New Mexico Bureau of Mines & Mineral Resources

Resource Map 20

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Coal resources of New Mexico

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Introduction

Coal production has played a significant role in the economic development of New Mexico beginning in the 1890s and continuing to the present. It is one of four mineral fuels produced in New Mexico, ranking third in value behind natural gas (including coalbed methane) and crude oil. Coal resources underlie 20% (15 million acres) of the state's total area. Most of the coal is in northern New Mexico, primarily in the San Juan and Raton Basins (Figs. 1 and 2). Several minor coal fields outside these basins have had significant production in the past, and some may become important in the future.

The resource map illustrates the major coal-bearing areas in New Mexico as delineated by the surface exposures of the coal-bearing formations. The map is based on the *New Mexico highway geologic map* published by the New Mexico Geological Society (Clemons et al., 1982). Use of several recently compiled geologic maps enhances the details of the outcrops of coal-bearing units shown on this map. Sources of these data are listed in the map references section. Only the coal-bearing sequences and significant adjacent units, such as intrusions, are displayed on the map. Figs. 3 and 4 and the stratigraphic correlation chart on the map sheet illustrate the stratigraphic sequences that include these coal-bearing units in the San Juan and Raton Basins. Discussions of coal thickness, coal characteristics, and the local structure and topography are included for each coal field. The demonstrated coal resources (measured and indicated combined as defined by Wood et al., 1983; subbituminous ≥ 2.5 ft thick, bituminous ≥ 2.3 ft thick) and the past and present production for each coal field are presented also. Remaining demonstrated resources (past production subtracted from demonstrated) for the San Juan Basin fields are based on recent work by the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) for the Energy Information Administration's Coal Demonstrated Reserve Base (Hoffman, 1994).

The coal resource map and text are a compilation of published and unpublished data. Collection and evaluation of these data were done through cooperative grants with the U.S. Geological Survey for data entry into the National Coal Resource Data System. Several other coal projects and related geologic mapping by the NMBMMR have provided data. This publication provides the most up-to-date geologic information about coal resources, a basic knowledge of the coal areas in New Mexico, and a list of publications about each coal area.

Acknowledgments

This project is an update of Tabet and Frost's (1978) *Coal fields and mines of New Mexico*, published by the NMBMMR as Resource Map 10. As a compilation of on-going work on the coal resources of New Mexico, there are many people and companies who have contributed by providing geologic data, historical information, and coal analyses. A significant part of the drill-hole data and coal-quality information that comprises the NMBMMR coal databases was collected as partial fulfillment of cooperative grants with the U.S. Geological Survey Coal Branch, in particular for the National Coal Resource Data System (NCRDS). Some of the geology on this map is taken directly from the *New Mexico highway geologic map* with permission from the New Mexico Geological Society.

The author would like to thank Frank Kottlowski (NMBMMR) for his enthusiastic support of this project, for the many discussions we have had on the coal areas in New Mexico, in particular the Pennsylvanian-age outcrops, and for his review of this manuscript. Orin Anderson and Glen Jones (NMBMMR) supplied the latest information on geologic mapping from the State Map Project (Anderson and Jones, 1994), a cooperative project with the U.S. Geological Survey. Discussions with Orin about Cretaceous stratigraphy and geology of the Gallup–Zuni area and his critique of this manuscript considerably improved the content. Kay Hatton (NMEMNRD) has been a constant source of information on coal mining and production in the state for many years, and the author is grateful for Kay's help on this and many other projects. Bill Speer (Consultant, Farmington, NM) and James Barker (NMBMMR) graciously reviewed the manuscript, and their comments added to the syntax and substance of the final product. Special thanks to Charles Chapin for actively supporting the publication of this resource map. Finally, I would like to thank Ed Beaumont for the numerous discussions and field trips throughout New Mexico that have given me the chance to draw upon his knowledge of coal geology in the state.

Coal-bearing areas and fields

Coal in New Mexico is concentrated in the northern half of the state primarily within the San Juan and Raton Basins. These two arcuate subsurface basins formed during the Laramide orogeny (80–40 m.y. ago). 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. Outlying fields adjacent to the San Juan Basin are the Datil Mountains, Salt Lake, Tierra Amarilla, and Rio Puerco fields.

Coal fields outside the major basins are: the Cerrillos field southeast 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.

Besides the defined coal fields, thin Cretaceous coal beds in the southern San Andres Mountains, northeast of Las Cruces, and in the northeast corner of the state were used locally for home fuel before 1900. Pennsylvanian coal crops out in north-central New Mexico at several localities near and in Santa Fe, southeast of Taos, northwest of Las Vegas, and north of Pecos and is in the subsurface in southeast New Mexico (Shomaker et al., 1971, pp. 177–179). These beds are some of the westernmost Pennsylvanian-age coals in the United States.

Coal-bearing rocks

San Juan Basin coal, Late Cretaceous in age, is concentrated in three major coal-bearing sequences. They are, in ascending order, the Crevasse Canyon, Menefee, and Fruitland Formations. The Raton field has two coal-bearing sequences, the Vermejo and 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 early Tertiary 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. Most of the small coal fields outside the major basins are within outcrops of the Mesaverde Group that are equivalent to the Menefee, Crevasse Canyon, or Tres Hermanos Formation.

Structural geology of the coal-bearing basins and other areas

The two major coal-bearing basins have simple geologic structure. Minor faulting occurs in both the Raton and San Juan Basins. Except along the steeper flanks, the dip of beds in most of the coal-bearing areas ranges from 2° to 6°. Several smaller coal fields in New Mexico are within or on the edge of the Rio Grande rift, which is marked by many faults, steeply dipping beds, and Cenozoic igneous activity. Igneous intrusions in the Cerrillos field have metamorphosed nearby Cretaceous coal to semianthracite and anthracite. Both the Datil Mountains and Sierra Blanca fields have thick layers of volcanic rocks overlying large areas of the coal-bearing strata. Extensive faulting and intrusive dikes have interrupted the coal-bearing units in the Sierra Blanca and Cerrillos fields. The Rio Puerco and Carthage fields are cut by many faults that create small blocks that contain fragmented coal-bearing sequences.

The San Juan Basin is roughly an asymmetric circular structural depression that is deepest in the northeastern part of the basin. Cretaceous and early Tertiary strata dip steeply into the basin along the Hogback monocline to the northwest and along the Archuleta arch and Nacimiento uplift to the east (Fig. 1). Gentle dips predominate in the south and southwest sections (Chaco slope) of the basin (Fig. 1). The deepest part of the basin is approximately 30 mi west of the Monero field on the northeast edge of the basin, where the Cretaceous coal beds are as much as 9,000 ft below the surface. Along the southern edge of the San Juan Basin several structural features affect the Cretaceous coal-bearing units (Fig. 1); faulting is more prevalent in this part of the basin.

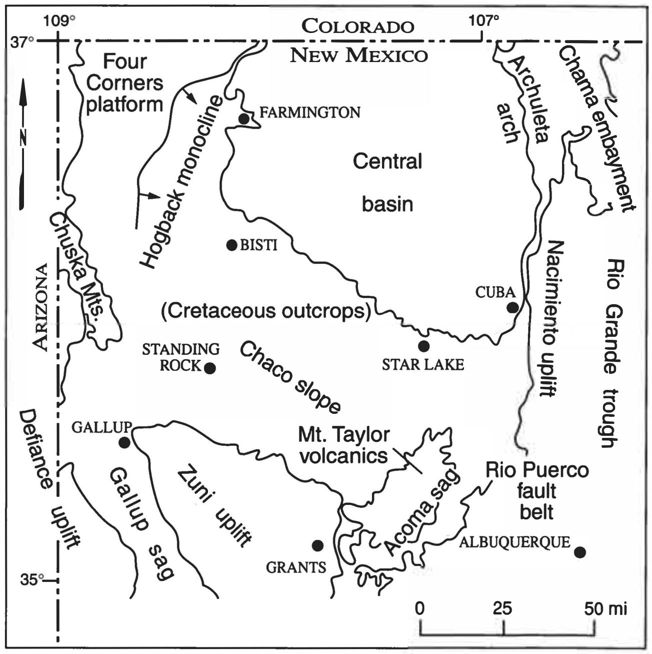

FIGURE 1—Tectonic map of San Juan Basin, New Mexico (from Beaumont, 1982, fig. 3; reprinted by permission of the American Association of Petroleum Geologists courtesy of E. C. Beaumont).

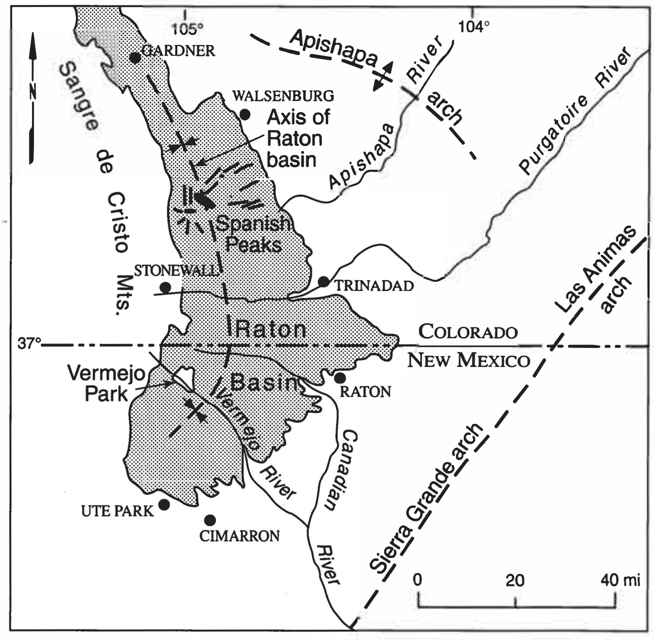

FIGURE 2—Simplified structural map of the Raton Basin, New Mexico and Colorado (from Pillmore, 1991).

These features are described in greater detail in discussions of the fields.

The Raton Basin is an arcuate, asymmetric syncline that extends from Colorado south–southwest into New Mexico and is bounded by the Sangre de Cristo Mountains to the west and the low Sierra Grande arch and Las Animas arch to the east (Fig. 2). The east limb has gentle dips of 1°–5° northwest and lacks significant faulting (Wanek, 1963). Steep dips, vertical to overturned beds, and faulting are associated with the Sangre de Cristo Mountains on the western edge of this basin. The Vermejo Park anticline, prominent in the New Mexico part of the basin, is the result of a buried intrusion (Pillmore, 1976).

Coal mining and production

Spanish settlers used small amounts of coal several centuries ago for home heating. Anthracite was mined in the Cerrillos field as early as 1858, and mining on a significant scale began in 1861 when U.S. Army troops from Fort Craig opened the Government mine in the Carthage field to supply coal for smithing at Forts Seldon, Bayard, and Stanton (Sherman and Sherman, 1977). Railroads depended on suitable steam coal nearby, and in 1899 coal production exceeded 1 million short tons (st) to meet the demands of the railroads and of the lead and copper smelters in the Southwest. Production exceeded 4 million st in 1918 because World War I stimulated use in nearby smelters, factories, and railroads.

