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Strippable Low-Sulfur Coal Resources of the San Juan Basin in New Mexico and Colorado

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Summary

This study was conducted for the Air Pollution Control Office of the Environmental Protection Agency (formerly the National Air Pollution Control Administration of the U.S. Department of Health, Education, and Welfare) to determine the amount, location, quality, and economic position of low-sulfur strippable coal in the San Juan Basin. The purpose is to permit nationwide energy-resource planning to include the San Juan coal, and to allow evaluation of it in terms of sulfur-oxide air pollution. The investigation was done by the New Mexico State Bureau of Mines and Mineral Resources under a federal grant matched I to 3 by the Bureau. In addition, much required analytical work was furnished by the U.S. Bureau of Mines.

The report is a compendium of short, more or less self-contained papers dealing with the various coal fields and areas (fig. 8), and with other pertinent subjects.

For the purposes of the study, coal reserves were estimated in two broad categories—those consisting of beds three feet thick or thicker beneath I o to 150 feet of overburden, and those in beds five or more feet thick beneath 150 to 25o feet of overburden. Data were gathered from all available sources, and include published geologic work, original geologic observation, private consultants' reports, logs of test holes drilled by holders of leases and exploration permits, logs of holes drilled by the New Mexico State Bureau of Mines and Mineral Resources, reserve calculations furnished by operators, and information from oil and gas tests. The best use was made of whatever data could be found for a particular area; therefore reserve estimates range in reliability from proven tonnages to speculation based on geologic inferences. An effort was made to give an evaluation of the reliability of each estimate.

Coal quality was determined from published and unpublished analyses by the U.S. Bureau of Mines, analyses furnished by operators, and U.S. Bureau of Mines analyses of samples collected during the study.

The San Juan Basin is a major physiographic subdivision of the Colorado Plateau in northwestern New Mexico and southwestern Colorado. The basin is about 200 miles long (north to south) and 130 miles wide, and includes about 26,000 square miles. The strippable coal areas lie along the basin margins—mainly the western and southern—in roughly concentric belts of outcrop of coal-bearing strata of Cretaceous age. The areas that contain strippable coal are, in general, rolling, sparsely grassed plains interrupted by low cuestas and mesas, and broad sandy washes.

Coal is found in three major zones of the Cretaceous sequence. In ascending order, they are: the Dakota Sandstone, the Mesaverde Group (which includes several coal-bearing formations), and the Fruitland Formation; the three are separated by barren strata of greatly varying thickness.

The Dakota Sandstone was studied only in the Cortez area (fig. 9); the coals were found to be of good quality (11,580 to 13,650 Btu per pound and 0.5 to 0.7 percent sulfur), but very irregularly distributed. A reserve of 13.1 million tons was estimated with some assurance to be present in the I o- to 150-foot category, and an additional 144.7 million tons was inferred for the remainder of the area to 250 feet. The overburden was found to be largely hard sandstone. Rail transportation is available no closer than 120 miles to the east or north over mountainous country.

Within the Mesaverde Group, coal is found in the Menefee Formation, in the Gibson and Dilco Members of the Crevasse Canyon Formation, and in the Gallup Sandstone. In the Hogback field and in the Barker Creek, Mesa Verde, Durango, and Pagosa Springs areas, the Menefee contains coals of strippable thickness but almost everywhere overburden is excessively thick. In the eastern part of the Durango area and in the Hogback field and the Pagosa Springs area, steep dips place the coal too deep within short distances from the outcrops; in the remainder, thick overlying sandstone beds preclude stripping.

The upper part of the Menefee was examined in the Newcomb, Chaco Canyon, Chacra Mesa, and La Ventana areas, and strippable reserves in rather lenticular beds were found in this part of the unit in the Newcomb and Chaco Canyon areas. The total estimated reserve is 115.8 million tons, of which all but 6.3 million lie beneath less than 15o feet of overburden. The coal is of subbituminous A or B rank, with sulfur content generally less than I.o percent. Overburden consists principally of thin sandstone and shale beds.

The Cleary Member, the lowest subdivision of the Menefee, contains coal in the Toadlena, Standing Rock, San Mateo, and La Ventana areas, and all but the Toadlena area contain significant reserves. The total estimated for all these areas is 174.7 million tons. Of the total, about 138.5 million lie in the Standing Rock area, slightly less than half being beneath less than 150 feet of overburden. The preliminary exploration upon which the estimates for the Standing Rock area are based seems to indicate the potential for a much larger quantity of coal. Heating value, as received for the area, ranged from 8,870 to 10310 Btu per pound; sulfur content was less than 1.0 percent in all samples analyzed.

The Gibson and Dilco Members of the Crevasse Canyon Formation were examined, where present, in the Gallup field and in the Crownpoint, South Mount Taylor, East Mount Taylor, Zuni, and Rio Puerco areas. Both units contain beds of minable thickness in the Gallup field and Crownpoint area, and the Gibson contains them in the Mount Taylor areas and the Rio Puerco area but, except for a major reserve in the Gallup field (in which the Gibson and the Cleary Member of the Menefee Formation are merged), thick overburden prohibits stripping on more than a minor scale. The Gallup field contains some 295 million tons of coal strippable at less than 150 feet of overburden, and an additional 201 million tons estimated to be present beneath 150 to 25o feet. The irregularity of the beds presents some mining problems, but the sandstone-shale overburden is not particularly difficult to strip mine.

The coals are generally of high-volatile bituminous C rank, with sulfur content commonly o.6 percent or less for the Gibson coal of the Gallup field.

The major strippable reserve in the Gallup field is currently being developed by the Pittsburg and Midway Coal Mining Co., and is served by a branch of the Atchison, Topeka, and Santa Fe Railway.

Coal beds assigned simply to the Mesaverde Group, where further subdivision is impractical or uncertain, were considered in the Monero and Tierra Amarilla fields. Although no reserves were estimated for the Monero field, principally because of steep dips and faulting in the area in which coal is known, the topographic and geologic conditions that prevail over most of the remainder of the field favor occurrence of strippable coal. Excessive overburden precludes strippable coal in the Tierra Amarilla field.

The Gallup Sandstone bears coal in the Zuni and Crownpoint areas, and in the Gallup field, but only in the Zuni area is the coal strippable. Though the beds are rather thin and highly lenticular, and overburden is massive sandstone in some areas, a reserve of 6.2 million tons was estimated.

The Fruitland Formation was examined in the Pagosa Springs area, and in the Durango, Red Mesa, Fruitland, Navajo, Bisti, and Star Lake fields and areas. Coal found in the Pagosa Springs and Durango areas was not strippable in significant quantities because of steep dips; all of the others contain important strippable coal—a total of some 2,463 million tons in the shallower category and perhaps 2,628 million tons in the deeper category. Of the total, roughly half lies in the Navajo field. Exploration is at an advanced stage in the Fruitland area and Navajo field, and mining has begun in the northern end of the Navajo field. The Bisti and Star Lake areas are not so well explored and no development has begun.

The Fruitland coals yield 8,500 to 10,500 Btu per pound, in general, and contain up to 35 percent ash as received. Sulfur content is generally less than 0.7 percent.

Overburden in all of the Fruitland areas consists of alternating irregular beds of fine-grained sandstone and soft shale, and presents no particular mining problem.

The Navajo mine of Utah Construction and Mining Co. is developed at the northern end of the Navajo field; in 1970 it was the largest coal mine in the United States with production of slightly over six million tons. A second mine, to be operated by Western Coal Co., will be opened during 1972 in the southern end of the Fruitland area.

Transportation of coal from any of the rich Fruitland Formation areas near the central part of the San Juan Basin would involve no less than a 60-mile haul to the nearest railroad. The Cleary Member coals along the southern rim of the basin are much closer to the railroad.

The economic feasibility of use of the San Juan Basin coals is an enormously complex matter, hinging upon such variables as energy requirements, distance and transportation costs, mining and reclamation costs, availability and associated costs of other coal supplies and of natural gas, oil, and nuclear fuel supplies, and capital costs of the various alternative plants in which fuels are to be used. Potential uses that have been considered for the San Juan Basin coals are minemouth electric-power generation, shipment out of the Basin by rail or pipeline (principally for power generation), and conversion at minemouth to synthetic hydrocarbons through liquefaction or gasification; in all of these uses, the coal must compete with other fossil fuels and with nuclear power.

The demand for energy, particularly in the form of electricity, is increasing at about five percent annually in the U.S.—somewhat more rapidly than the increase in population. Coal supplied about 20.6 percent of the total demand in 1969, and about 65 percent of the energy required in generating electricity.

