.M., 1983a, Major depositional cycles and regional correlations of upper Cretaceous rocks, southern Colorado Plateau and adjacent areas, *in* M.W. Reynolds, E.D. Dolly, eds., Mesozoic paleogeography of the west-central United States, Rocky Mountain Paleogeography Symposium 2: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 201–224.

Molenaar, C.M., 1983b, Principal reference section and correlation of Gallup Sandstone, northwestern New Mexico, in Contributions to mid–Cretaceous paleontology and stratigraphy of New Mexico—part II: New Mexico Bureau of Mines and Mineral Resources Circular 185, p. 29–40.

Molenaar, C.M., Nummendal, D., Cobban, W.A., 1996, Regional stratigraphic cross sections of the Gallup Sandstone and associated strata around the San Juan Basin, New Mexico, and parts of adjoining Arizona and Colorado, U.S. Geological Survey Oil and Gas Investigation Chart, 143.

Molenaar, C.M., Cobban, W.A., Merewether, E.A., Pillmore, C.L., Wolfe, D.G., and Holbrook, J.M., 2002, Regional stratigraphic cross sections of Cretaceous rocks from east-central Arizona to the Oklahoma panhandle, U.S. Geological Survey Miscellaneous field studies map MF-2382 ver. 1, Sheet 1 of 3.

NETL, website, Coal-Fired Power Plants; Where is the coal in the United States?: http/::www.netl.doe.gov:technologies:coalpower:cfpp:cfpps:coalsources.htm (accessed September 4, 2013).

New Mexico Bureau of Geology and Mineral Resources, 2003, Geologic Map of New Mexico: scale 1:500,000, 2 sheets.

New Mexico State Mine Inspector, 1912–1962, Annual Reports of the State Mine Inspector of New Mexico for the Year Ending: New Mexico Energy and Minerals Department, Albuquerque, New Mexico.

New Mexico Territorial Mine Inspector, 1882–1911, Annual Reports of the United States Mine Inspector to the Secretary of the Interior for the Territory of New Mexico for the Fiscal Year, Government Printing Office, Washington, D.C.

Nickelson, H.B., 1988, One hundred years of coal mining in the San Juan Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 111, 226 p.

Nummedal, D., and Molenaar, C.M., 1995, Sequence stratigraphy of a ramp-setting strand plain successions: the Gallup Sandstone, New Mexico, *in* Van Wagoner, J.C. and Bertram, G.B. eds., Sequence stratigraphy of foreland basins deposits—Outcrop and subsurface examples from the Cretaceous of North America: American Association of Petroleum Geologists Memoir 64, p. 277–310.

O'Sullivan, R.B., and Beaumont, E.C., 1957, Preliminary geologic map of western San Juan Basin, San Juan and McKinley Counties, New Mexico: U.S. Geological Survey Oil and Gas Investigations Map 190. 1:125,000 scale.

Open University, 2013, Energy resources: Coal, 1.3 Coal-forming environments today, http://www.open.edu/openlearn/science-maths-technology/science/environmental-science/energy-resources-coal/content-section-1.3

Osburn, J.C., 1982, Geology and coal resources of three quadrangles in the central Datil Mountains coal field: New Mexico Bureau of Mines and Mineral Resources Open-File Report 164, 82 p.

Peabody Energy, 2012, El Segundo Mine, http/::www.peabodyenergy.com:content:277:Publications:Fact-Sheets:El-Segundo-Mine (accessed April 2, 2012)

Pillmore, C.L., 1969, Geology and coal deposits of the Raton coal field, Colfax County, New Mexico: Mountain Geologist, v. 6, no 3, p. 125–142.

Pillmore, C.L., 1976, Commercial coal beds of the Raton coal field, Colfax County, New Mexico, *in* Ewing, R.C., Kues, B.S., eds., Vermejo Park, New Mexico Geological Society, 27th Annual Field Conference, Guidebook, p. 227–251.

Pillmore, C.L., 1991, Geology and coal resources of the Raton coalfield, *in* Molina, C.L., Jobin, D.A., O'Conner, J.T., and Kottlowski, F.E. eds., Coalfields of New Mexico: Geology and resources: U.S. Geological Survey Bulletin 1972, p. 45–68.