Conversion to diesel fuel by the railroads and the increased use of natural gas in homes and industry caused a decline in underground coal mining, lowering the state's coal production to less than 1 million st in 1950 and to a low of 85,212 st in 1958. Several economically marginal coal-mining areas lost their markets when rail lines were abandoned for more direct or more economic routes.

Coal production increased dramatically upon the introduction of large-scale surface mining in McKinley and San Juan Counties in the early 1960s. The combination of inexpensive strippable coal and the increased demand for electric power in Arizona, New Mexico, and California led to the opening of McKinley mine (Pittsburg and Midway Coal Company) near Gallup in 1962 and the Navajo mine (Utah Construction and Mining) near Fruitland in 1963. Utah Construction and Mining became Utah International and in 1986 became a subsidiary of Broken Hill Proprietary Company, Ltd (BHP). Public Service Company of New Mexico (PNM) and Western Coal Company's San Juan mine north of the San Juan River began surface operations in late 1972. In 1977 Utah International 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 operated by the San Juan Coal Company, a wholly owned subsidiary of BHP. Near Raton, the Kaiser Coal Corporation York Canyon No. 1 mine (underground) began operations in 1966, and their West York Canyon surface mine in 1972. The Kaiser Cimarron mine, also known as the Upper York exploration mine (underground), began production in 1985. The sale of the Kaiser Coal Corporation York Canyon complex and other coal holdings in the Raton Basin to Pittsburg and Midway Coal Mining Company, a subsidiary of Chevron, was completed in February 1989. In 1995 Pittsburg and Midway operated the Ancho, Eastridge, Road Canyon, and York Canyon surface mines and the Cimarron underground mine, all west of Raton. The Cimarron underground mine closed in late 1995. As of June 1996 only the Ancho mine was in production.

Trends in New Mexico coal production mirror the national trends of increased productivity from fewer surface mines (Maksimovic, 1993). From 1988 through 1995, New Mexico annual total coal production exceeded 20 million st. In 1988 nine mines were producing in the state; all were surface mines except one underground mine in the Raton field. By 1992 the number of operating mines had decreased to seven, six surface and one underground, and the 1993 total production of 28,294,480 st (K. Hatton, pers. comm. 1994) was greater than the previous record high of 21,736,854 st in 1988 (Hatton, 1988–1994). The number of companies operating New Mexico coal mines decreased from five in 1988 to three in 1993. These companies are BHP Minerals International, Inc. (Navajo mine) and its subsidiary San Juan Coal Company (San Juan and La Plata mines); Pittsburg and Midway Coal Mining Company (McKinley mine and the York Canyon complex); and Lee Ranch Coal Company (Lee Ranch mine), a division of Hanson Natural Resources Company.

San Juan Basin

Introduction and geologic setting

The San Juan Basin covers more than 26,000 mi² in northwestern New Mexico and adjoining southwestern Colorado. Approximately 600 mi² are underlain by surface-minable coal. Coal in this basin is part of a thick Late Cretaceous-age sequence, deposited during many major advances and retreats of the northwest-trending (approximately N55°W) shorelines of an epicontinental sea. These Cretaceous 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 swamp 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, 1971).

The basal Dakota Sandstone marks the first major marine transgression of the Cretaceous seaway in the San Juan Basin (Fig. 3). The Dakota is a variable sequence of marine sandstone, lacustrine shale, nonmarine shale, and coal (Shomaker et al., 1971). The only minable coal of the Dakota is in southwestern Colorado, near Cortez. The Dakota Sandstone is overlain by the Mancos Shale and its members, which represent the marine section of the first transgressive phase. Subsequent retreat of the shoreline (R-1) resulted in deposition of the marine Atarque Sandstone in the Salt Lake field. The Atarque is overlain by the coal-bearing Moreno Hill Formation in this field, but north of the Salt Lake field

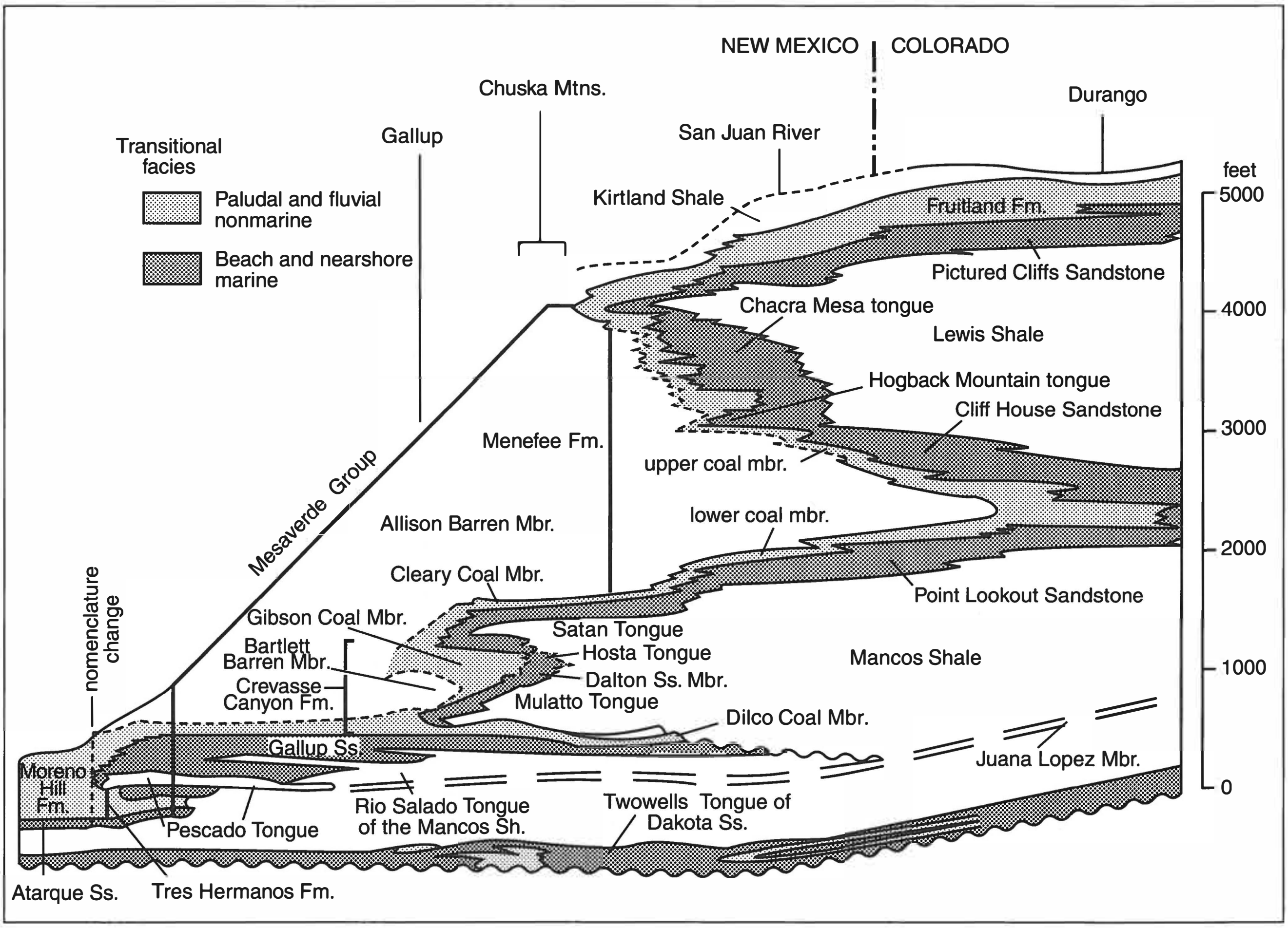

FIGURE 3—Stratigraphic diagram showing sequence, thickness, and nomenclature of Cretaceous rocks in San Juan Basin, New Mexico (modified from Beaumont, 1982, fig. 2; reprinted by permission of the American Association of Petroleum Geologists courtesy of E. C. Beaumont).

the Moreno Hill is the basal member of the Tres Hermanos Formation. The Moreno Hill is, in part, laterally equivalent to the coal-bearing Carthage Member of the Tres Hermanos Formation (see stratigraphic correlation on sheet). Molenaar (1983) indicates a pivot point in this older Late Cretaceous shoreline near the town of Gallup. The shoreline east of this point had a N30°W trend, and to the west the shoreline trend was N60°W. The pivot point appears to be a result of increased sediment supply in this area (Anderson, pers. comm. 1993). The Tres Hermanos deposition was limited to a wedge south of Gallup that includes the Zuni, Datil Mountains, Carthage, and Jornada fields and probably the Sierra Blanca area. To the north, the Carthage Member of the Tres Hermanos is laterally equivalent to the main body of the marine Gallup Sandstone (Anderson, 1990). The retreat of the shoreline that deposited these units was short lived, and the following transgression (T-2 of Molenaar, 1977, 1983) is represented by the Fite Ranch Member of the Tres Hermanos Formation that intertongues with and is overlain seaward by the Pescado Tongue of the Mancos Shale. The coal-bearing Ramah unit (Anderson, 1990) and Torrivio Member of the nonmarine Gallup Sandstone and the overlying Dilco Coal Member of the Crevasse Canyon are part of the later retreat (R-2) of the shoreline. The upper Dilco Coal, Bartlett Barren, and Gibson Coal Members of the Crevasse Canyon Formation, Dalton Sandstone, and marine Mancos Shale were deposited during the ensuing shoreline shift to the southwest (T-3). The Dilco Coal, Bartlett Barren, and Gibson Coal Members crop out in the Gallup and Crownpoint fields and in the Rio Puerco and Mount Taylor areas. The uppermost part of the Gibson Coal Member is part of the next retreat (R-3) of the shoreline. The following major shoreline shift (T-4) was relatively abrupt, and in some areas the paludal upper Gibson Coal Member is overlain directly by marine Mancos Shale (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. During this progradation across the San Juan Basin, the coastal-barrier Point Lookout Sandstone stratigraphically rose 1,200 ft and moved over a horizontal distance of 130 mi (Molenaar, 1977, p. 164). The Point Lookout is exposed intermittently from northeast of Gallup to the northeast edge of the basin near Monero. The final transgression of the shoreline (T-5) within the San Juan Basin is represented by the deposits of the upper Menefee Formation, the Cliff House Sandstone, and the lower Lewis Shale. Within this overall transgressive sequence are minor regressions and major stillstands in the shoreline that deposited the La Ventana Tongue and Chacra Mesa tongue (Beaumont and Hoffman, 1992) of the Cliff House Sandstone. Shoreward the La Ventana and Chacra Mesa intertongue with the upper coal member of the Menefee Formation. The marine upper Lewis Shale, coastal Pictured Cliffs Sandstone, coal-bearing Fruitland Formation, and nonmarine Kirtland Formation were deposited during the last retreat of the epicontinental sea from the basin.

Coal-bearing sequences and fields

The major coal-bearing formations of the Mesaverde Group in the San Juan Basin are, in ascending order, the Gallup Sandstone and the Crevasse Canyon and Menefee Formations (Fig. 3). A fourth and stratigraphically higher major coal-bearing formation, the Fruitland, is a later continuation of similar sedimentation.