The competitive relationship of coal and oil is the least important, because oil is used principally in transportation. Natural gas and coal, however, compete in much the same markets, and in 1970 the San Juan Basin producer price for gas was about $0.135 per million Btu compared with a price of $0.14 to $0.16 for San Juan Basin coal. Comparable costs for nuclear fuel were about $0.20 per million Btu, and capital costs for utilization are far higher than for coal.

The construction of a 273-mile coal pipeline from Black Mesa Basin in northeastern Arizona to Bullhead City, Nevada, and planned construction of a railroad from Black Mesa to Page, Arizona, demonstrate the feasibility of this sort of investment in transportation facilities to serve electric generating plants.

The existence of an uncommitted 35,000 to 40,00o acre-foot water supply in the Navajo Reservoir enhances the value of the San Juan coal for both minemouth (or nearly so) power generation, and for gasification. A 240-million cubic-foot-per-day gasification plant (using the Hygas process) would require a supporting reserve of only 20 to 145 million tons of coal, and could readily be located on the existing natural gas pipeline system and thus serve the southern California market.

Increasing costs of underground mining and more stringent pollution control regulations, along with growing industrial demand, may make low-sulfur San Juan Basin coals attractive in the Midwestern market area.

There is little doubt of coal's future importance as a fuel resource, and the San Juan Basin coals in particular represent a strongly competitive energy source for continued growth of the western United States.

Introduction

The San Juan Basin, for purposes of this report, is considered to be the region bounded by outcrops of the Dakota Sandstone and underlain by Dakota and younger strata in northwest New Mexico and southwest Colorado (fig. 1). In this general basinal area, the Dakota Sandstone forms cuestas facing outward from the basin, and dipping inward toward its center.

Including the Cortez area Dakota outcrops, the Tierra Amarilla coal field, the Rio Puerco Mesaverde outcrop area, and the Gallup subbasin to the southwest, all of which lie outside of the structurally defined San Juan Basin, the region consists of about 26,00o square miles. Its dimensions are approximately 200 miles north-south and about 13o miles east-west. In the north-central area, the Cretaceous coals are too deep to be strippable, but in broad areas along the west, southwest, and south sides of the basin, large regions are underlain by strippable coal. On the east side the coals dip too steeply in most areas to allow strip mining.

TOPOGRAPHY

The San Juan Basin is topographically a basin in only a comparative sense, in that its mesas, rolling plains, badlands, and sharp canyons are lower than surrounding mountain ranges. The lowest altitudes are along the San Juan River between Farmington and Shiprock, with the 5,000-foot contour crossing the river at about the Hogback, eight miles east of Shiprock. The area along the lower reaches of Chaco River, approximately outlined by the Navajo Fruitland field (fig. 2), is at about 5,500 feet above sea level. Elevations rise in all directions from this Shiprock-Navajo field area. Cuba, on the east side of the basin, is at an altitude of 6,910 feet above sea level, La Ventana at 6,52o feet, Monero at 7,325 feet, and Tierra Amarilla at 7,525 feet altitude.

On the north, Durango, in the valley of the Animas River (which feeds into the San Juan River at Farmington), is at an altitude of 6,505 feet, Pagosa Springs, on the San Juan River, is at 7,110 feet, and Cortez (actually outside of the San Juan Basin proper) is at 6,200 feet above sea level. Along the west side of the basin, Newcomb is at an altitude of 5,56o feet, being only 9 miles west of the Chaco River. On the south, Crownpoint is at an altitude of 6,97o feet and San Mateo is at 7,300 feet; Grants is south of the San Juan Basin in the valley of Rio San Jose at an altitude of 6,45o feet.

Gallup lies in the Gallup-Zuni Basin, a physiographic division of the San Juan Basin that extends southward from the southwest corner of the main structural basin; the city is at an altitude of 6,500 feet, lying along the westward-draining Rio Puerco. Zuni, farther to the south along the westward-draining Zuni River, is at an altitude of 6,400 feet. The Zuni Mountains southeast of Gallup rise to 9,256 feet altitude in Mount Sedgwick. Mount Taylor, on the south side of the San Juan Basin, is an ancient volcano rising to 11,389 feet above sea level. It stands above the surrounding San Mateo Mountains and the northeastward-projecting Cebolleta Mesa which lie between 8,000 and 8,500 feet. Some of the higher mesas on the southwest side of the San Juan Basin are about 8,000 feet in altitude; Hosta Butte in the southern part of the Crownpoint Crevasse Canyon area is 8,62o feet above sea level. These mesas form gently northward-dipping slopes cut on resistant Cretaceous sandstones, and have abrupt southward-facing escarpments carved from the coal-bearing strata and interbedded sandstones.

On the west side of the Toadlena Menefee area, higher peaks of the Chuska Mountains rise from 9,300 to 9,56o feet in altitude. On the northwest, the La Plata Mountains in the Mesa Verde Mesaverde area range from 9,000 to 11,000 feet in altitude with the higher peaks over 13,000 feet. North of Durango are the towering San Juan Mountains with many peaks above 13,000 and 14,000 feet.

On the east side of the basin, Brazos Peak in the Brazos Range, a southeast extension of the San Juan Mountains, rises to 1 1,274 feet southeast of Chama. The Monero and Tierra Amarilla Mesaverde fields are actually in the Chama Basin, a part of the San Juan Basin which is drained to the south by the Rio Chama, a tributary of the Rio Grande. Average altitudes in the Chama Basin are 7,500 to 8,000 feet.

East of Cuba, the San Juan Basin abruptly abuts against San Pedro Mountain, altitude 10,264 feet. The mountainous terrain extends southward in Sierra Nacimiento, with the higher peaks east of La Ventana rising to over 9,500 feet. The Rio Puerco Mesaverde area on the southeast corner of the study region is between 5,50o and 6,000 feet in elevation above sea level.

VEGETATION

Most of the northern, eastern, and southern edges of the San Juan Basin is mesa country dotted with juniper, piñon, or ponderosa pine. Much of the basin proper is rolling sandy grassland, with large areas of badlands virtually devoid of vegetation along the streams. Overgrazing has reduced much of the grasslands to very sparse cover.

DRAINAGE

The northern and northwestern part of the San Juan Basin is drained by the San Juan River and its tributaries, the Animas River through the Durango area, Mancos River in the Mesa Verde area, and McElmo Creek in the Cortez area (fig. 2). Most of the western part of the basin is drained by the Chaco River, also a tributary of the San Juan River. Its headwaters are on the west side of the Continental Divide, about 25 miles west of Cuba and just north of Star Lake; it flows westward through Chaco Canyon National Monument almost to Newcomb, then turns abruptly to flow northward into the San Juan River west of Farmington.

The Continental Divide runs roughly southward from east of Pagosa Springs, crossing over the Monero area and then southward almost to Cuba. Then it trends southwest across Star Lake, Hosta Butte south of Crownpoint, and into the northwestern Zuni Mountains. Running southeast-