Pillmore, C.L., and Flores, R.M., 1987, Stratigraphy and depositional environments of the Cretaceous–Tertiary boundary clay and associated rocks, Raton Basin, New Mexico and Colorado; *in* Fassett, J.E. and Rigby, J.K., eds., The Cretaceous–Tertiary boundary in the San Juan and Raton Basins, New Mexico and Colorado: Geological Society of America Special Paper 209, p. 111–130.

Pittsburg and Midway, 1989, McKinley Mine Brochure, Pittsburg and Midway.

Read, C.B., Duffner R.T., Wood G.H., and Zapp, A.D., 1950, Coal Resources of New Mexico: U.S. Geological Survey Circular 89, 24 p.

Reports of the United States Mine Inspector for the Territory of New Mexico to the Secretary of the Interior, 1882–1912, Annual Reports.

Roberts, L.N.R., and Kirschbaum, M. A., 1995, Paleogeography of the late Cretaceous of the western interior of middle North America—Coal distribution and sediment accumulation: U.S. Geological Survey Professional Paper 151, 115 p.

Roberts, L.N.R., and McCabe, P.J., 1992, Peat accumulation in coastal-plain mires: A model for coals of the Fruitland Formation (Upper Cretaceous) of southern Colorado, USA, International Journal of Coal Geology, v. 21, p. 115–138.

Roybal, G.H., Hoffman, G.K., and Campbell, F.W., 1981, Stratigraphic sequence and drilling data from Fence Lake area: New Mexico Bureau of Mines and Mineral Resources Open-File Report 145, 59 p.

Scott, D.C., and Luppens, J.A., 2013, Assessment of coal geology, resources, and reserve base in the Powder River Basin, Wyoming and Montana: U.S. Geological Survey Fact Sheet 2012–3143, 6 p., http://pubs.usgs.gov/fs/2012/3143/

Sears, J.D., 1925, Geology and coal resources of the Gallup–Zuni Basin, New Mexico: U.S. Geological Survey Bulletin 767, 53 p.

Sears, J.D., 1936, Geology and fuel resources of the southern part of the San Juan Basin, New Mexico Part 1—the coal field from Gallup eastward toward Mount Taylor: U.S. Geological Survey Bulletin 860–A, 29 p.

Shaler, M.K., 1907, A reconnaissance survey of the western part of the Durango–Gallup coal field of Colorado and New Mexico: U.S. Geological Survey Bulletin 316, p. 376–426.

Shomaker, J.W., Beaumont, E.C., and Kottlowski, F.E., 1971, Strippable low–sulfur coal resources of the San Juan Basin in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Memoir 25, 189 p.

Shomaker, J.W., and Holt, R.D., 1973, Coal resources of the Southern Ute and Ute Mountain Indian Reservations, Colorado and New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 134, 22 p.

Shomaker, J.W. and Whyte, M.R., 1977, Geologic appraisal of deep coals of the San Juan Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 155, 39 p.

Slack, P.B., and Campbell, J.A., 1976, Structural geology of the Rio Puerco fault zone and its relationship to Central New Mexico tectonics, *in* Woodward, L.A., and Northrop, S.A. eds., Tectonics and mineral resources of southwestern North America: New Mexico Geological Society Special Publications no. 6, p. 46–52.

Slagle, E.S., 1991, History of coal mining in the Sierra Blanca coal field, Lincoln and Otero Counties, New Mexico, *in* Barker, J.M., Kues, B.S., Austin, G.S., Lucas, S.G., eds., Geology of the Sierra Blanca, Sacramento, and Capitan Ranges, New Mexico, New Mexico Geological Society, 42nd Annual Field Conference Guidebook, p. 54–57.

Speer, W.R., 1971, Chacra Mesa upper Menefee area, *in* Shomaker, J.W., Beaumont, E.C., and Kottlowski, F.E., Strippable low–sulfur coal resources of the San Juan Basin in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Memoir 25, p. 56–63.