The 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 19 individual coal fields or coal areas (see map) defined by formation and political boundaries (Shomaker et al., 1971). These delineations were made by Shomaker et al. (1971) to facilitate a discussion of the surface-minable low-sulfur coal within the basin and are the field designations used in the following discussions.

1) Fruitland Formation fields: Fruitland, Navajo, Bisti, Star Lake
2) Menefee Formation fields: Barker Creek, Hogback, Toadlena, Newcomb, Chaco Canyon, Chacra Mesa, La Ventana, San Mateo, Standing Rock, Monero
3) Crevasse Canyon, Gallup Sandstone, and Tres Hermanos Formation fields: Gallup, Zuni, Crownpoint, South Mount Taylor, East Mount Taylor, Rio Puerco

Fruitland Formation coal fields—coal geology, economic activity, and resources

Fruitland field—The Fruitland field includes the Fruitland Formation exposures from the San Juan River north to the New Mexico–Colorado State line, trending north–northeast for approximately 25 mi. 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° east) in the southern part of this field. The angle of dip increases from 18° to 30° southeast at the Hogback monocline on the western edge of the coal-bearing sequence in the northern Fruitland field.

Several thick minable coal seams near the base of the Fruitland Formation average approximately 16 ft thick. Near the Colorado border, one seam is almost 50 ft thick. These coal beds are high in ash content and have low sulfur values. The apparent rank of the Fruitland field coal is high-volatile C and B bituminous (American Society for Testing Materials, 1981). The weighted averages (averages of analyses for the entire coal bed) for the proximate, sulfur, and calorific values on an as-received basis are:

	Average	Std. dev.	No. of samples
Moisture (%)	8.99	4.67	105
Ash (%)	17.95	5.69	105
Volatile matter (%)	31.76	7.25	85
Fixed carbon (%)	37.08	8.26	86
Sulfur (%)	0.80	0.30	103
Calorific value (Btu/lb)	9,786	1,954	105
Lbs of sulfur/MMBtu	0.89	0.39	108

Small coal mines were opened in the Fruitland field 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, exploratory projects were started that resulted in some of the present-day, large strip-mining operations. Most of the surface-minable resources of the Fruitland field are within the lease areas of the San Juan mine and the La Plata mine (San Juan Coal Company, subsidiary of BHP Minerals). The Fruitland coal area between these two mines is primarily on the Ute Mountain Ute Indian Reservation. A drilling program conducted by Public Service Company of New Mexico delineated 10–14 million st of surface-minable coal on this Ute Mountain property, although the beds have steep dips owing to their proximity to the Hogback monocline (Shomaker and Holt, 1973). At the northern end of the Fruitland field the La Plata mine produces from four coal beds.

Demonstrated resources (coal equal to or thicker than 2.33 ft and within a 0.75-mi radius of a known coal occurrence) of surface-minable coal beneath overburden of less than 200 ft in the Fruitland field are approximately 550 million st; the resources within 150 ft of the surface are 545 million st; the average coal-bed thickness is 7.4 ft. Most of these surface-minable resources are in the southern part of the field where the San Juan mine supplies coal to the San Juan Power Plant of Public Service Company of New Mexico and Tucson Electric Power Company. The La Plata mine of San Juan Coal Company, just south of the Colorado boundary, also supplies coal to the San Juan Power Plant. Underground resources (200–1,000 ft) are 861 million st.

Navajo field—The Navajo field is defined by the Fruitland Formation exposures within the Navajo Indian Reservation, a distance of approximately 35 mi from the San Juan River south to Hunters Wash and Coal Creek (T23N) and east to the boundary of the reservation. The predominant dip of the Fruitland beds is less than 5° east–northeast. Little or no significant faulting is evident in the Navajo field. This area is dissected by the Chaco River; north of the river, badlands are the dominant topography, and to the south are rolling hills. Coal beds are numerous near the base of the Fruitland Formation, and the number of minable beds increases to eight in the southern part of the field (Shomaker et al., 1971). Oscillations of the Late Cretaceous shoreline and minor stillstands helped to create the relatively thick coal beds en echelon to the north; increasingly older beds are southward (Shomaker et al., 1971, p. 108).

Coal in the Navajo field has an apparent rank of subbituminous A to high-volatile C bituminous; quality decreases slightly 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. The weighted averages of coal analyses for the Navajo field on an as-received basis are:

	Average	Std. dev.	No. of samples
Moisture (%)	13.09	1.89	39
Ash (%)	19.29	3.23	39
Volatile matter (%)	31.36	2.61	39
Fixed carbon (%)	35.90	3.78	39
Sulfur (%)	0.79	0.27	37
Calorific value (Btu/lb)	9,124	647	39
Lbs of sulfur/MMBtu	0.88	0.36	40

Very little mining, except for small, temporary pits opened by the local Navajos for home heating fuel, was done before 1953 in the Navajo field. Utah Construction and Mining became interested in the Navajo field 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 Company became interested and negotiated with the Navajo Tribe for a power-plant site. The Four Corners Power Plant was constructed, and three units became operational in 1963. By 1970 two additional units had been built, and Utah Construction reached full production at the Navajo mine (Nickelson, 1988). In 1986 Utah International was acquired by BHP Minerals, Incorporated, present operator of the Navajo mine and holder of the coal leases for the northern two-thirds of the Navajo field.

In the late 1950s El Paso Natural Gas Company (El Paso) was interested in developing a coal gasification plant using coal from the southern Navajo field. In 1959 a prospecting permit was acquired from the Navajo Nation, and exploratory drilling began on the 85,760 acres south of the Utah Construction lease. In 1963 El Paso negotiated a lease with the Navajo Nation for 22,640 acres for a minimum of 10 yrs. 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 two lease sales El Paso and Consolidation Coal (Consol) acquired a 10-yr lease in 1968. At this time Consol reevaluated the resources in the southern Navajo field. Consol estimated approximately 0.7 billion st 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 had been completed and a mining permit obtained, but the Navajo Tribe had not approved the plan. To save the investment the lease was renegotiated in August 1976 for a substantial bonus and a percentage royalty. In compliance with the terms of the new lease, development of the Burnham mine began in 1978 (Nickelson, 1988). This mine had its first production in 1980 and continued production until 1984. The Burnham mine was idled in 1985, and Consol relinquished its lease in 1991. For this operation to be economically feasible, the mine needed a railroad spur built across the Navajo Indian Reservation (Nickelson, 1988).

Demonstrated surface-minable coal resources in the Navajo field, ≥ 2.5 ft thick to depths of 200 ft, are approximately 1.34 billion st; the average bed thickness is 5.6 ft. Resources within 150 ft of the surface are 1.1 billion st. Limited data are available for coal at depths of 200–1,000 ft; demonstrated resources for underground mining are 185 million st.

Bisti field—This field includes the Fruitland Formation exposures that trend southeast from the eastern boundary of the Navajo Indian Reservation, more or less parallel to the Late Cretaceous shoreline. The Bisti field is approximately 35 mi long and is arbitrarily separated from the Star Lake field at the boundary between R9W and R8W. The Bisti field is within the Chaco slope physiographic area, resulting in gentle dips of 3°–5° north–northeast. The Fruitland Formation and overlying Kirtland Formation rock types erode into badlands topography. Overburden in the Bisti field is largely shale and fine-grained friable sandstone, and significant faulting and/or high-angle dips are absent; therefore, surface mining is relatively economical.

Coal beds in the Bisti field average 6 ft in thickness, but they can be as much as 30 ft thick. The thicker, more continuous coal beds in the Bisti field are in the middle of the Fruitland coal-bearing sequence (Hoffman et al., 1993) rather than at the base of the Fruitland Formation. These low-sulfur, high-ash Fruitland 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 and calorific values. The as-received weighted-average analyses from the Bisti field are:

	Average	Std. dev.	No. of samples
Moisture (%)	13.93	3.33	44
Ash (%)	19.29	5.42	44
Volatile matter (%)	31.13	2.85	44
Fixed carbon (%)	35.60	4.46	44
Sulfur (%)	0.52	0.09	44
Calorific value (Btu/lb)	8,754	883	44
Lbs of sulfur/MMBtu	0.61	0.12	48

The Bisti field represents the largest underdeveloped surface-minable coal resource in the San Juan Basin. The De-Na-Zin mine and Gateway mine of the Sunbelt Mining Company were in the northwest part of the Bisti area. Both mines became inactive in December of 1988. Most of the Preference Right Lease Applications (PRLA), issued for federal leases in the 1970s, have been rejected, and a few are in appeal (Pat Romero, BLM, pers. comm. 1995) in the Bisti field.

Preference Right Lease Applications are a result of a moratorium on coal leasing or prospecting by the Department of the Interior. In 1973 the Secretary of the Interior issued a discretionary order that suspended the issuance of any prospecting permits until further notice. The memorandum did not restrict the rights of holders of prospecting permits issued before that directive from obtaining preference-right coal leases under previous regulations. These applications, made under the old federal leasing provisions, allow for the leasing of any acreage under a valid federal prospecting permit (Speer et al., 1977). All prospecting permits have expired, but up to the early 1990s there were several active PRLAs in the San Juan Basin, particularly in the Bisti and Star Lake fields. The Bureau of Land Management has processed (1994) the remaining 11 PRLAs through a 13-step procedure. All of these PRLAs have been rejected, one with no contest of the decision. The remaining PRLAs will go to the Interior Board of Land Appeals (Jim Olsen, BLM, pers. comm. 1994). Lack of transportation is a major economic hindrance, and although a railroad has been proposed to provide access to the Star Lake and Bisti areas, there have been difficulties in obtaining right-of-way.

The Bisti and De-Na-Zin Wilderness areas (see map) are within the Bisti field and include 3,946 and 19,700 acres of public land, respectively. Both areas contain Fruitland Formation and Kirtland Shale outcrops that erode into a badlands topography. The wilderness areas are managed by the Farmington BLM and have been withdrawn from mineral entry; therefore, these areas can not be considered part of the economic Bisti field coal resource.

Preliminary estimates, based on widely spaced drilling and on outcrop data, indicate that approximately 872 million st 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 st. Underground (200–1,000 ft) demonstrated resources are 1.17 billion st.

Star Lake field—The Star Lake field extends east–northeast from the Bisti field for 55 mi. The Fruitland Formation becomes increasingly sandy and pinches out at the eastern edge of this area, southeast of the town of Cuba. Hunt (1984) believed 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° north–northwest into the basin, and some normal faulting has occurred within the Star Lake field.

The Fruitland coal beds in the Star Lake field are thin and lenticular and rarely exceed 10 ft. Analyses from cores suggest that the coal has an apparent rank of subbituminous A to high-volatile C bituminous. These coal beds have a greater average ash yield and a lower average sulfur value than any of the other Fruitland Formation fields. The weighted averages of the Star Lake coal analyses on an as-received basis are:

	Average	Std. dev.	No. of samples
Moisture (%)	12.66	2.16	52
Ash (%)	22.42	4.43	52
Volatile matter (%)	31.75	2.05	52
Fixed carbon (%)	33.21	3.08	52
Sulfur (%)	0.55	0.12	52
Calorific value (Btu/lb)	8,636	702	52
Lbs of sulfur/MMBtu	0.70	0.44	52

The first mining in the Star Lake field was by Navajo Indians who were obtaining home-heating fuel. This area was included in the early coal investigations by the U.S. Geological Survey in the 1930s (Dane, 1936), but exploratory activities did not begin until the 1960s. Exploration led to limited leasing of federal coal in the late 1960s. Now (1995) there are no producing mines in this field, although federal coal leases (T19N R6W, T20N R6W) are still active for the Chaco Energy Star Lake Project. Access is a major problem in developing this area. The proposed Star Lake Railroad would provide access, but problems of right-of-way have hampered the development of this line.