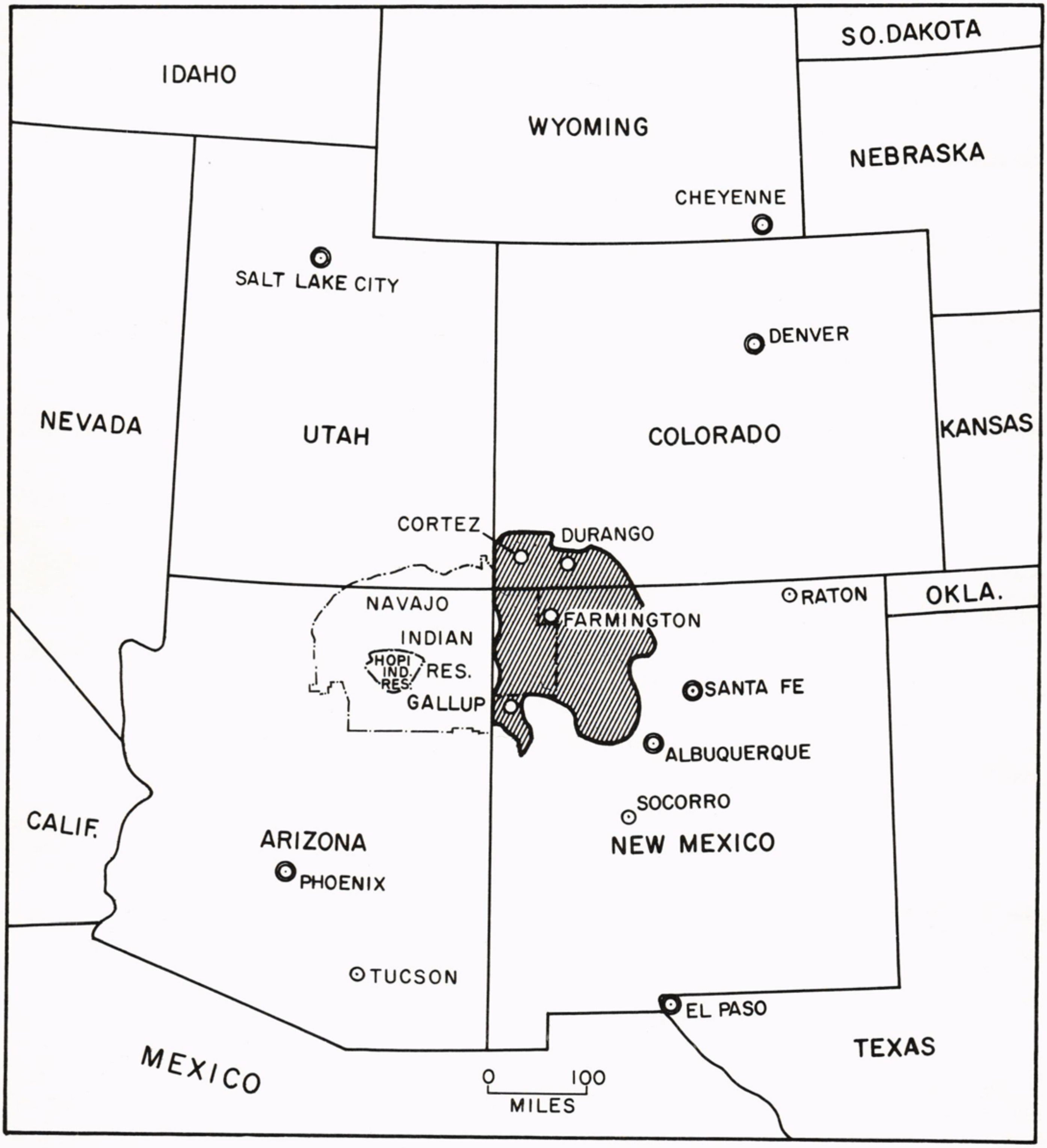

Figure 1

Index map of southwestern United States showing location of San Juan Basin as defined for coal study

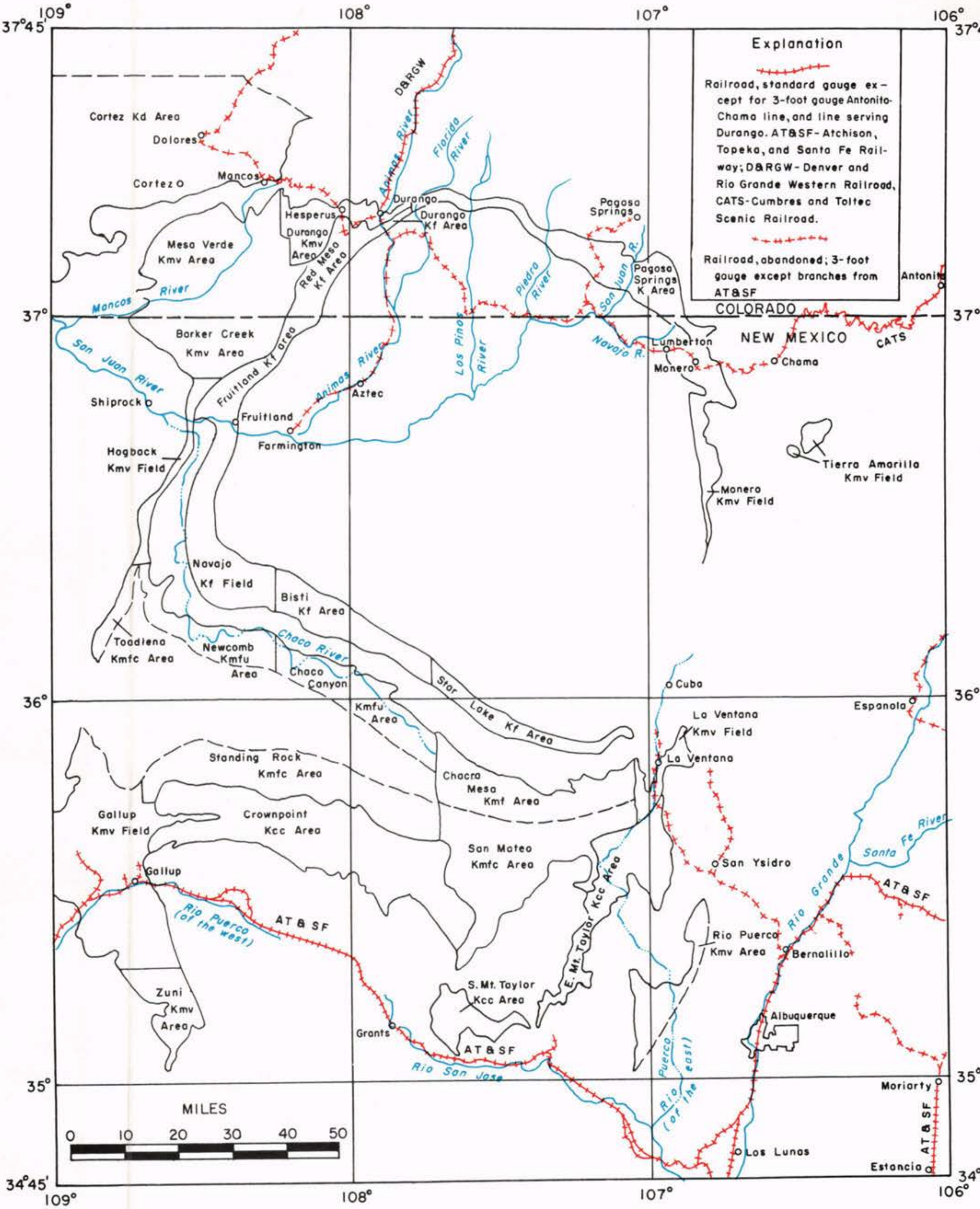

Figure 2

MAP SHOWING RAILROADS, ABANDONED RAILROADS, AND MAJOR STREAMS IN AND NEAR THE SAN JUAN BASIN, NEW MEXICO AND COLORADO ward along the crest of the Zuni Mountains, the Continental Divide turns southward from the Zuni Mountains' southeast end to wander in a general southward direction into western New Mexico.

Rio Chama and its tributaries drain the Chama subbasin. Rising north of Cuba on San Pedro Mountain, Rio Puerco (of the east) drains the southeastern part of the San Juan Basin, with its westernmost tributaries reaching into the eastern part of the Standing Rock and Crownpoint coal areas. Rio Puerco (of the west) drains the Gallup field, and the Zuni River flows through the Zuni area. Both join the Little Colorado River in northeastern Arizona.

CLIMATE

Much of the San Juan Basin is an arid country with annual precipitation less than io inches. However, the eastern and southern mesas do receive 12 to 16 inches, as do the Chuska and Zuni Mountains. The Mount Taylor area, San Pedro Mountain, and the Chama area have more than 20 inches of annual precipitation. More than half of the arid region's rain is from summer thunderstorms, derived from moisture brought northwestward from the Gulf of Mexico. This precipitation is more effective in the San Juan Basin than it is farther south in New Mexico, owing to lower temperatures and less free-surface evaporation.

Only the San Juan River and its major northern tributaries, McElmo Creek, Mancos River, La Plata River, Animas River, and Rio Los Piños are permanent streams within the San Juan Basin, although the Rio Chama and some of its tributaries in the Chama subbasin flow all year. Short stretches of Rio Puerco (of the east) south of Cuba, Rio San Jose, and Chaco River flow most of the year, but the sandy alluvium along most of their length swallows stream flow except after heavy rains.

Recharge of either surface water or underground water from precipitation in the San Juan Basin and surrounding areas is limited, a factor that will affect water usage for any industrial complex utilizing strippable low-sulfur coal.

The overall climate of the San Juan Basin is moderate in terms of temperature and arid to semiarid with respect to moisture. Skies are clear, sunshine abundant, precipitation light, relative humidity is low, and evaporation over water surfaces is high. Temperatures change greatly from night to day and from winter to summer. The dry, clear air permits both rapid gain and rapid loss of heat. Precipitation is varied according to the seasons, with most of it (except in the higher mountains) as rain in summer, with the winters relatively dry.

The vertical air temperature gradient is about 5° F per i,000 feet, so that average temperatures are greatly affected by elevation. The average temperature at Fruitland, altitude 5,2o feet in the San Juan River valley, for July is 74° F, and for January 3o° F. At Durango, altitude 6,505 feet, the January and July averages are 25° F and 67° F, respectively. At Chama, altitude 7,860 feet, the January and July averages are 21.5° F and 63° F. On the southwest side of the basin at Gallup, altitude 6,500 feet, the January and July average temperatures are 27° F and 70° F, respectively. Thus the basinwide average January temperature is about 26° to 3o° F, and the average July temperatures 70° to 74° F.