Speer, W.R., Beaumont, E.C., and Shoemaker, J.W., 1977, Coal resources of the San Juan Basin, New Mexico, New Mexico Bureau Mines Mineral Resources Open-File Report, 84, p. 1–107.

Tabet, D.E., 1979, Geology of Jornada del Muerto coal field, Socorro County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 168, 19 p.

Tabet, D.E., 1979, Summary of the geology of the Engle coal field, New Mexico Bureau Mines Mineral Resources Open-File Report, 115, p. 1–8.

Tabet, D.E., 1981, Geology and coal resources, Pinehaven quadrangle: New Mexico Bureau of Mines and Mineral Resources Open-File Report 154, 71 p.

Tabet, D.E., and Frost, S.J., 1979. Coal Geology of the Torreon Wash area, southeast San Juan Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 49, 3 sheets, text.

Teichmuller, M., 1982, Origin of the petrographic constituents of coal, *in* Stach, E., Mackowsky, M.-Th., Teichmuller, M., Taylor, G. H., Chandra, D., and Teichmuller, R., eds., Stach's textbook of coal petrology: Gebruder Borntraeger, p. 219–294.

Teichmuller, M., and Teichmuller, R., 1982, The geological basis of coal formation, *in* Stach, E., Mackowsky, M.-Th., Teichmuller, M., Taylor, G.H., Chandra, D., and Teichmuller, R., eds., Stach's textbook of coal petrology: Gebruder Borntraeger, p. 5–86.

Tweto, O., 1979, Geologic map of Colorado: U.S.Geological Survey in cooperation with the Colorado Geological Survey, scale 1:500,000.

Wallin, E.T., 1983, Stratigraphy and paleoenviroments of the Engle coal field, Sierra County, New Mexico, [M.S. thesis], New Mexico Institute of Mining and Technology, Socorro, New Mexico, p. 1–127.

Wanek, A.A., 1963. Geology and fuel resources of the southwestern part of the Raton coal field, Colfax County, New Mexico: U.S. Geological Survey Coal Investigation Map 45.

Wood, G.H., Kehn, T.M., Carter, M.D., and Culbertson, W.C., 1983, Coal resource classification system of the U. S. Geological Survey: U.S. Geological Survey Circular 891, 65 p.

GLOSSARY

Agglomerating—coal that during volatile matter determinations, produces either an agglomerate button capable of supporting a 500-gram weight without pulverizing, or a button showing swelling or cell structure.

Agglomerate—collected or formed into a mass.

Anthracite— a rank class of nonagglomerating coals as defined by the American Society of Testing and Materials having more than 86 percent fixed cargon and less than 14 percent volatile matter on a dry, mineral-matter free basis. This class of coal is divisible into the semiantracite, anthracite, and meta-anthracite groups on the basis of increasing fixed carbon and decreasing volatile matter (See Table 1).

Anticline—In structural geology, an anticline is a fold that is convex up and has its oldest beds at its core.

Apatite—a group of phosphate minerals, usually referring to hydroxylapatite, fluorapatite and chlorapatite, with high concentrations of OH- F- and Cl- ions, respectively, in the crystal.

Arcuate—curved or bowed.

Argillaceous—clastic sedimentary rocks containing silt- or clay-sized particles that are less than 0.0625 mm and/or clay minerals.

Bioturbation—the reworking of soils and sediments by animals or plants. Its effects include changing texture of sediments (diagenetic), bioirrigation and displacement of microorganisms and non-living particles.

Bituminous—a rank class of coals as defined by the American Society of Testing and Materials high in carbonaceous matter, having less than 86 percent fixed carbon and more than 14 percent volatile matter on a dry, mineral -matter-free basis and more than 10,500 Btu on a moist, mineral-matter free basis. This class may be either agglomerating or nonagglomerating and is divisible into the high-volatile C,B, A; medium; and low-volatile bituminous coal groups on the basis of increasing heat content and fixed carbon and decreasing volatile matter (See Table 1).

Calcite—a carbonate mineral and the most stable polymorph of calcium carbonate.