Conservative estimates of the demonstrated surface-minable coal resources for the Star Lake area (≥ 2.5 ft thick; ≤ 200 ft deep) are 946 million st. The demonstrated-resource estimates for coal within 150 ft of the surface are 624 million st. The average thickness of an economic coal bed is 6.6 ft. Peabody Coal has announced resources of 162 million st to depths of 150 ft for their Star Lake mine property, leased by Chaco Energy Company. Demonstrated resources for coal at depths of 200–1,000 ft are 327 million st.

Menefee Formation coal fields—coal geology, economic activity, and resources

Barker Creek field—The Barker Creek field is the northeastern-most Menefee Formation field in the New Mexico part of the San Juan Basin. It is defined by the Colorado–New Mexico boundary on the north and the township line between T31N and T30N to the south. 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 greatly influences the dip (10°–38° east–southeast) of the beds, 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 members (Shomaker et al., 1971) are present in the Barker Creek field, one in the upper 250 ft and a lower member within 100 ft of the Point Lookout contact (Hayes and Zapp, 1955). Total coal thicknesses reported by Hayes and Zapp (1955) were 19.2 ft in the upper member and 17.3 ft in the lower member. These measurements represent the composite thickness of multiple thin beds, and Shomaker et al. (1971) reported no exposed coal beds thicker than 2.4 ft in the lower coal member.

The few analyses available indicate that the Barker Creek coal beds are low-ash, low-sulfur coal and have an apparent rank of high-volatile C bituminous. The averages of three as-received analyses from the Barker Creek area are:

	Average	Std. dev.	No. of samples
Moisture (%)	10.23	0.76	3
Ash (%)	7.03	4.06	3
Volatile matter (%)	38.40	0.88	3
Fixed carbon (%)	44.33	2.72	3
Sulfur (%)	0.90	0.00	1
Calorific value (Btu/lb)	11,497	689	3

Nickelson (1988) reported two mines in the Barker Creek field, the Hepler mine and the Fisherdeck prospects. The Hepler mine opened in 1882 and operated until 1890. Several prospects were opened by C. W. Fisherdeck in 1905 for the Arizona and Colorado Railroad (Shaler, 1906). No production was reported from these operations.

Estimated demonstrated resources for the upper coal member (within 200 ft of the surface and ≥ 2.33 ft thick) are 48 million st. The lower coal member demonstrated resources with a maximum 200-ft overburden are 20 million st. 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 member are 115 million st.

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. The north and south boundaries are T30N R15–16W and T26N R17–18W. The contacts of the Pictured Cliffs Sandstone and the Point Lookout Sandstone with the Menefee Formation define the east and west boundaries, respectively. The east boundary along the Hogback monocline is a sharp, steep slope. The Menefee beds dip as much as 38° east along this structure; the dip decreases to 10° east in the southern part of the field (O'Sullivan and Beaumont, 1957).

Two Menefee coal members are in the Hogback field. The lower member is poorly developed except near the San Juan River along the northern edge of this field. Coal-bed thickness in the lower member ranges from a few inches to 11.3 ft (Lease, 1971a). The upper member is just below the contact with the Cliff House Sandstone and in some areas intertongues with these overlying barrier-beach sandstones. Total coal thickness ranges from 2.5 to 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 and low sulfur values. The average apparent rank of the coal sampled is high-volatile C bituminous. Averages of three weighted analyses are:

	Average	Std. dev.	No. of samples
Moisture (%)	9.92	1.77	3
Ash (%)	15.68	11.08	3
Volatile matter (%)	34.00	4.22	3
Fixed carbon (%)	40.40	7.11	3
Sulfur (%)	0.70	0.20	3
Calorific value (Btu/lb)	10,053	1,533	3
Lbs of sulfur/MMBtu	0.69	0.15	3

Past mining in the Hogback field was restricted to the area near Coal Creek (T30N R16W). Seventeen small mines, most operated by Navajo Indians, were mentioned by Hayes and Zapp (1955). These early mines operated from the 1900s into the 1950s, the last mine ceasing operation in 1976. Coal from the Hogback field mines was used for domestic purposes, and no active mines are reported at the present.

Estimated resources within 200 ft of the surface are 45 million st for the Hogback field, and estimates of deep resources (200–1,000 ft deep) from sparse data are 21 million st. The high-angle dips are prohibitive to surface mining (Lease, 1971a).

Toadlena field—The Toadlena field is defined by the Menefee Formation outcrops in T23–24N R18–19W, east of the Defiance monocline and south of the Tocito dome in a small northern tributary of Captain Tom Wash (Lease, 1971b). The strike of the beds is northeast, and the dip is 4°–12° southeast (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 the coal is covered by thick sandstone overburden and the beds have a significant dip, no surface-minable resources have been calculated.

Newcomb field—The Newcomb field on the Navajo Indian Reservation encompasses the southwestern edge of the upper Mesaverde Group outcrop where the strike of the beds changes from north–south to northwest–southeast. The coal-bearing rocks in the Newcomb field are in the upper part of the Menefee Formation, which contains numerous lenticular coal beds of irregular thickness. Generally these are 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 to masses of red clinker (Shomaker et al., 1971). In several localities coal beds do reach economic thicknesses of 4–8 ft and have reasonable lateral continuity. The upper Menefee Formation coals in this area have an apparent rank of subbituminous A or B, low sulfur values (<1%), and low to moderate ash yields of 6.6–13.0%. Resource estimates of surface-minable coal beneath less than 200 ft of overburden total at least 72 million st. Underground demonstrated resources to a depth of 1,000 ft are 54 million st. These figures are based on sparse data, and more exploratory 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 to the La Ventana field (R3W) on the southeast edge of the basin. 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 province, the beds have gentle dips of 1°–5° north–northeast. The northern boundary of the fields is defined by the Cliff House Sandstone that caps the prominent northeast-trending Chacra Mesa.

The Chaco Canyon field contains outcrops of the upper coal member of the Menefee Formation. The Cleary Coal Member is in the subsurface. Much of this area is covered by northwest-trending valleys and mesas capped by Cliff House Sandstone that overlies and intertongues with the upper coal member. In the Chacra Mesa field both the Cleary Coal and upper coal members of the Menefee Formation are exposed. 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 commonly overlain by a very thick overburden of Cliff House Sandstone that inhibits surface mining (Speer, 1971).

Analyses for the Chaco Canyon field indicate that these are low-ash, moderate-sulfur coals having an apparent rank of subbituminous A. The averages of four weighted-average analyses from the Chaco Canyon area are:

Chaco Canyon field
upper coal member

	Average	Std. dev.	No. of samples
Moisture (%)	16.33	2.31	4
Ash (%)	7.88	2.00	4
Volatile matter (%)	33.18	1.10	4
Fixed carbon (%)	42.38	0.87	4
Sulfur (%)	1.38	0.62	4
Calorific value (Btu/lb)	10,210	17	3
Lbs of sulfur/MMBtu	1.63	1.13	4

Recent work in the Chacra Mesa field (Roybal et al., 1987, 1988) resulted in the following as-received, weighted averages.

Chacra Mesa field
upper coal member

	Average	Std. dev.	No. of samples
Moisture (%)	15.29	3.05	14
Ash (%)	9.69	3.29	14
Volatile matter (%)	35.24	2.57	14
Fixed carbon (%)	39.73	2.38	14
Sulfur (%)	0.72	0.41	14
Calorific value (Btu/lb)	10,207	615	14
Lbs of sulfur/MMBtu	0.72	0.43	14

Chacra Mesa field
Cleary Coal Member

	Average	Std. dev.	No. of samples
Moisture (%)	11.94	6.14	2
Ash (%)	11.05	2.57	2
Volatile matter (%)	37.44	5.36	2
Fixed carbon (%)	39.07	4.07	2
Sulfur (%)	0.45	0.11	2
Calorific value (Btu/lb)	10,898	1,605	2
Lbs of sulfur/MMBtu	0.45	0.15	2

The upper coal member coal beds are higher in moisture and sulfur and lower in ash and calorific values than the Cleary Coal Member coals; however, both sets of analyses indicate coals low in sulfur and moderate in ash yield. The upper coal and Cleary coal have apparent ranks of subbituminous A and high-volatile C bituminous, respectively.

Small drifts and pits operated by the Navajo Indians are the only mines in the Chacra Mesa and Chaco Canyon areas. The Blake mine in the Chaco Canyon field, mentioned by Bauer and Reeside (1921), was in the north rim area of Tsaya Canyon, 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. The coal from both these mines was used at local trading posts and for domestic heating purposes (Nickelson, 1988).

Geologic work on the Menefee coal at depths greater than 500 ft (Shomaker and Whyte, 1977) has shown thick, extensive deposits in the Chacra Mesa area, with resources in the millions of short tons. Geologic investigations by the NMBMMR (Tabet and Frost, 1979; Roybal et al., 1987, 1988) indicate demonstrated resources of 140 million st 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 st. The average thickness of the coal bed in this resource calculation is 3.5 ft. Demonstrated resources at depths less than 250 ft are at least 30 million st in the region north of La Vida Mission and northwest of Chaco Culture National Historical Park where good quality coal beds are 5–6 ft thick (Shomaker et al., 1971). Underground demonstrated resources for the Chacra Mesa field are 269 million st. Estimates of demonstrated resources within 200 ft of the surface for the entire Chaco Canyon field are 16 million st. Underground resources for this field are 83 million st, 51 million st in the upper coal member and 32 million st in the Cleary Coal Member.

La Ventana field—The La Ventana field is on the southeastern edge of the San Juan Basin. The beds are gently dipping (2°–5° north–northwest) in the western part of the field. The eastern La Ventana field is close to the Nacimiento uplift where the dip of the beds increases from 35°–45° northwest–west to vertical. This area includes the Cleary Coal and upper coal members 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. There are significant resources in the Cleary Coal Member and upper coal member of the Menefee Formation. For the entire La Ventana field at least 130 million st of low-ash moderate-sulfur demonstrated resources are within 200 ft of the surface, 56 million st in the upper coal member of the Menefee and 75 million st in the Cleary Coal Member. Thick sandstone overburden associated with the upper coal member throughout the field and steep dips in the eastern part of the field limit the amount of surface-minable coal. The upper coal beds average 4.3 ft thick, but individual beds can be as much as 12 ft thick; the average coal thickness within the Cleary Coal Member is 4 ft. The upper and Cleary Coal members' underground resources are 133 million st. The apparent rank of coal in both members of the Menefee is subbituminous A. The Cleary coal beds are higher in ash and lower in sulfur as indicated by the weighted-average as-received analyses given below.