In the San Juan Basin, particularly in the Chaco River valley and neighboring areas, the dry exposed topsoil, scanty vegetation, and strong, turbulent winds give rise to much blowing dust and some dust storms during the dry months of late fall, winter, and early spring. Dust devils, vertical vortices of rapidly moving, dust-laden air, are common in the summer. Local sand dune areas have been developed in the basin, particularly on the leeward side of broad, sandy stream bottoms. As the average wind is from the southwest, the dunes are developed in most places to the northeast of sandy areas.

POPULATION

About 150,000 people live in and around the margin of the San Juan Basin, with more than half of that number residing on farms, ranches, and in small villages and towns under 500 population. Farmington is the only city with more than 20,000 population, Durango and Gallup being in the 10,000 to 20,000 class, and Cortez and Grants in the 5,000 to 10,000 class.

Residents of the Navajo, Ute Mountain, Southern Ute, Jicarilla, Zuni, and Laguna Indian Reservations constitute a significant part of the population. While the region is sparsely populated, it offers a sizable reservoir of employees. Many are unskilled to semiskilled, but for the most part they can be trained, particularly for mechanical types of work. For example, more than half of the employees of the Navajo mine and the Four Corners power plant near Fruitland are Navajos, trained by Utah Construction and Mining Co. and by Arizona Public Service Co. to do their skilled tasks.

TRANSPORTATION

The main line of the Atchison, Topeka, and Santa Fe Railway (an Amtrak route) skirts the southern part of the San Juan Basin, from Albuquerque through Grants and Gallup into Arizona and to the West Coast (fig. 2). The narrow-gauge tracks of the Cumbres and Toltec Scenic Railroad, owned jointly by the States of New Mexico and Colorado, run from Chama northeastward to Antonito, and then connect with the standard-gauge Denver and Rio Grande Western line to Alamosa and Walsenburg, Colorado.

Gallup, Farmington, Durango, and Albuquerque are serviced by Frontier Airlines; Continental, Trans-World, and Texas-International Airlines also maintain scheduled flights to Albuquerque. Interstate Highway 4o (fig. 3) provides quick access from Arizona along the southern edge of the basin to Gallup, Grants, and Albuquerque on its way east to Amarillo, Tulsa, and St. Louis. U.S. Highway 16o enters the region from Alamosa, Colorado, and passes through Pagosa Springs, Durango, and Cortez along the northern edge of the region on its way to Moab, Utah. U.S. Highway 55o skirts the northern part of the San Juan Basin from U.S. Highway 5o at Montrose, Colorado, through Durango, Aztec, and Farmington, to Shiprock. U.S. Highway 666 runs along the west side of the basin from Cortez southward

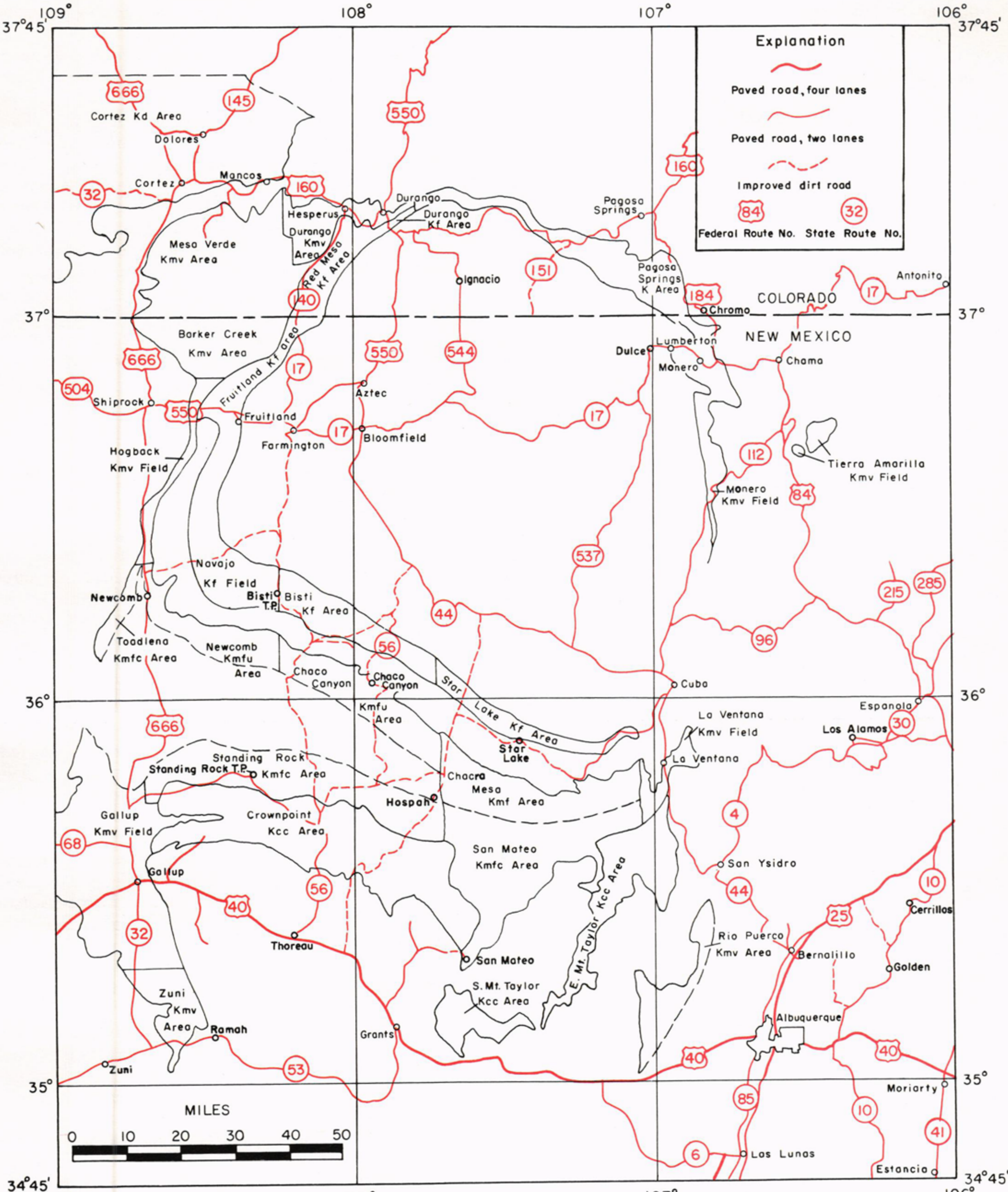

Figure 3
MAP SHOWING PRINCIPAL ROADS AND HIGHWAYS IN AND NEAR SAN JUAN BASIN, NEW MEXICO AND COLORADO

through Shiprock and Newcomb to join Interstate 40 at Gallup. U.S. Highway 84 cuts across the northeastern corner of the region from Pagosa Springs southeastward through Chama and Tierra Amarilla to Santa Fe.

New Mexico Highway 17 runs eastward from Farmington through Monero to Chama, and New Mexico Highway 44 cuts across the San Juan Basin from Aztec to Cuba to join Interstate Highway 25 at Bernalillo, 18 miles north of Albuquerque. Other state roads, some paved, service parts of the basin; most areas are easily reached on fair-weather Indian Reservation, county, and ranch roads.

INDUSTRY

Gas pipelines (fig. 4) of El Paso Natural Gas Co. crisscross the basin, leading westward to the West Coast and southeastward to southeastern New Mexico and west Texas. Oil pipelines and petroleum products pipelines of Texas-New Mexico Pipeline Co., Four Corners Pipeline Co., and El Paso Natural Gas Products Co. transport materials outside the San Juan Basin to the southeast, northwest, and west.

The San Juan Basin gas field (fig. 4) is the second largest producing gas field in the conterminous United States and produces considerable amounts of oil and distillate. Gas production in 1969 was 551 million MCF (MCF = thousands of cubic feet); through 1969 the San Juan Basin had yielded 6.3 billion MCF, mainly from the Upper Cretaceous reservoirs, and 167 million barrels of oil.

Mining of uranium is another large industry of the basin. It is concentrated along the southern edge, with the uranium ore being obtained mainly from the Jurassic sandstones that underlie the coal-bearing Cretaceous strata. Through 1969, the cumulative production of uranium from the southern San Juan Basin was 79,410 tons of U_3O_8, with 36 mines supplying ore to three mills. Exploration of new uranium ore bodies has been vigorously pursued, with seven new deposits found in 1969. Reserves, as of January 1, 1970, were estimated to be 86,000 tons U_3O_8.