Chalcedony—a cryptocrystalline form of silica, composed of very fine intergrowths of the minerals quartz and moganite. These are both silica minerals, but they differ in that quartz has a trigonal crystal structure, while moganite is monoclinic.

Clastic material—consisting of fragments of rocks or of organic structures that have been moved individually from their places of origin.

Coalification—the conversion of plant material into coal by natural processes, as by diagenesis and, in some instances, metamorphism.

Detrital—particles of recognizable rock or mineral grains often transported through sedimentary processes into depositional systems such as riverbeds, lakes or the ocean, forming sedimentary deposits.

Dolomite—an anhydrous carbonate mineral composed of calcium magnesium carbonate, ideally $CaMg(CO_3)_2$. The word dolomite is also used to describe the sedimentary carbonate rock, which is composed predominantly of the mineral dolomite (also known as dolostone).

En echelon—adjective describing geologic features that are in an overlapping or staggered arrangement. Each is relatively short but collectively they form a linear zone.

Epicontinental—situated upon a continental plateau or platform, as an epicontinental sea.

Feldspar—a group of minerals distinguished by the presence of alumina and silica (SiO_2) in their chemistry. This group includes aluminum silicates of soda, potassium, or lime. It is the single most abundant mineral group on Earth. They account for an estimated 60% of exposed rocks, as well as soils, clays, and other unconsolidated sediments, and are principal components in rock classification schemes. The minerals included in this group are the orthoclase, microcline and plagioclase feldspars.

Floodplain or flood plain—an area of land adjacent to a stream or river that stretches from the banks of its channel to the base of the enclosing valley walls and experiences flooding during periods of high discharge.

Fluvial—of or pertaining to rivers; produced by river action, as, a fluvial plain.

Fluvio-lacustrine—sediments produced by both rivers and lakes.

Foreland basin—a structural basin that develops adjacent and parallel to a mountain belt. Foreland basins form because the immense mass created by crustal thickening associated with the evolution of a mountain belt causes the lithosphere to bend, by a process known as lithospheric flexure. The width and depth of the foreland basin is determined by the flexural rigidity of the underlying lithosphere, and the characteristics of the mountain belt. The foreland basin receives sediment that is eroded off the adjacent mountain belt, filling with thick sedimentary successions that thin away from the mountain belt.

Fossiliferous—containing fossils, generally used in describing sedimentary rocks.

Geothermal gradient—the rate of increase in temperature per unit depth in the Earth. Although the geothermal gradient varies from place to place, it averages 25 to 30°C/km [15°F/1,000 ft]. Temperature gradients sometimes increase dramatically around volcanic areas.

High angle faults—a fault with a dip greater than 45°.

Humification—the formation of humus during the decomposition of organic materials in soils or peat.

Humus—a dark brown or black colloidal mass of partially decomposed organic matter in the soil.

Illite—a non-expanding, clay-sized, micaceous mineral. Illite is a phyllosilicate or layered alumino-silicate. Its structure is constituted by the repetition of tetrahedron—octahedron—tetrahedron (TOT) layers.

In situ alteration—a mineralogical change at low pressures due to invading fluids or the influence of oxygen. In situ indicates the alteration is taking place locally.

Inland lacustrine— inland lake environment.

Interbedded—occurring between beds, or lying in a bed parallel to other beds of different material.

Intertonguing—the intergradation of markedly different rocks through a vertical succession of thin interlocking or overlapped wedge shaped layers.

Isopachs—contours that connects points of equal thickness. Commonly, the isopachs, or contours that make up an isopach map, display the stratigraphic thickness of a rock unit.

Kaolinite—group of common clay minerals that are hydrous aluminum silicates. Chemical composition $Al_2Si_2O_5(OH)_4$; they comprise the principal ingredients of kaolin (china clay). Kaolinite is a layered silicate mineral, with one tetrahedral sheet linked through oxygen atoms to one octahedral sheet of alumina octahedra.

Lagoonal—pertaining to a lagoon, a shallow body of water, especially one separated from a sea by sandbars or coral reefs.