Cleary Coal Member

	Average	Std. dev.	No. of samples
Moisture (%)	15.58	4.01	28
Ash (%)	11.06	3.31	28
Volatile matter (%)	34.83	1.90	28
Fixed carbon (%)	38.79	4.24	28
Sulfur (%)	1.01	0.62	20
Calorific value (Btu/lb)	10,400	620	27
Lbs of sulfur/MMBtu	0.99	0.60	28

Upper coal member

	Average	Std. dev.	No. of samples
Moisture (%)	16.40	2.54	20
Ash (%)	8.14	4.34	20
Volatile matter (%)	34.81	2.68	20
Fixed carbon (%)	40.63	3.09	20
Sulfur (%)	1.36	0.55	20
Calorific value (Btu/lb)	10,171	696	20
Lbs of sulfur/MMBtu	1.35	0.49	21

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 of the mines in this area have been underground. Early mining (1884–1900) was concentrated along the eastern edge of the field near the village of La Ventana, 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 was built from Bernalillo to La Ventana. Washouts along the Rio Puerco were a problem for the railroad, and by 1931 the trains were no longer running to the mines. Only a few mines continued to operate to meet local fuel needs. In 1964 Consolidation Coal 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. Lack of rail transportation and poor economic conditions hindered the development of this mine, and Ideal Basic relinquished their leases. Recent mining (from 1976 to mid-1984) in the La Ventana field has been limited to the Arroyo No. 1 mine in the Cleary Coal Member north of San Luis.

San Mateo and Standing Rock fields—The San Mateo field is northwest of the Mount Taylor volcanic complex and south of the Chacra Mesa field. It includes exposures of the Allison and Cleary Coal Members of the Menefee Formation (Fig. 3). The San Mateo and San Miguel Creek domes, structural features in the southern San Mateo field, were positive 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. The Standing Rock field, northwest of the San Mateo field, is within the Chaco slope; therefore, the units dip gently north–northwest into the basin. The arbitrary boundary between the San Mateo and Standing Rock fields is the western border of R8W.

Coal beds in the Cleary Coal Member of the Menefee Formation crop out 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 is present locally; usually these lenticular seams are within the first 100 ft above the Point Lookout Sandstone contact.

Demonstrated resources for the San Mateo field are estimated at more than 450 million st of coal within 200 ft of the surface. Estimated coal resources within 150 ft of the surface are 238 million st. Underground demonstrated resources are estimated to be more than 317 million st.

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 st of surface-minable coal (within 200 ft) having an average thickness of 5 ft. Of this total demonstrated resource, 228 million st are within 150 ft of the surface. Underground resources are estimated at 448 million st. Both the Standing Rock and San Mateo fields have moderate ash yields and low to moderate sulfur values. The apparent rank of these Cleary Coal Member coals is subbituminous A. Weighted-average analyses on an as-received basis for both fields follow.

Standing Rock field

	Average	Std. dev.	No. of samples
Moisture (%)	17.03	1.42	27
Ash (%)	13.32	3.35	27
Volatile matter (%)	33.83	1.41	27
Fixed carbon (%)	35.81	2.79	27
Sulfur (%)	1.06	0.38	27
Calorific value (Btu/lb)	9,429	552	27
Lbs of sulfur/MMBtu	1.09	0.41	30

San Mateo field

	Average	Std. dev.	No. of samples
Moisture (%)	14.36	2.45	45
Ash (%)	13.14	3.46	45
Volatile matter (%)	35.54	1.97	41
Fixed carbon (%)	36.60	3.10	41
Sulfur (%)	0.93	0.35	45
Calorific value (Btu/lb)	9,865	1,088	45
Lbs of sulfur/MMBtu	0.92	0.37	44

The Santa Fe Pacific Minerals Corporation (Santa Fe) Lee Ranch mine is in the south-central part of the San Mateo field. The Lee Ranch mine started operations in mid-1982. 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. Production increased from slightly more than 2.7 million st in 1990 to more than 4.1 million st in 1991. Coal shipments from the mine are under long-term contract to the Plains Electric Generating Station near Prewitt, New Mexico, and the Tucson Electric Power Company in Springerville, Arizona (New Mexico Energy, Minerals and Natural Resources Department, 1994 permitting activity list). In early 1993 Santa Fe entered into an agreement with Hanson Natural Resources Company, Incorporated, to trade its coal holdings, including the Lee Ranch mine, for some of Hanson's gold assets (Dillard, 1993). The trade was finalized on June 25, 1993. Mining in the Standing Rock field has been limited to small pits opened on outcrops of coal by Navajo Indians for domestic use.

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 approximately 26 mi. The coal-bearing rocks strike north–south 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. 1). 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 parallel the eastern edge of the basin and are associated and contemporaneous with the folding that took place along the eastern San Juan Basin (Dane, 1948) during the Laramide tectonic activity. Widespread high-angle or normal faulting caused displacement of less than 100 ft (Dane, 1948), generally to the west. The dips of the 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; therefore, the coal beds are mainly in the central and southern parts of the field.

Considerable shallow coal is present in the central Monero field on the backslopes of cuesta blocks, although very little drill-hole data are available. Preliminary estimates of demonstrated resources to a depth of 200 ft are 8 million st. 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 st, but dips greater than 5° and faulting make underground mining difficult. These moderate-sulfur, moderate-ash coal beds are of high-volatile bituminous B to A apparent rank. Some of the seams have coking qualities (Averitt, 1966), but these resources have not been determined. Weighted averages of as-received analyses are given below.

	Average	Std. dev.	No. of samples
Moisture (%)	3.90	1.88	14
Ash (%)	10.16	3.10	14
Volatile matter (%)	36.91	1.58	12
Fixed carbon (%)	48.74	3.13	12
Sulfur (%)	1.85	1.01	14
Calorific value (Btu/lb)	12,373	963	13
Lbs of sulfur/MMBtu	1.50	0.84	13

Near Monero and Lumberton, coal was mined for many years on a small scale in underground mines, principally for the Denver and Rio Grande Western Railroad and local domestic use. Coal mines operated in the Monero area from 1899 until 1970, producing a total of 1.6 million st.

Crevasse Canyon Formation, Gallup Sandstone, and Tres Hermanos Formation fields—coal geology, economic activity, and resources

Gallup field—On the southwestern edge of the San Juan Basin, the Gallup field extends southward into a shallow, northward-plunging syncline, the Gallup sag (Fig. 1). The eastern edge of this field is defined by the steeply dipping Mesaverde Group exposures along the Nutria monocline. The western edge of the field is delineated by the Defiance uplift. Between these two structures, the attitudes of the coal-bearing sequence are influenced by the Torrivio and Gallup anticlines and the intervening syncline, the Gallup sag. The arbitrary southern limit is the township line between T12N and T11N.

North of the town of Gallup, the Cretaceous coal-bearing beds are covered by Tertiary strata of the Chuska Mountains. The Mesaverde Group coal-bearing units in the Gallup field are the Gallup Sandstone, the Dilco Coal Member of the Crevasse Canyon Formation, and the Cleary Coal and Gibson Coal Members of the Menefee and Crevasse Canyon Formations, undivided (Cleary–Gibson Coal Members). The landward pinchout of the Point Lookout is northeast of the Gallup field, consequently no lithologic division exists between the Menefee and Crevasse Canyon Formations (see Fig. 3) near the town of Gallup. Thus, the coal-bearing Cleary–Gibson Coal Members form a thick coal-bearing sequence shoreward of this pinchout.

Coal in the Gallup Sandstone is of limited extent (Sears, 1925). It has been mined underground, but no strippable resources appear to be economic. Estimated coal resources for the Gallup Sandstone in the Gallup field are 1.2 million st 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 being the most extensive (Sears, 1925). The Cleary–Gibson Coal Member 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 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 mi of lateral continuity.

Underground mines in the Gallup area removed considerable blocks of coal from the 1880s to the 1950s. From 1882 to 1961 33.3 million st of coal were mined from the Gallup coal field (New Mexico Territorial Mine Inspector, 1882–1911; New Mexico State Mine Inspector, 1912–1961). The Cleary–Gibson remaining demonstrated coal resources to a depth of 200 ft are 449 million st, 328 million st of these resources are within 150 ft of the surface. Pittsburg and Midway estimates 170 million st of recoverable reserves for the McKinley mine area (Pittsburg and Midway brochure, 1989). The demonstrated coal resources (≤ 200 ft) of the Dilco Coal Member are 161 million st from coal beds having an average thickness of 4.2 ft. Underground estimated resources are 356 million st and 196 million st for the Cleary–Gibson Coal and Dilco Coal Members, respectively.

Both the Dilco and Cleary–Gibson coals range from high-volatile C bituminous to subbituminous A apparent rank, although the Dilco coal has a higher moist, mineral-matter-free calorific value (mmfBtu; used to determine rank) because of the lower moisture content of this coal. These are low-sulfur, low- to moderate-ash steam coals. Averages of weighted-average analyses on an as-received basis are:

Dilco Coal Member

	Average	Std. dev.	No. of samples
Moisture (%)	9.36	3.52	14
Ash (%)	9.08	5.59	14
Volatile matter (%)	35.17	10.37	14
Fixed carbon (%)	39.14	11.87	14
Sulfur (%)	0.76	0.32	14
Calorific value (Btu/lb)	10,343	3,220	13
Lbs of sulfur/MMBtu	0.71	0.18	12

Cleary–Gibson Coal Members

	Average	Std. dev.	No. of samples
Moisture (%)	13.82	1.71	34
Ash (%)	9.32	4.56	35
Volatile matter (%)	37.42	3.79	35
Fixed carbon (%)	38.59	4.40	35
Sulfur (%)	0.53	0.13	35
Calorific value (Btu/lb)	10,507	894	35
Lbs of sulfur/MMBtu	0.50	0.14	35

Underground mining in the Gallup field began in the 1880s following the construction of the main line of the Atchison, Topeka, and Santa Fe Railway through Gallup. Peak production from the underground mines was approximately 825,000 st in 1920. Underground mining continued on a large scale until 1951 when diesel engines replaced coal-fired steam engines on the railroads, decreasing the market for coal. Large-scale strip mining began in mid-1961 when Pittsburg and Midway Coal Mining Company opened its McKinley mine. The McKinley mine now produces approximately 6–8 million st per year, supplying the following power plants: Cholla (Arizona Public Service) in Joseph City, Arizona; Coronado (Salt River Project) in St. Johns, Arizona; Apache (Arizona Electric Coop) in Cochise, Arizona; and Irvington Station (Tucson Electric) in Tucson, Arizona. Three other small surface mines have operated in the Gallup area, but all of these have closed and undergone reclamation.

Zuni field—The Zuni field is at the southern end of the Gallup (or Gallup–Zuni) sag (Fig. 1). Coal-bearing Cretaceous rocks extend south of Zuni Pueblo, but south of the Zuni Indian Reservation they are covered by Cenozoic volcanic rocks, and the coal beds are thin.