Coal mining and production of electricity from coal-fed power plants is the third largest industry in the basin. The McKinley strip mine (northwest of Gallup) of Pittsburg and Midway Coal Mining Co. in 1969 shipped about 44o,- 000 tons of steam coal to the Arizona Public Service Co.'s Cholla power plant at Joseph City in eastern Arizona. The Navajo strip mine of Utah Construction and Mining Co., near Fruitland, produced an estimated six million tons of coal during 197o to supply the immediately adjacent Four Corners power plant operated by Arizona Public Service Co. The Navajo mine is the largest coal mine in the Western Hemisphere, and the Four Corners power plant, with a total capacity of 2,085 megawatts, is the largest generating facility west of the Mississippi River.

Ground has been broken for construction of the San Juan power plant, at Waterflow west of Farmington, to be used jointly by Public Service Co. of New Mexico and Tucson Gas and Electric Co. Total capacity will be 1,035 megawatts; this capacity will require strip mining of 3.4 million tons of coal per year.

Sawmills and small wood-working plants are associated with the higher mesas and the mountain ranges surrounding the San Juan Basin. The various Federal agencies, especially the Bureau of Indian Affairs, and services for tourists provide employment, the latter particularly in areas along Interstate 4o and on the southern flanks of the San Juan Mountains. Most of the industrial shops and plants are small, except for the oil refineries and gas-processing plants. They serve mainly the mining and petroleum industry, provide local services for the cities (such as bottling plants, newspapers, sand-and-gravel pits), and serve the sparse agricultural and ranching population. Three electronic components plants have been built to utilize Indian labor: the Fairchild Semiconductor plant at Shiprock, the Amizuni Corp. plant at Zuni, and the Burnell and Co., Inc. plant at Laguna.

Overall the San Juan Basin is classified as a scenic rural region with major production from the petroleum and mining industries, and with most of the population engaged in ranching, farming, governmental service, and tourist servicing.

BACKGROUND OF THE STUDY

Air pollution of the heavily industrialized regions in eastern and middle United States during the late 1960's has been partly caused by emission of sulfur dioxide from coal-burning plants. As many of the coals in the East and Midwest contain three to ten percent sulfur, burning of this coal requires expensive equipment to retain the sulfur gases, and to prevent their escape into the atmosphere. Dependent upon freight rates, a less costly alternative is to transport low-sulfur coal to the regions where high-sulfur coal has been used. In the late 1960's, therefore, the National Air Pollution Control Administration of the U.S. Department of Health, Education, and Welfare, now the Air Pollution Control Office of the Environmental Protection Agency, began cooperative efforts with other state and federal agencies to evaluate the reserves of low-sulfur coal in the United States, and to estimate the economic factors—which vary greatly from place to place—that would affect usage of low-sulfur coal.

Mining costs to strip-mine coal from large open pits are much less than for almost any type of underground mine. The major usage of low-sulfur steam coal in the western United States at this time must be of the lower cost strippable coal, particularly if the coal is to be transported any distance. In the Southwest region, therefore, the National Air Pollution Control Administration was primarily interested in strippable low-sulfur coal.

After preliminary plans were made in early 1969 by Dr. Albert P. Talboys (then Acting Chief of the Office of Fuel Resources for the National Air Pollution Control Administration) with Beaumont and Kottlowski, the U.S. Department of Health, Education, and Welfare approved a cooperative grant in June 1969 (Grant No. 69A-3401 D) for the New Mexico State Bureau of Mines and Mineral Resources to determine the extent and economics of strippable low-sulfur coal in the San Juan Basin of northwestern New Mexico and southwestern Colorado. The funds granted by the U.S. Department of Health, Education, and Welfare were matched 1 to 3 by the New Mexico State Bureau of Mines and Mineral Resources. The study was given the code name of Project CLEANAIR because of its objectives.

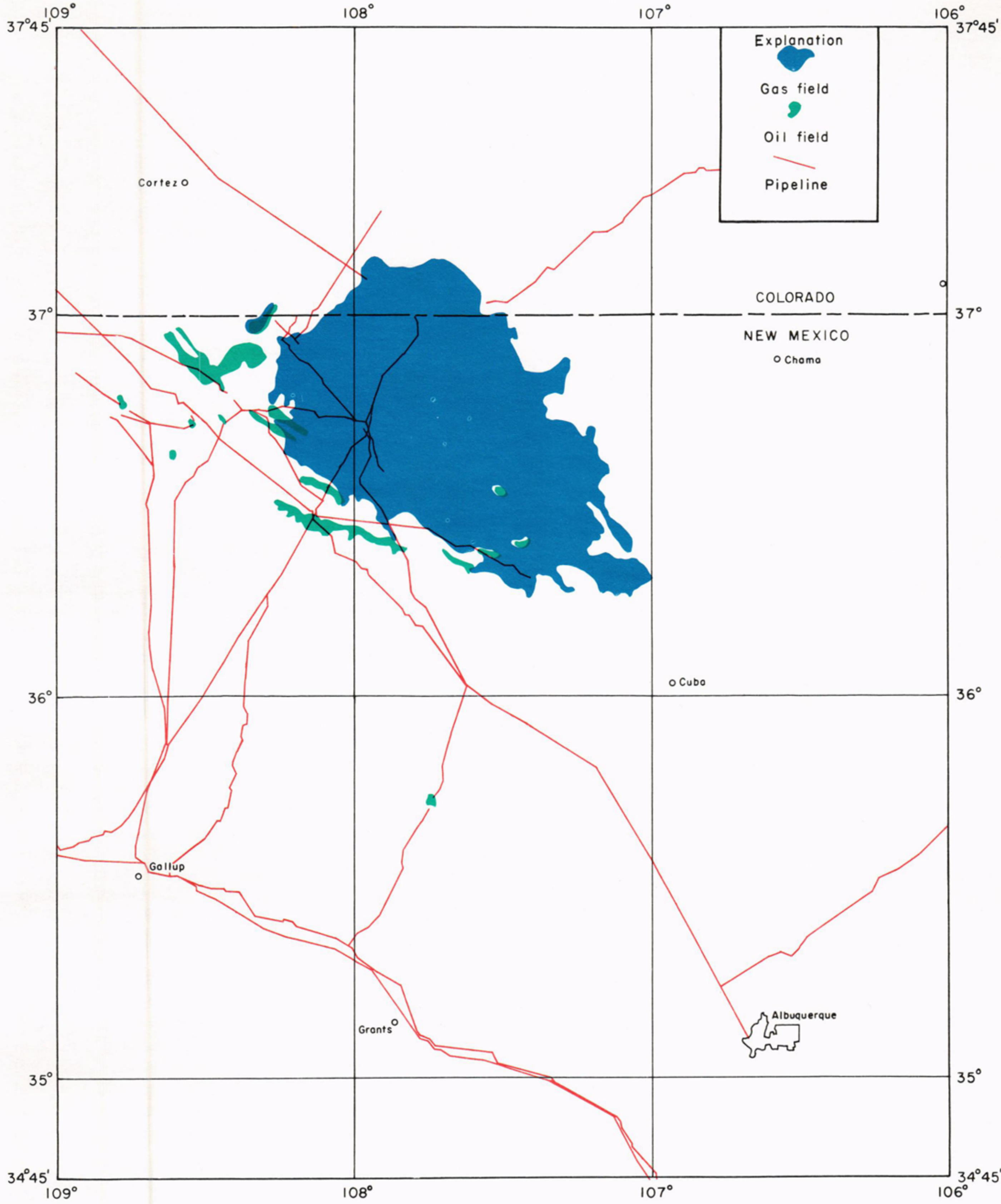

Figure 4
Map showing principal oil fields, gas fields, and pipelines in San Juan Basin

One of the major determinations envisioned was the sulfur content of the San Juan coals. Collection of fresh, usable coal samples was indeed a problem. Eventually, sampling of outcrop coal was abandoned, and only coal cores from exploration drilling by private companies or coal samples from newly cut highwalls of strip mines were sampled for chemical analysis. The sulfur content of the San Juan Basin coals, from our data and from the numerous chemical analyses made by private companies, as well as previous analyses by the U.S. Bureau of Mines, is uniformly low, under one percent for most coals. Therefore, evaluation of the sulfur content was considered a minor objective.