Laramide orogeny—a period of mountain building in western North America that started in the Late Cretaceous, 70 to 80 million years ago, and ended 35 to 55 million years ago, in the Paleogene.

Lenticular—adjective describing a rock unit with a lens-shaped cross-section.

Lithosphere—includes the crust and the uppermost mantle, which constitute the hard and rigid outer layer of the Earth.

Longwall mining—a form of underground coal mining where a long wall of coal is mined in a single slice.

Metamorphosed—to undergo metamorphism. Mineralogical and structural adjustments of solid rocks to physical and chemical conditions differing from those under which the rocks originally formed. Changes produced by surface conditions such as compaction are usually excluded. The most important agents of metamorphism include temperature, pressure, and fluids.

Moist, mineral-matter free basis—a theoretical analysis calculated from basic analytical data and expressed as if the mineral-matter had been removed and the natural moisture retained. Used in determining the rank of coal.

Neritic—relating to, or denoting the shallow part of the sea near a coast and overlying the continental shelf.

Nonagglomerating—coal that during volatile matter determinations produces a button not capable of supporting a 500-gram weight without pulverizing. A coal button showing no swelling or cell structure.

Normal faults—faults extending the crust in a direction perpendicular to the fault trace. Because the hangingwall moves downward, normal faults place younger rocks over older rocks

Outcrop—a rock formation that is visible on the surface.

Paleolatitude—the latitude of a place at some time in the past, measured relative to the earth's magnetic poles in the same period. Differences between this and the present latitude are caused by continental drift and movement of the earth's magnetic poles.

Paralic—pertaining to marine coastal environments, such as lagoonal, littoral, shallow neritic, etc.

Passive margin—the transition between oceanic and continental lithosphere which is not an active plate margin. It is constructed by sedimentation above an ancient rift, now marked by transitional lithosphere.

Progradation—a seaward advance of the shoreline resulting from the nearshore deposition of sediments brought to the sea by streams, rivers.

Pyrite—an iron sulfide mineral with the chemical formula FeS_2.

Room and pillar—a mining system where the mined material is extracted across a horizontal plane, creating horizontal arrays of rooms and pillars. Parallel drifts are driven, with connections made between these drifts at regular intervals creating pillars between areas called rooms.

Rutile—a mineral composed primarily of titanium dioxide, TiO_2. Rutile is the most common natural form of TiO_2.

Semi-anthracite—a coal intermediate between anthracite and bituminous coal; especially coal approaching anthracite in nonvolatile character.

Siderite—a mineral composed of iron (II) carbonate ($FeCO_3$). Siderite is commonly found in hydrothermal veins, and is associated with barite, fluorite, galena, and others. It is also a common diagenetic mineral in shales and sandstones, where it sometimes forms concretions. In sedimentary rocks, siderite commonly forms at shallow burial depths and its elemental composition is often related to the depositional environment of the enclosing sediments.

Siltstones—a very fine-grained consolidated clastic rock composed predominantly of particles of silt sized material.

Smectite—clay mineral group including the dioctahedral minerals such as montmorillonite, and the trioctahedral minerals such as Lithium-rich hectorite. The basic structural unit is a layer consisting of two inward-pointing tetrahedral sheets with a central alumina octahedral sheet. Smectites commonly result from the weathering of basic rocks. Smectite formation is favored by level to gently sloping terranes that are poorly drained, mildly alkaline (such as in marine environments), and have the high Si and Mg potentials. Other factors that favor the formation of smectites include the availability of calcium and the paucity of potassium. Poor drainage is necessary because otherwise water can leach away ions (e.g. Mg) freed in the alteration reactions.

Strike slip faults, basin—strike slip faults are vertical (or nearly vertical) fractures where the blocks have mostly moved horizontally. If the block opposite an observer looking across the fault moves to the right, the slip style is termed right lateral; if the block moves to the left, the motion is termed left lateral. Basins formed along strike-slip faulting generally subside rapidly and show features of both rift-type and foreland-type basins.

Subbituminous—a rank class of nonagglomerating coals having a heat value content of more than 8,300 Btu's and less than 11,500 Btu's on a moist, mineral-matter free basis. This class of coal is divisible on the basis of increasing heat value into the subbituminous C, B, and A coal groups. (See Table 1).