Coal in the Zuni field is within the Dilco Coal Member of the Crevasse Canyon Formation, Gallup Sandstone, and Tres Hermanos Formation (Fig. 3; Sears, 1925; Anderson, 1987; Anderson and Stricker, 1987). The coal in the Gallup Sandstone is below the Torrivio Member in what has been called the Ramah unit (Anderson and Stricker, 1987). This coal-bearing unit has coal as much as 7 ft thick, but generally the coal beds are thin and do not have great lateral extent. The coal 'zones' within the Carthage Member of the Tres Hermanos are at the base and top of this unit; the coal beds are thin (1.2–4.8 ft) and lenticular (Anderson and Stricker, 1987). Dilco Coal Member demonstrated resources from available outcrop and sparse drill-hole data are only 23 million st for depths less than 200 ft. Anderson (1987) estimated coal resources in the Gallup Sandstone of approximately 49 million st in the southeastern corner of the Zuni field. Demonstrated resources for the Crevasse Canyon Formation (200–1,000 ft) are 31 million st. Gallup Sandstone underground estimated resources are 11 million st.

Analyses of the coal beds in the Gallup Sandstone, Ramah unit, have the following ranges on an as-received basis (Anderson and Stricker, 1987).

Moisture (%)	4.4–10.6
Ash (%)	8.8–36.0
Volatile matter (%)	31.8–37.6
Fixed carbon (%)	38.7–42.4
Sulfur (%)	0.6–1.5
Calorific value (Btu/lb)	10,470–11,250

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

Crownpoint field—The Crownpoint field is the largest coal field (930 mi²) in the San Juan Basin, encompassing the Crevasse Canyon Formation exposures from northeast of the Gallup field to the west edge of the San Mateo field. The southern edge of this field is influenced by the Zuni uplift, and faulting is widespread along the southeast border (see map, Fig. 1). The coal-bearing units are the Gallup Sandstone and the Dilco Coal and Gibson Coal Members of the Crevasse Canyon Formation.

No economic coal is known within the Gallup Sandstone in this area, and the Dilco coal beds are thin and lenticular (Sears, 1934; Dillinger, 1990). The Gibson Coal Member contains the only coal considered economic in the Crownpoint field. Economic coals in the Crownpoint field are on average 3.6 ft thick; maximum thickness is 15.5 ft. Estimated surface-minable demonstrated resources (≤ 200 ft deep) are 663 million st. Underground demonstrated resources are 430 million st. These coals are subbituminous B–A, the beds are highly lenticular, and in most of the field they are overlain by thick, massive Hosta Tongue sandstone in the mesa and canyon terrain on the southwestern rim of the San Juan Basin. The average weighted-average analyses of Gibson Coal Member coals on an as-received basis are:

	Average	Std. dev.	No. of samples
Moisture (%)	15.59	1.62	13
Ash (%)	11.95	5.29	13
Volatile matter (%)	35.02	2.93	13
Fixed carbon (%)	37.02	3.39	13
Sulfur (%)	1.44	0.73	13
Calorific value (Btu/lb)	10,037	923	13
Lbs of sulfur/MMBtu	1.49	0.86	13

The first mine to open in this field was the Crownpoint mine that operated from 1918 to 1951. This mine supplied coal to the Indian schools and the Bureau of Indian Affairs (BIA) facilities at the town of Crownpoint. Nine other mines operated sporadically from the 1920s to the 1950s. United Electric Coal Company obtained coal leases in the 1960s for the Crownpoint area and did exploratory drilling. Although several leases were acquired, no development has followed because of the transportation problems and poor economic conditions.

South Mount Taylor and East Mount Taylor fields—The coal-bearing 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 in the South and East Mount Taylor coal fields. This area was first mapped in detail by Hunt (1936). In most places, the thick Tertiary volcanic sequence of Mount Taylor overlies minable Gibson coal and prevents surface mining except in small areas in the South Mount Taylor field at Guadalupe and Rinconada Canyons, northeast of Grants. These coal beds range from 2.5 ft to 7 ft in thickness, but they are highly lenticular and have demonstrated resources (≤ 200 ft deep) of 14 million st. The resource estimates of the Dilco coal in the South Mount Taylor field are slightly greater than 5 million st (Dillinger, 1989). The Dilco Coal Member intertongues northeastward with marine strata and thus contains essentially no coal seams in the East Mount Taylor field. The few analyses of these Gibson–Dilco coals show an as-received heating value of approximately 11,200 Btu/lb, a sulfur content of 0.6%, and an ash yield of approximately 6%. Small drifts have been opened to mine coal for local use.

Rio Puerco field—The Rio Puerco field is an irregular outcrop belt of Mesaverde Group coal-bearing rocks in the Rio Puerco valley, an outlier of the San Juan Basin. It is approximately 15 mi southeast of the East Mount Taylor field and extends from T8N to T14N and from R1E to R3W.

Coal is present in both the Dilco Coal and Gibson Coal Members of the Crevasse Canyon Formation in the Rio Puerco field, but the Dilco coal is too thin to be economic. The Gibson coal beds average 3.8 ft thick, although seams as much as 5.6 ft thick have been mined for local use in the northern part of the field (Hunt, 1936). The field is within the Rio Puerco fault zone (Fig. 1), a north–northeast-trending swarm of normal, en echelon faults (Slack and Campbell, 1976); thus, the coal-bearing outcrops are in narrow, steeply dipping fault blocks. In no place do the coal beds appear favorable for stripping, although the eastern part of the field is covered by sand that masks the underlying bedrock. Estimated demonstrated resources from the surface to a depth of 200 ft are 25 million st.

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 available these coal beds appear to be low-ash, low- to moderate-sulfur coals. Averages for the as-received analyses in the Rio Puerco field are:

	Average	Std. dev.	No. of samples
Moisture (%)	14.60	6.72	4
Ash (%)	8.35	1.71	4
Volatile matter (%)	35.38	2.98	4
Fixed carbon (%)	41.68	3.03	4
Sulfur (%)	0.93	0.41	4
Calorific value (Btu/lb)	9,445	203	4
Lbs of sulfur/MMBtu	0.98	0.38	4

Mining in the Rio Puerco field began in the 1920s and continued into the 1940s. Nickelson (Abandoned Mine Lands Project, field notes) reported six small mines and a total production of 30,987 st.

Raton Basin–Raton field

Introduction

The Raton field covers 900 mi² in northeastern New Mexico and is part of a large, asymmetrical, arcuate basin on the eastern edge of the Rocky Mountains that was formed during the Laramide orogeny (Baltz, 1965). The basin is bounded on the east by the Sierra Grande arch and the Las Animas arch in New Mexico and Colorado, respectively, and on the west by the Sangre de Cristo Mountains (Fig. 2; Pillmore, 1991). The Canadian and Vermejo Rivers 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 in a few localities is the overburden thin enough to allow surface mining, although considerable resources underlie this overburden. The east limb of the Raton Basin dips gently (1°–5°) northwest and generally lacks significant faulting (Wanek, 1963). The Vermejo anticline, a prominent structure in the northwest Raton coal field, has 2,500 ft of structural relief across 3.85 mi. This structure is attributed to a buried intrusion as delineated by drill-hole records (Pillmore, 1976).

Coal-bearing sequences

The Vermejo and Raton Formations are the coal-bearing units of the Raton Basin (Fig. 4). 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 that contains extensive coal beds, including the Raton coal bed, that were deposited in back-barrier brackish swamps and lower coastal-plain distributary channels (Fig. 4). Most of the thick, laterally extensive coal beds are back barrier in origin and are aligned subparallel to the north–northeast Late Cretaceous shoreline (Pillmore, 1991). Coal in the upper Vermejo Formation accumulated in poorly drained swamps on the upper coastal plains (Pillmore and Flores, 1987). To the northeast 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 zone, and the upper coal zone (Fig. 4). The lower coal zone includes all of the Cretaceous-age rocks of the formation; the Cretaceous–Tertiary 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-thick coal bed, 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 Cretaceous–Tertiary 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 10 ft or greater in thickness. Seven coal beds within the upper coal zone in the central and eastern parts of the Raton coal field are described in detail by Pillmore (1976, 1991). The Raton Formation coarsens and interfingers to the west with the wholly continental Poison Canyon Formation (Fig. 4).

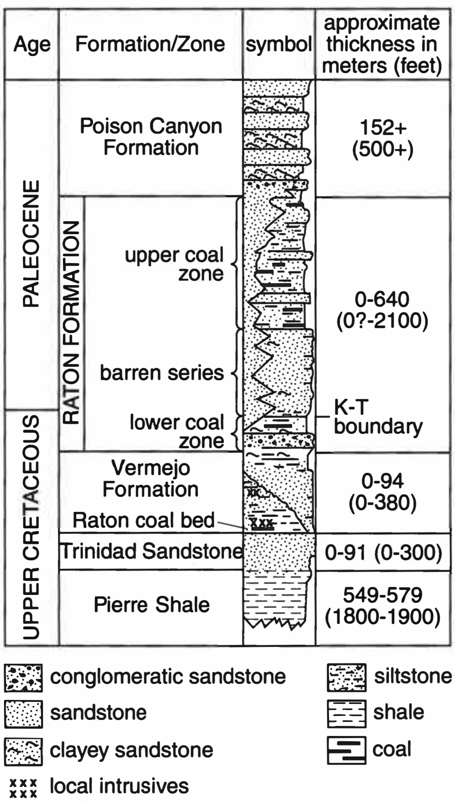

FIGURE 4—General stratigraphic column for Raton coal field (modified from Pillmore and Flores, 1987; reprinted by permission).

Coal geology and resources

Resources estimated by Pillmore (1969) for the northern part of the field are 700 million st of coking coal; Wanek's (1963) estimate for the entire field is 1.5 billion st. Using a minimum of 14 inches of coal for resource estimates and including inferred resources, Read et al. (1950) estimated 4.7 billion st in the Raton field. In a recent paper Pillmore (1991) estimated 1.5 billion st of demonstrated (≥ 2.5 ft thick) coal resources in this field and approximately 8 billion st of inferred resources. The Vermejo Formation has demonstrated resources (≥ 2.5 ft thick) of 971 million st, and the Raton Formation has 513 million st of demonstrated resources. The inferred resources, 8 billion st, are mainly in thinner beds distributed throughout the Raton field (Pillmore, 1991, p. 49).

The Vermejo and Raton Formations contain low-sulfur, moderate-ash coal. Most of these coal seams have an apparent rank of high-volatile A to B bituminous, and many are coking coals. The averages of the weighted-average as-received analyses for the Raton field are:

Vermejo Formation

	Average	Std. dev.	No. of samples
Moisture (%)	2.75	0.96	20
Ash (%)	14.49	4.02	20
Volatile matter (%)	34.83	1.80	20
Fixed carbon (%)	48.24	3.28	20
Sulfur (%)	0.72	0.13	20
Calorific value (Btu/lb)	11,786	1,582	19
Lbs of sulfur/MMBtu	0.58	0.11	18

Raton Formation

	Average	Std. dev.	No. of samples
Moisture (%)	4.27	3.19	28
Ash (%)	12.88	5.11	28
Volatile matter (%)	34.90	3.18	28
Fixed carbon (%)	47.72	5.86	28
Sulfur (%)	0.57	0.14	28
Calorific value (Btu/lb)	11,921	1,764	27
Lbs of sulfur/MMBtu	0.47	0.13	27

Economic activity

Several minable coal beds are 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 the

Raton coal bed near the base of the Vermejo Formation, the Vermejo coal bed near the top of the Vermejo Formation, and 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 is 6–13 ft thick at the Pittsburg and Midway York Canyon No. 1 and Cimarron mines, both underground operations.