Considerable previous data were available mainly from the coal resources studies of the U.S. Geological Survey. Early reports were by Schrader (1906) on the Durango-Gallup coal field, Taff (1907) on the Durango coal district, Shaler (1907) on the western part of the Durango-Gallup coal field, Gardner (1909a) on the coal field between Gallina and Raton Spring in the eastern San Juan Basin, Gardner (1909b) on the coal field between Durango and Monero, on the coal field between Gallup and San Mateo (Gardner, 909c), Gardner (1910) on the coal field between San Mateo and Cuba, by Collier (1919) on the coal south of Mancos in Montezuma County, Colorado, and by Bauer and Reeside (192I) on coal deposits in the middle and eastern parts of San Juan County, New Mexico.

Relatively detailed work on the coals in the southern part of the San Juan Basin was done by Sears (1925) for the Gallup-Zuni Basin, Sears (1934) for the area eastward from Gallup to Mount Taylor, Dane (1936) for the La Ventana-Chacra Mesa coal field, and Hunt (1936) for the Mount Taylor coal field.

Beginning in the late 1940's and early 1950's, mapping of the coal geology, principally on a quadrangle basis, led to the reports by Zapp (1949) on the Durango area, Beaumont (1954) of the Beautiful Mountain area, Allen and Balk (1954) on the Fort Defiance and Tohatchi quadrangles, Wanek (1954) of the Mesa Verde area, Barnes, Baltz, and Hayes (1954) of the Red Mesa area, Beaumont (1955) of the Ship Rock and Hogback quadrangles, O'Sullivan (1955) on the Naschitti quadrangle, Beaumont and O'Sullivan (1955) of the Kirtland quadrangle, Hayes and Zapp (1955) on the Barker Dome-Fruitland area, Zieglar (1955) of the Toadlena quadrangle, O'Sullivan and Beaumont (1957) on the western San Juan Basin, Hinds (1966) of the Johnson Trading Post quadrangle, Fassett (1966) on the Mesa Portales quadrangle, Doney (1968) of the Cebolla quadrangle, and Landis and Dane (1969) on the Tierra Amarilla coal field.

Coal-drilling data or reserve data were made available by most of the private companies holding leases in the San Juan Basin. Field checking of coal outcrops for Project CLEANAIR was done mainly by Shomaker and Lease, with individual fields and areas by Speer, Beaumont, Kottlowski, Pierce, Nicholson, and Parkhill.

As our field exploration proceeded, and as information was obtained from private companies concerning their drilling exploration for coal reserves, it was realized that while in areas where information was available the reserve estimates could be reasonably accurate, in many areas of the San Juan Basin, data from outcrops, coal drilling, and oil test drilling were too sparse for accurate evaluation, and too few chemical analyses (or fresh samples from which to obtain chemical analyses) were available.

Application was then made to the U.S. Department of Health, Education, and Welfare, with the help and advice of Russell C. Flegal and Robert M. Jimeson of the National Air Pollution Control Administration's Washington, D.C. staff, for supplemental matching funds to drill test holes and core coals in selected localities where the geologic evidence favored presence of thick, low-sulfur, strippable coal deposits. The supplemental funds were granted in May 1970, and the exploratory drilling program was completed in October 1970.

Through cooperative funding by the National Air Pollution Control Administration and the U.S. Bureau of Mines, washability tests and chemical analyses were made of the cored coal obtained during the drilling. Albert W. Deurbrouck, Supervisory Mining Engineer, U.S. Bureau of Mines, directed the washability testing and Forrest E. Walker, U.S. Bureau of Mines Chemist, was in charge of the chemical analytical work.

Overall supervision was by Kottlowski and Beaumont, under the leadership of Don H. Baker, Jr., Bureau director, with field operations mainly directed by Shomaker. Facets of the economic appraisal were by Speer, Beaumont, and Griswold. The coal-coring program was supervised by Shomaker with Lease doing most of the geologic work in cooperation with the drilling contractor, Kenneth Harlan. Parts of the text were edited by all writers involved, but the main responsibility for the technical editing is that of Dr. Stuart A. Northrop, Shomaker, Beaumont, and Kottlowski.

ACKNOWLEDGMENTS

Dr. Albert P. Talboys, in 1969 the Acting Chief of the Office of Fuel Resources, National Air Pollution Control Administration, U.S. Department of Health, Education, and Welfare, encouraged initiation of this cooperative project. His enthusiasm and direct help were greatly appreciated. The prompt cooperation on financial matters by Charles D. Yaffe, former Director, Don R. Goodwin, former Acting Director, and Robert L. Ajax, Chief of the Division of Control Agency Development, National Air Pollution Control Administration, facilitated our operations. Guidance by Russell C. Flegal and Robert M. Jimeson, Physical Science Administrators, Washington office, and T. Kelly Janes from the Cincinnati office of the National Air Pollution Control Administration, aided completion of Project CLEANAIR.

Federal Bureau of Mines personnel cooperated with us in many aspects of the project. Sebastian J. Aresco, Chief, Coal Sampling and Inspection Division, College Park, Maryland office, coordinated our coal sampling program; Albert W. Deurbrouck, Pittsburgh Energy Research Center, was in charge of the washability tests; Forrest E. Walker and Roy F. Abernethy, Pittsburgh Energy Research Center, oversaw the chemical analyses of our coal samples; Ottey M. Bishop, Chief, Denver Office of Mineral Resources, provided us with the U.S. Bureau of Mines' computer program RESERV; this was demonstrated to our computer personnel by Benjamin J. Pollard, Denver office. Joseph Blake Smith, U.S. Bureau of Mines Denver office, aided with advice gained from his reserve calculations studies in the northern Rocky Mountains region.

William E. Hale, District Chief, Water Resources Division Albuquerque office of the U.S. Geological Survey, made available on a sharing basis the drill-hole logging facilities that were so capably utilized by Jim D. Hudson and J. A. Basler for our core-drilling program. Howard B. Nickelson and David R. Stewart, U.S. Geological Survey Conservation Division, allowed us access to some of their coal reserve data. John W. Rold, Director of the Colorado Geological Survey, cooperated with our work in southwestern Colorado.

The enthusiasm, practical competence, and overtime hours of Kenneth Harlan, the contract driller for our coal-coring exploration program, assured its success. This exploration program, resulting in the drilling of 15 coal test holes, was subsidized by the U.S. Department of Health, Education, and Welfare and by the New Mexico State Bureau of Mines and Mineral Resources. The drilling found more coal reserves, on the basis of funds spent for drilling as compared to the value of the coal discovered, than any other program of which we are aware.

Up-to-date and historical information on coal mines was freely given by William H. Hays, New Mexico State Mine Inspector, and Angelo J. Pais, his Deputy Inspector for Coal. William P. Montgomery, writer for the Albuquerque Journal, supplied us with background material from his series of articles on usage of coal in the Four Corners region. Merle E. Hanson, Edd Beach, and Ronald J. Shaffer, New Mexico Tech, programmed and ran our experimental computer programs, and adapted the U.S. Bureau of Mines' program RESERV to the Tech computer, an IBM 360 Model 44. Dr. Howard A. Meyerhoff, Tulsa consulting geologist, edited the economic factors chapter and made pertinent suggestions.

Staff members of the New Mexico State Bureau of Mines and Mineral Resources worked on various aspects of Project CLEANAIR. Robert A. Bieberman, Petroleum Geologist, provided us with oil and gas test data and Dr. Robert H. Weber, Senior Geologist, did the mineralogic studies of sulfur from the San Juan Basin coals. Alex. Nicholson, Geologist-Editor, aided in field checking and preliminary editing before his untimely death. Drafting was by Michael Wooldridge and William E. Arnold.

Geologic Structure and Physiography

Structural elements of the San Juan Basin have been described in several articles by Kelley (1950, 1951, 1955, 1957, and 1967) and an excellent structure contour map was published by Silver (1950) in the New Mexico Geological Society's first guidebook. The major structural features were outlined more than fifty years ago by coal geologists such as Bauer and Reeside (1921), and by Darton (1928), Sears (1925; 1934), Hunt (1936), and Dane (1936).

The San Juan Basin (fig. 5) is the southeastern part of the Colorado Plateau physiographic province and makes up the eastern half of the Navajo section, mainly in northwestern New Mexico but extending into southwestern Colorado. The central plains part of the basin, underlain by almost horizontal strata, and dissected to greater and lesser extents by sandy arroyos, begins at about 36° N. Lat. and reaches northward to Durango, with its eastern boundary the monodines and anticlines extending northward from the Nacimiento uplift, and the western edge at the Hogback and its southward extensions.

The Nacimiento uplift, a thrust block that has moved westward at steep angles over basinal strata, abruptly borders the basin on the east. North of the Nacimiento Mountains and San Pedro Mountain, the monoclines and anticlines along the east margin of the main San Juan Basin are grouped into the Archuleta anticlinorium (Dane, 1948; Muehlberger, 1960), and separate the Chama platform or Chama embayment from the main basin.