Sublittoral—relating to the region of the ocean bottom between the low tide line and the edge of the continental shelf, ranging in depth to about 200 m (656 ft). Unlike areas of the littoral zone, the sublittoral zone is always submerged.

Subsidence—a sinking of a large part of the earth's crust relative to a datum, such as sea level.

Syncline—a fold in rocks in which the strata dip inward from both sides toward the axis of the fold. Younger strata are closer to the center of the fold.

Tectonic activity—large-scale processes such as earthquakes, volcanoes and mountain building.

Turonian—representing rocks deposited worldwide during the Turonian Age, which occurred 93.9 million to 89.8 million years ago during the Upper Cretaceous Period

Zircon—a mineral $ZrSiO_4$. The chief ore of zirconium.

ABBREVIATIONS

Ag—silver
A-S—acid-sulfate
Au—gold
Be—beryllium
Bbls—barrels
BBO—billion bbls oil
BCF—billion cubic feet (ft^3)
BHP—Broken Hill Proprietary or bottom hole pressure if one is discussing geothermal, oil and gas wells
BHT—Bottom hole temperature (in a well)
BLM—U.S. Bureau of Land Management
Btu/lb—British thermal units per pound of fluid
CPD—Carlsbad potash district
CSDP—Continental Scientific Drilling Program
CO_2—Carbon dioxide
Cu—copper
D—Derivative waters (geothermal)
DPA—Designated Potash Area
DG—Deep geothermal waters
EMNRD—Energy, Mineral, and Natural Resources Department (New Mexico)
GCC—Grupo Cementos de Chihuahua (cement)
GPM—Great Plains Margin
HDR—hot dry rock (geothermal)
I/S—illite/smectite clays
JPSB—Jemez Pueblo-San Juan Basin type
ka—thousand years ago
KCl—potassium chloride
km—kilometers
LANL—Los Alamos National Laboratory
LBL—Lawrence Berkeley Laboratory
lbs—pounds
Li—lithium
m—meters
Ma—million years ago
Myr—Million years old
MBO—thousand bbls oil
mi—miles
MOP—muriate of potash
MORB—mid-ocean ridge basalt
MRI—Magnetic resonance imaging
MVT—Mississippi Valley-type
MWe—Megawatts (electrical)
NMBMMR—New Mexico Bureau of Mines and Mineral Resources
NMBGMR—New Mexico Bureau of Geology and Mineral Resources
NMMMD—New Mexico Mining and Mineral Division
NMIMT—New Mexico Institute of Mining and Technology
NURE—National Uranium Resource and Evaluation
OSHA—Occupational Safety and Health Administration
oz—ounces
oz/short ton—ounces per short ton
P & A'd—plugged and abandoned (well)
PGE—platinum group elements (platinum, Pt; palladium, Pl; osmium, Os; ruthenium, R; iridium, I; and rhodium, Rh)
Pb—lead
PNM—Public Service Company of New Mexico
ppb—parts per billion
ppm—parts per million
REE—rare earth elements
RGR—Rio Grande Rift
SMCRA—Surface Mine Control and Reclamation Act
Th—thorium
TCF—trillion cubic feet (ft^3)
U—uranium
µm—micrometers
UNOCAL—Union Oil Company of California
USDOE—U.S. Department of Energy
USGS—U.S. Geological Survey
USBM—U.S. Bureau of Mines
VCNP—Valles Caldera National Preserve
VMS—Volcanogenic massive sulfide
WIPP—Waste Isolation Pilot Plant
Wt%—weight per cent
Y—yttrium
Zn—zinc
Zr—zirconium
δ—delta value used in isotope measurements
°C—degrees centigrade

INDEX

New Mexico Bureau of Geology and Mineral Resources
801 Leroy Place
Socorro, New Mexico 87801
geoinfo.nmt.edu

New Mexico Geological Society, Inc.
801 Leroy Place
Socorro, New Mexico 87801
nmgs.nmt.edu