Coal was discovered in the Raton area in the 1820s and has been mined in the Raton field since the 1870s (Lee, 1917, p. 13). From the 1870s to the mid-1960s most of the coal mined was from the Raton bed or equivalent beds at the base of the Vermejo Formation in the underground mines near Koehler, Van Houten, Brilliant, and Dawson. These early mines were along the eastern edge of the field, at the mouths of canyons. Production in the Raton field from 1898 to 1965 totaled 63.7 million st. A significant part of the coal produced from these early operations during the late 1800s through the early 1900s was coked and shipped to smelters in the Southwest and East. The present phase of mining began with the opening of the Kaiser Steel Corporation York Canyon underground mine in 1966 and a surface operation in 1977 in the York Canyon area, southeast of Vermejo Park. Kaiser controlled most 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 Company, a subsidiary of Chevron Corporation. The surface and oil and gas rights for this acreage were purchased by Pennzoil. Pittsburg and Midway submitted a mine plan in March 1993 for new operations, the Ancho, East Ridge, and Road Canyon surface mines, which would be in the York Canyon area. The East Ridge, Road Canyon, and West York mines closed in December 1994. The underground Cimarron closed in September 1995. Only the Ancho surface mine is active (June 1996) in the Raton field.

Smaller coal fields in New Mexico— coal geology, resources, and economic activity

Salt Lake field

The Salt Lake field covers 750 mi² in west-central New Mexico. It is separated from the Zuni field to the northeast by the Atarque monocline, which trends southeast from near Ojo Caliente, and by a tongue of the Bandera lava flows. The coal-bearing Moreno Hill Formation, named by McLellan et al. (1983), is laterally equivalent to the Tres Hermanos Formation, Gallup Sandstone and Crevasse Canyon Formation in the southwestern San Juan Basin (Fig. 3; Hook et al., 1983). Outcrops of the Moreno Hill Formation form a west-facing arcuate belt centered around Zuni Salt Lake; this outcrop belt is traversed by NM–601 and NM–36. Coal-bearing units within the field dip 3°–5° to the southeast, are only slightly displaced along faults, and show only minor flexures in different parts of the field because of Tertiary volcanism (Campbell, 1989).

Recent resource evaluation by investigators at the NMBMMR and the U.S. Geological Survey indicates 323 million st of demonstrated coal resources (minimum 2.5 ft thick, ≤200-ft depth; Campbell, 1981, 1989; Roybal and Campbell, 1981; NMBMMR coal database); seams average 5 ft thick but are as much as 14 ft thick. Coal in the Moreno Hill Formation is moderate ash and low sulfur and has an apparent rank of subbituminous A. Below are the averages of 58 weighted-average as-received analyses.

	Average	Std. dev.	No. of samples
Moisture (%)	14.71	3.19	58
Ash (%)	17.07	4.07	58
Volatile matter (%)	31.67	2.65	58
Fixed carbon (%)	36.19	3.76	58
Sulfur (%)	0.69	0.22	52
Calorific value (Btu/lb)	9,166	837	56
Lbs of sulfur/MMBtu	0.77	0.24	50

Exploration and lease sales in the 1980s 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 and Improvement and Power District, a public entity (SRP, Phoenix, Arizona) obtained several of the coal leases and conducted drilling programs in 1982 and 1984 on these leases. SRP acquired the Santa Fe Minerals coal leases from the 1981 state lease sale in 1983. SRP also acquired state leases from Northwestern Resources in 1986. In March of 1985, a reserve study was done by John T. Boyd Company (Denver office) for SRP, and a mine plan was submitted to the Energy, Minerals and Natural Resources Department in May 1985. A mining permit was issued in November of 1986 for the Fence Lake #1 mine.

Mining began in secs. 10 and 11 of T3N R17W in January 1987, and mining and reclamation were completed in July 1987. The Fence Lake #1 mine was a test mine to facilitate a suitability test burn of this coal for SRP's Coronado Generating Station (Greenberg, 1987). Initial requirements for this burn were 80,000 st, but final production was 100,000 st. The mine was closed when the tests at Coronado were completed.

Drilling by SRP was done in 1988 in preparation for Lease by Application for federal coal surrounding their state leases. The Lease by Application was initiated in December 1988 beginning with an environmental impact statement (EIS) done by Dames and Moore for SRP. The final EIS was approved in October 1990, and the San Juan Regional Coal Team (RCT) and BLM approved the lease sale in December 1990. The BLM director (Larry Woodard) announced at the February 20, 1991, RCT meeting that the sale would be limited to public-body set-aside leasing.

The Federal lease sale was announced in late May–early July 1991. Bids were made July 31, 1991, at the BLM office in Santa Fe. Two tracts were offered in T3–4N R16–17W, totaling 6,442.28 acres of public land and federal mineral estate. Recoverable reserves from two minable seams were estimated by the BLM to be 29.63 million st. SRP had the winning bid ($2.4 million) and signed the first federal coal lease agreement in New Mexico in 12 yrs on September 25, 1991. This acquisition brought SRP lease acreage in the Salt Lake area to 18,000 acres and SRP reserves to 120 million st. SRP was granted a mining permit renewal in November 1991. The final EIS was issued in April 1995. SRP hopes to be in production by late 1997.

Datil Mountains field

The Datil Mountains area is at the junction of Socorro, Catron, and Cibola Counties, in west-central New Mexico. The field lies on the southeastern edge of the Colorado Plateau between the Zuni and Lucero–Ladron uplifts in a synclinal extension of the San Juan Basin, referred to as the Acoma sag. The Datil Mountains field encompasses 760 mi² of rugged terrain accessible only by secondary roads.

Exposures of the Tres Hermanos and Crevasse Canyon Formations delineate this field. These coal-bearing units crop out in the northern part of the field in rugged forested terrain and are influenced by several intrusions of Tertiary age. To the south, the coal-bearing units are overlain by thick volcanic tuffs and flows; structure is complicated by broad-scale faulting and folding. Coal beds in most of this field are less than 3 ft thick, although local lenses are as much as 7 ft thick. Work in the Datil Mountains field by Frost et al. (1979) and Osburn (1982), combined with other available data at the NMBMMR, suggests that the demonstrated resources (≥2.5 ft thick, ≤200 ft deep) are approximately 47 million st; 31 million st of coal are within 150 ft of the surface. The average thickness of the coal beds in these estimates is 3 ft.

Coal seams in the Datil Mountains field have a moderate ash yield, a low sulfur value, and an apparent rank of subbituminous A. The averages of the weighted-average as-received analyses are:

	Average	Std. dev.	No. of samples
Moisture (%)	6.24	3.96	10
Ash (%)	12.84	6.34	10
Volatile matter (%)	38.28	2.97	10
Fixed carbon (%)	42.69	2.47	10
Sulfur (%)	0.72	0.54	10
Calorific value (Btu/lb)	11,465	869	10
Lbs of sulfur/MMBtu	0.66	0.55	10

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 st of coal. The Hot Spots mine reportedly produced 85 st of coal between 1927 and 1931 (Nickelson, Abandoned Mine Land Project, unpublished notes).

Tierra Amarilla field

This small field is an outlier of the coal-bearing Menefee Formation approximately 12 mi east of the edge of the San Juan Basin southeast of Tierra Amarilla. The field is on the eastern flank of the Chama embayment (Fig. 1), and the lowest part of this basin is marked by the Chama syncline 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. Most of the coal seams in these Menefee Formation exposures are thin and lenticular, and most are overlain by excessive overburden, including massive sandstones of the Cliff House, which prevents surface mining. Three to four upper Menefee coal beds exposed in the western part of the Tierra Amarilla field reach a maximum thickness of 20 inches (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 49 inches in places. Samples from the Dandee mine indicate that the coal is of subbituminous A apparent rank, contains 1.0–1.1% sulfur, yields approximately 8% ash, 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 million st for the entire Tierra Amarilla field for coals greater than 2.3 ft thick.

Very little mining took place in the Tierra Amarilla field except for local use; Landis and Dane (1969) located four prospects or small mines in this area. The Dandee mine operated from 1944 until 1954, and the White mine opened in 1935 and operated for several years (Landis and Dane, 1969; Nickelson, 1988). Production from these mines was limited and for domestic use.

Cerrillos field

The Cerrillos field is in the broken foothill country northwest of the Ortiz Mountains south of the broad Rio Galisteo valley, which is traversed by the main line of the Atchison, Topeka, and Santa Fe Railway. 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 as much as 6 ft thick and have yielded considerable tonnages of anthracite and bituminous coal. From the base upward, the four main coal seams are the Miller Gulch, Cook and White, White Ash, and Ortiz Arroyo or 'B' seams (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 Ortiz Arroyo or 'B' bed immediately overlying the intrusive body.

Read et al. (1950) estimated 46.5 million st of bituminous coal and 11.4 million st of anthracite in the Cerrillos field. Beaumont (1979) believes 5.2 million st to be a more realistic resource figure for this field because Read et al.'s (1950) parameters of calculation are unrealistic; a 14-inch-thick coal is too thin to be economical, and 3,000 ft is an impractical depth for mining in this area. The New Mexico Bureau of Mines and Mineral Resources database estimated resource is 21 million st.

The Cerrillos coal beds are moderate-ash, moderate-sulfur coals that have an apparent rank of high-volatile B to A bituminous. Some of the coal reaches the anthracite rank. The weighted-average analyses (as-received) for the Cerrillos field are:

	Average	Std. dev.	No. of samples
Moisture (%)	3.30	1.93	15
Ash (%)	11.69	7.73	15
Volatile matter (%)	23.33	11.19	13
Fixed carbon (%)	60.57	13.40	13
Sulfur (%)	1.14	0.45	12
Calorific value (Btu/lb)	12,559	882	15
Lbs of sulfur/MMBtu	0.95	0.42	11

The Miller Gulch bed was mined from the late 1880s to early 1890s before the railroad spur was completed to Madrid. Upon completion of the spur several mines produced from the White Ash bed north and south of Madrid from 1882 to 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. One of the largest mines in this bed, the Cook and White, opened in 1889 and continued to produce until 1906. An explosion caused by methane gas led to the closure of this mine. The Ortiz Arroyo or 'B' bed overlies the Madrid sill on the east side of Miller Gulch. The sill's irregular surface caused the variable thickness of the Ortiz Arroyo coal bed. 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 st of bituminous and anthracite coal. From 1888 to 1957 as much as 45,000 st of anthracite was mined annually from the Cerrillos field and shipped to users throughout the central and western parts of the nation.