The San Juan Mountains, with an uplifted southern core of Precambrian rocks, and the intrusive masses of the La Plata Mountains border the basin on the north, the gently southward-dipping strata of the northern part of the "Central Basin" being upturned in moderate to steep monoclines along the basin's northern border.

The Cortez Dakota coal area of this report is outside and to the northwest of the San Juan Basin in an area of almost horizontal strata between the Paradox basin to the northwest and the Four Corners platform. The Four Corners platform, lying along the northwestern border of the basin, is mainly a monoclinal feature with its strata dipping at moderate angles to the east, southeast, and south, separated from the Central Basin by the sharp monocline of the Hogback.

The Defiance uplift is a pronounced border on the west between the San Juan Basin and the Black Mesa Basin in northeastern Arizona. Tertiary beds of the Chuska Mountains mask, somewhat, the eastward-dipping monoclinal elements of this western side of the basin.

The Gallup-Zuni syncline or Gallup sag extends southward from the southwestern corner of the San Juan Basin, forming a shallow structural trough that extends southward into Catron County. This syncline is squeezed between, on the west, the Defiance uplift and anticlines that extend south-southeastward from the Defiance, and on the east, the northwest-southeast-trending Zuni uplift. Some of the more productive coal beds near Gallup occur in the northern part of the Gallup-Zuni syncline.

The southern margin of the San Juan Basin is the most complex; the almost horizontal strata of the Central Basin dip at slightly higher angles (and thus, locally dip too steeply to allow extensive strip mining) southward along the Chaco slope, which encompasses the area from 36° N. Lat. southward to south of Grants. West of Grants, the Chaco slope abuts against the Zuni uplift, but southeast of Grants, Cretaceous and older rocks are exposed in the Acoma embayment, a subbasin of the San Juan Basin in which the strata dip but a few degrees, the dip direction being mainly northward.

Mainly east of Grants is the junction of the Chaco slope from the west, the Acoma embayment from the south, and the Rio Grande fault belt from the east. In this area, on the southeast flank of the San Juan Basin, are the faults and folds of the uranium-producing Ambrosia Lake district, the Mount Taylor syncline, which is overlain by the Cenozoic lavas of Mount Taylor and Cebolleta Mesa, and the Rio Puerco fault belt. Cretaceous strata in the Rio Puerco fault belt, the Rio Puerco Mesaverde coal area of this report, occur in a series of fault blocks, locally buried by lava flows from some of the numerous basaltic necks and plugs.

The most striking structural features of the San Juan Basin are hogback ridges, called monoclines by Kelley (1951), and caused by steep dips of the strata on the outer, basinward limb of an anticline and the accompanying inner synclinal bend. The Hogback monocline is essentially continuous from the northwest side of the Central Basin, around the north rim, and then southward to the west edge of the Nacimiento uplift. The most spectacular exposures of this hogback are where the San Juan River cuts the Hogback between Shiprock and Farmington, and on the southeast edge of the basin where New Mexico Highway 44 crosses the southern tip of the Nacimiento uplift west of San Ysidro. The Nutria monocline, which borders the west side of the Zuni uplift and the east side of the Gallup-Zuni syncline, is a prominent feature along Interstate 40 just east of Gallup.

The entire Hogback monocline, a horseshoe-shaped figure opening southward, does bring the coal-bearing strata into a belt, one to five miles wide, in which the beds dip too steeply for any appreciable amount of coal to be strip mined. Outside of this belt, the strata dip relatively gently in the Central Basin, with the dips becoming more and more steep outward, especially on the Chaco slope. The center of the "Central Basin" is actually in the geographically northeastern part of the San Juan Basin, centering near Archuleta, New Mexico.

For the most part, the San Juan Basin is a country of sandstone ribs and shale flats, with sand sheets and local sand dunes near the dry washes. As the sedimentary beds dip gently, and have been subjected to long periods of erosion in an arid to semiarid climate, ruled by spring and autumn winds and sparse summer thunderstorms, the tableland mesa, rock terrace, dry arroyo, cuesta, canyon, and erosional escarpment are the distinctive physiographic landscape forms.

Dutton (1885) best described the basin's features and caught its spirit, as follows:

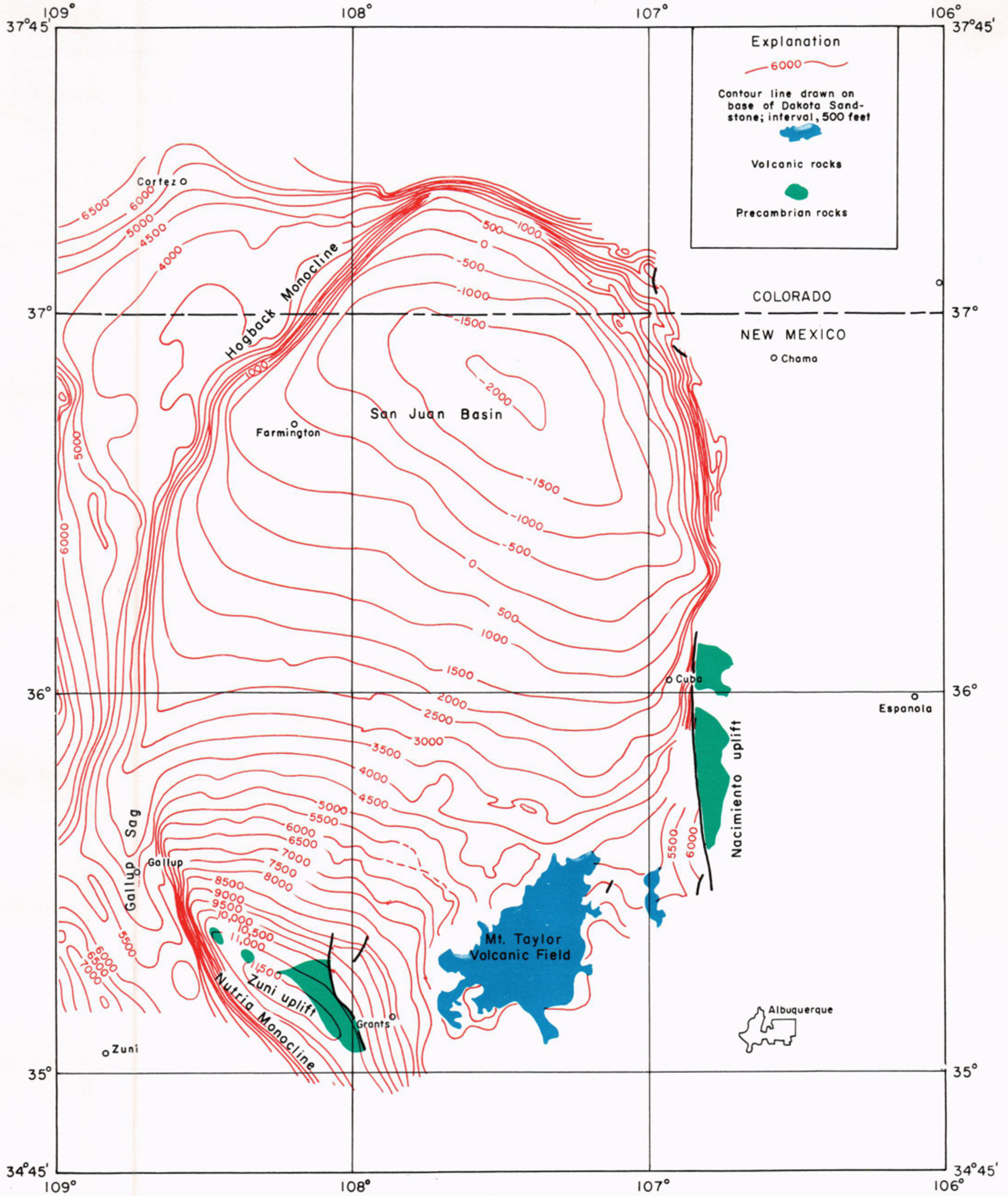

Figure 5
Map showing structure of San Juan Basin. Modified from Silver (1950)

"The wide expanses of featureless plains, . . . the naked strata lined off at their partings, the yellowish or ashy soil, the brilliant sunlight and torrid heat, the blue haze of the atmosphere, like an ethereal veil between us and surrounding objects, all these are the true characteristics of [this part of] the [Colorado] Plateau country . . . a region of little diversity. The land is for the most part flat and monotonous, its smooth surface barely broken by low ledges of sandstone and shale, much too insignificant to be called cliffs and mesas [except locally], nor yet sufficiently scoured by erosion to form badlands [although Bisti is translated as badlands]."