Hagan field

The Hagan field is northeast of Albuquerque, 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. Campbell (1907) called this coal area the Una Del Gato field for a settlement south of Hagan, 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 that 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 ft to 5 ft thick crop out in the Menefee Formation (Black, 1979) within this Mesaverde section. The coal-bearing Menefee dips 25°–35° east–northeast 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 3.5 million st of low-ash, low-sulfur coal. The average of 10 as-received analyses follows:

	Average	Std. dev.	No. of samples
Moisture (%)	10.56	2.14	10
Ash (%)	8.26	2.42	10
Volatile matter (%)	37.95	3.86	10
Fixed carbon (%)	43.23	3.08	10
Total sulfur (%)	0.66	0.13	10
Calorific value (Btu/lb)	10,508	1,477	8
Lbs of sulfur/MMBtu	0.62	0.10	8

Several small underground mines opened near Hagan in 1902, and another group of small mines operated from 1927 to 1939 near Hagan (New Mexico Territorial Mine Inspector, 1902–1911; New Mexico State Mine Inspector, 1912–1940). In 1904, a few small mines were opened near Coyote (T14N R6E) 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. Mesaverde coal-bearing rocks crop out in a small down-dropped fault block, the Tijeras graben, in a 1 mi² area (Kelley and Northrop, 1975). The strata are folded by two synclines and the intervening anticline, creating steep dips. 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 (New Mexico Territorial Mine Inspector, 1882–1911). Read et al. (1950) estimated resources of 1.6 million st for the Tijeras field, although these resources were calculated from coals less than 2.33 ft thick.

Sierra Blanca field

Coal-bearing strata in the Sierra Blanca field along the northeast margin of the Tularosa Basin crop out near Capitan, Fort Stanton, White Oaks, Three Rivers, and Carrizozo in Lincoln County. These outcrops form a broken semicircle on the west, north, and east sides of Sierra Blanca. The Sierra Blanca field is part of a 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 intruded by numerous dikes and sills of the Sierra Blanca igneous complex. Good exposure of the complete Cretaceous section is lacking, making it difficult to map individual units; however, the Cretaceous section is thought to include the Rio Salado Tongue of the Mancos Shale, Tres Hermanos Formation, D-Cross Tongue of the Mancos Shale, the Gallup Sandstone, and the Crevasse Canyon Formation (see Fig. 3, stratigraphic correlation). Not much of the coal can be surface mined because of dips greater than 5° and excessive overburden. The average coal thickness is 4 ft, and estimated resources within 200 ft of the surface are 14 million st.

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. An unusually large number of sandstone "rolls," lenses of sandstone that replace parts of the seams, particularly in the Capitan area, make mining expensive and prohibitive. The averages of 15 as-received weighted-average analyses for this field are:

	Average	Std. dev.	No. of samples
Moisture (%)	5.53	4.51	15
Ash (%)	13.51	5.32	14
Volatile matter (%)	31.46	7.91	14
Fixed carbon (%)	47.24	5.94	14
Sulfur (%)	0.75	0.16	15
Calorific value (Btu/lb)	11,174	1,787	15
Lbs of sulfur/MMBtu	0.68	0.13	12

The earliest mines in the Sierra Blanca field opened in the 1880s near White Oaks northeast of Carrizozo. The Old Abe coal mine, which opened in 1898 and continued to operate until 1927, 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.

Coal mining in the Capitan area also started in the 1880s when the army opened a mine to meet the needs of nearby Fort Stanton, near Ruidoso. 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. The New Mexico Fuel Company opened coal mines in this area and shipped coal to smelters in Arizona from 1899 to 1905. During this time, the EP&NE railroad extended its line to Santa Rosa with a spur to Dawson, southwest of the town of Raton, 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 mined on a small scale into the 1930s for domestic use. 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. Coal leases here, until recently, were held by Peabody Holding Company, a subsidiary of Hanson, PLC.

Carthage field

The Carthage coal field in east-central Socorro County is on the northwest edge of the Jornada del Muerto, an extensive syncline–graben. Two coal seams, ranging from 4 ft to 7 ft thick, are in the lower part of the Mesaverde Group, which is probably equivalent to the Crevasse Canyon Formation (Hook et al., 1983). Only the lower Carthage seam has been mined; it is excellent coking coal of high-volatile C bituminous apparent rank. The Tres Hermanos Formation crops out in this field, but the coals within this unit rarely exceed 2 ft in thickness (Osburn, 1983).

Most of the easily mined coal has been removed; resources may be as much as 30 million st. The averages of eight weighted-average analyses on an as-received basis are:

	Average	Std. dev.	No. of samples
Moisture (%)	3.58	1.54	8
Ash (%)	10.86	3.33	8
Volatile matter (%)	36.53	3.05	8
Fixed carbon (%)	49.04	3.29	8
Sulfur (%)	0.84	0.18	8
Calorific value (Btu/lb)	12,531	695	7
Lbs of sulfur/MMBtu	0.67	0.13	7

The Carthage field is approximately 10 mi² and faulted into a mosaic of small blocks that make mining difficult and expensive. Nonetheless U.S. Army troops stationed at nearby Fort Craig began mining in the field in 1861, supplying coal for smithing to Forts Seldon, Bayard, and Stanton (Sherman and Sherman, 1977). This was the earliest recorded "large-scale" mining in New Mexico. In the late 1800s and early 1900s, the Carthage field supplied coking coal to many smelters in southwestern New Mexico and northern Mexico. Between 1950 and 1975 only a single small underground mine operated intermittently, providing coal for local heating, such as to the public schools in Socorro (F. Kottlowski, pers. comm. 1993).

Jornada del Muerto field

From 5 mi to 25 mi east and northeast of the Carthage field, Mesaverde Group coal-bearing rocks underlie the northwest edge of Jornada del Muerto. The coal-bearing unit here is equivalent to the Dilco Coal Member of the Crevasse Canyon Formation (Tabet, 1979). Windblown sands conceal much of the bedrock, and the area is remote. The few outcrops of coal are similar to that mined in the Carthage field, but maximum coal thickness is only 3 ft. Drilling could delineate considerable resources, because the Cretaceous strata extends for at least 10 mi in a narrow southeast–northwest band, but steep dips and faulting may make mining difficult.

Two analyses available (U.S. Bureau of Mines, unpubl. data 1943) for the Jornada del Muerto field average on an as-received basis:

Moisture (%)	2.7
Ash (%)	8.3
Volatile matter (%)	42.6
Fixed carbon (%)	46.5
Sulfur (%)	0.8
Calorific value (Btu/lb)	13,140

Two small mines operated in the past in the Jornada field. One of these, the Law mine, produced from a 4-ft-thick coal bed (Tabet, 1979). This mine closed in 1927 because of the displacement of the coal bed by faulting.

Engle field

The Engle area is approximately 50 mi south of the Carthage field. 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 in the Mesaverde Group, but the apparent maximum thickness of the coal seams is 4 ft. Sparse drilling indicates 0.5 million st of estimated resources from 0 to 200 ft below the surface. Deep coal resource estimates (200–1,000 ft deep) are 8.5 million st. The results of one as-received analysis for the Engle field are:

Moisture (%)	12.0
Ash (%)	20.1
Volatile matter (%)	24.4
Fixed carbon (%)	43.5
Sulfur (%)	0.4
Calorific value (Btu/lb)	7,665

Kelley and Silver (1952) described a mine in sec. 12 T14S R4W in a 15-inch seam. Tabet (unpubl. rept. ca 1979) felt this mine was probably the same one mentioned in the Territorial Mine Inspectors report of 1909 that was 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.

Other coal deposits

Pennsylvanian coal beds and laminae in north-central New Mexico are mainly in the Sandia Formation of the Magdalena Group, although some coals are in younger Pennsylvanian units. Thicker beds (≥ 4 ft) are impure, lenticular, and cut out in many place by channels filled by pebbly sandstone (F. Kottlowski, written comm. 1993). Pennsylvanian-age coal was mined for local use along the Pecos River, northwest of Las Vegas, and in northeast Santa Fe (Kottlowski, 1963) but lacks commercial importance.

Cretaceous-age coal in Doña Ana County, northeast of Las Cruces near Love Ranch, is mentioned in the literature. This coal appears to be in a sequence equivalent to the Gallup Sandstone (Seager, 1981, pp. 33–34; Kottlowski et al., 1956, pp. 63, 66–68) and was mined in the late 1860s for use at Fort Seldon (Kottlowski and Beaumont, 1965). The thin Cretaceous coal lenses (< 2.5 ft thick) in northeast Union County are within the Dakota Sandstone. These coal beds have been mined for domestic use but have no present economic value (Baldwin and Muehlberger, 1959).

Summary

New Mexico coal is low sulfur, low to high ash, and subbituminous to bituminous in rank; less common are deposits of anthracite coal, particularly in the Cerrillos field. Major coal-bearing sequences in the state were deposited during the Late Cretaceous and early Tertiary. Most of the coal areas are relatively flat lying except along the edges of the San Juan and Raton Basins and in the smaller coal fields that have been influenced by major regional faulting or by igneous intrusions, particularly those fields in the Rio Grande rift. Most of the coal produced today is used for steam generation, although significant deposits of coking coal exist in the Raton Basin and have been used in metallurgical processes in the past. Deep coals in both the Raton and San Juan Basins contain significant amounts of coalbed methane. Extensive exploration and development drilling of these resources began in the late 1980s, particularly in the San Juan Basin.

Estimated remaining resources (estimated indicates the quantities of resources are known imprecisely [Wood et al., 1983]) from the surface to 1,000 ft total 40 billion st of coal, of which 10 billion st are surface minable. Table 1 gives a breakdown by field, and in some cases by formation, of the resources available. This table is a compilation of data from resources calculated by Read et al. (1950), Shomaker and Whyte (1977), Landis and Dane (1969), and as determined from the NMBMMR computerized coal database funded in part by a grant from the U.S. Geological Survey for data entry into the National Coal Data System and a Department of Energy, Energy Information Administration Coal Demonstrated Reserve Base project (Hoffman, 1994). The figures in Table 1 differ from those in the field descriptions in this text because different parameters were used to calculate demonstrated resources. In Table 1 a minimum thickness of 2 ft was used for all the coal areas, and the surface category is 0–250 ft instead of 0–200 ft. The figures in the text are calculated from point-source data, unless otherwise referenced. The figures in Table 1 are a compilation of 58 resource estimates from several sources, and the depth and thickness parameters were dictated by what was available in these references.

TABLE 1—Estimated remaining coal resources in New Mexico (millions of short tons). Measured and indicated resources combined; based on coal greater than 2 ft thick. Surface resources, 0–250 ft; deep resources, 250–1,000 ft

Coal area	Surface resources	Deep resources	Combined	Total
San Juan Basin				
Fruitland Fm.	4,738[1]	23,768[2]		28,506
Menefee Fm.	2,144[1]	2,630[2]		4,774
Crevasse Canyon Fm.	2,372[1]	1,583[1]		3,955
Gallup Sandstone	97[1]	49[1]		146
Raton Basin (NM)			1,484[3]	1,484
Tierra Amarilla			1[5]	1
Cerrillos	23[1]			23
Hagan			4[4]	4
Datil Mountains	73[1]	39[1]		112
Salt Lake	411[1]	60[1]		471
Jornada and **Carthage**			28[4]	28
Sierra Blanca	22[1]	41[1]		63
Engle	9[1]	15[1]		24
Total	9,889	28,185	1,517	39,591

[1] Data from New Mexico Bureau of Mines coal database

[2] Shomaker and Whyte, 1977; numbers are from Shomaker and Whyte minus Hoffman 1994 figures in 0–250 ft depth column

[3] Pillmore, 1991

[4] Read et al., 1950

[5] Landis and Dane, 1969

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