Stratigraphic Distribution of Coal in San Juan Basin

by Edward C. Beaumont

Coal in the San Juan Basin of New Mexico and Colorado occurs through a wide range of stratigraphic units within the Cretaceous System. These sedimentary rocks were deposited near the margin of the widespread Cretaceous epeirogenic sea under conditions characterized by more or less constantly changing shoreline positions. The result is a jagged wedge of nonmarine sediments intertonguing to the northeast with marine sediments.

REGIONAL DEPOSITIONAL SETTING

The vast epeirogenic sea that occupied the central part of the continent through much of the Cretaceous Period spread westward into the present San Juan Basin region essentially during the Late Cretaceous Epoch. A part of the Dakota Sandstone is classified as partly Early Cretaceous in age, but, in effect, this marine invasion is a Late Cretaceous phenomenon. An even older Cretaceous unit of continental origin, the Burro Canyon Formation, is considered to be entirely of Early Cretaceous age.

The initial westward incursion of the sea into the region was by far the most extensive. Marine sediments belonging to the Mancos Shale extend well beyond the limits of the San Juan Basin into central Arizona.

In a general way, the shifting shorelines marginal to this vast continental sea maintained roughly parallel trends throughout most of the Cretaceous. There were many variations in detail, but a predominant trend averaging about N. 55^0 W. can be calculated for most of the major transgressive and regressive phases. Toward the close of the period, as the sea withdrew for the final time, there was a major shift in shoreline as sediments presumably began to be supplied from the north and west.

DEPOSITIONAL ENVIRONMENTS ASSOCIATED WITH COAL

There are sedimentary rocks of both marine and non-marine origin associated with the Cretaceous coal deposits. These strata can be divided broadly into four categories based on the environments in which they originated. Each of the depositional environments has produced sedimentary rocks with particular characteristics, and each is gradational in varying degrees with the adjacent unit.

Under ideal conditions the balance between sediment supply and crustal subsidence would be such that the integrity of each of the depositional facies would be maintained despite a constantly shifting shoreline. To a considerable extent this is true, but apparently there were times during the depositional history when advances and retreats of the sea margin were too rapid for deposition in each of the environmental zones to have kept pace.

The four major environments of deposition associated with the coal are as follows from marine to nonmarine:

(I) Offshore deposits characterized by muds with intercalated streaks and bands of fine-grained sand and silt, zones of calcareous concretions, and thin beds of limestone. This zone corresponds to the neritic zone of earlier usage and the sublittoral zone of more current usage.

(2) Beach and nearshore deposits characterized by moderately clean sand with interbedded bands of mud and silt. This zone essentially corresponds to the littoral zone, and, in the case of beach sands beyond the reach of high tide, the supralittoral zone. Where the shore is protected from wave action, as in an estuary or lagoon, the dominant sediment type may be mud.

(3) Coastal-swamp (paludal) deposits characterized by a predominance of organic-rich muds and silts and variable concentrations of nearly pure organic matter (which was later to become coal). This is the environment nearest the shoreline that can be classified as truly nonmarine although these areas were probably inundated by sea water during storm periods and the water under normal conditions was probably somewhat brackish.

(4) Floodplain deposits characterized by fluvial and lacustrine accumulations. In the Cretaceous of the San Juan Basin, there is commonly a predominance of sandstone several hundred feet stratigraphically removed from the margin of this environment. This provides a basis for dividing this broad zone into low- and high-floodplain zones, the latter being characterized by fluviatile sands and the former, the low-floodplain zone, being typified by mixed fluviatile and lacustrine sediments.

ENVIRONMENTS RESULTING IN THE ACCUMULATION OF COAL

The organic matter that was accumulated, preserved, and subsequently coalified is considered to have been deposited primarily in the paludal (swamp) environment in the lowlands shoreward from the sea margin. There are indications that some coal beds were the result of deposition in a lacustrine environment, but it is likely that the lake was deteriorating into a swamp. It is also likely that concentrations of organic matter accumulated in the lagoonal environment to form significant coal beds, but, again, it is probable that the lagoon had become choked and stagnant and was close to the swamp environment before accumulation and preservation of vegetal matter could be effected. It is generally assumed that the preservation of the original peaty layers could have occurred only under anaerobic conditions.

The optimum environment for coal accumulation would have been that of the swamp with its stagnant toxic bottom, shallow-water, and nearly current-free conditions choked with an abundance of flora. It is assumed that most of the peat accumulated in place (autochthonous) although undoubtedly some fraction of the material was transported varying distances prior to deposition to form allochthonous coal.

INTERRUPTIVE CONDITIONS

The environments favorable to the accumulation of sufficient thickness of vegetal matter to produce coal of economic value parallel the coastline. It is reasonable to expect that these linear trends were interrupted locally by such features as deltas, estuaries, and open lagoons. Streams and rivers carrying sediment to the sea margin had reduced currents as they spread across the nearly flat coastal plain. The load reduction of these waters resulted in the formation of deltaic deposits which would in effect displace the paludal environment with elastic sediments. It is likewise conceivable that estuarine conditions or embayments may have opened directly to the sea both with or without appreciable deltaic deposition.

CONCEPTS OF TRANSGRESSIVE AND REGRESSIVE DEPOSITION

An explanation of the intertonguing marine and nonmarine Cretaceous strata in the San Juan Basin presumes an oscillating shoreline with accompanying migration of the attendant environments of deposition. The principles of transgressive deposition have been recognized for many years. The mechanism for the accumulation and preservation of regressive deposits has been set forth by Sears, Hunt, and Hendricks (1941) in their summary treatise based on the detailed investigation carried out by the U.S. Geological Survey along the southern margin of the San Juan Basin (Sears, 1934; Hunt, 1936; and Dane, 1936).

These definitive investigations of the coal-bearing Mesaverde rocks covering many thousand square miles led to the conclusion that both the transgressive and the regressive deposits were accumulated under subsiding conditions in the geosynclinal trough. It is easy enough to visualize the shoreward spread of the sea margin under conditions of subsidence, but Sears, Hunt, and Hendricks (1941, p. 104) concluded that the regressive movements of the sea were also accomplished during periods of crustal subsidence. They reasoned that the rate of subsidence decreased or perhaps reached a near standstill during regressive phases, and that there were only two variables: (I) the rate of subsidence, and (2) the rate of sediment supply. They cited several arguments favoring constant subsidence, but the one which is the most convincing is expressed in the need for a slight sinking of the older deposits beneath the profile of equilibrium to allow for subsequent undisturbed sedimentation and preservation of the older material. The requirement for regression would simply be an excess of sediment over the rate of subsidence. As the geosynclinal trough was gradually but irregularly downwarped, the shoreline and the four major depositional environments either shifted shoreward or seaward as the case might be.

This writer has observed that in the San Juan Basin the transgressive nearshore and beach facies tend to be lacking in the crossbedded, massive sands that are associated with some typical beach deposits. In many instances the thinner bedded, shale-laminated shallow-water sandy sequences are likely to be in close proximity to the paludal deposits.

Sears, Hunt, and Hendricks (1941) did not see evidence of an upward movement of the trough, but subsequent investigations (Dane, 196o; Bozanic, 1955) indicate that at least one episode of positive crustal movement occurred. Inasmuch as the evidence for this activity is principally in the midst of the offshore shale sequence, and of little direct consequence to the deposition of coal, it will not be discussed in detail.

AGE RANGE OF SIMILAR ROCKS IN THE SAN JUAN BASIN

In broad terms the intertonguing marine and nonmarine strata in the San Juan Basin may be pictured as an irregular wedge of nonmarine rocks on the south penetrating northward into marine strata. With minor exception, the various facies represented in the earlier part of the system are indistinguishable from the strata laid down during the final retreat of the sea. In other words, elements of the Dakota Sandstone are essentially the same as the corresponding facies of the Pictured Cliffs Sandstone. Although the transgressive-regressive reversal following deposition of the Dakota is far beyond the margin of the San Juan Basin, it is safe to say that deposition was essentially continuous and uninterrupted throughout the remainder of Cretaceous time. This is best illustrated or followed in the nearshore and beach deposits, the migrating positions of which mark the shifting shoreline through the accumulation of more than 6,000 feet of sediment.

With only minor exception, the nature of the material being supplied to the coast was similar throughout this period and conditions of sedimentation are presumed to have remained very similar. This led to lithologically similar sequences of strata in the southern part of the San Juan Basin being assigned to the Mesaverde Formation (Sears, **1934; Hunt, 1936;** and Dane, 1936), a stratigraphic unit named much earlier for a lithologically similar sequence in southwestern Colorado (Holmes, 1877, p. 244). Sears, Hunt, and Hendricks (1941, p. 105) realized that the relationships were not direct but emphasized that "the Mancos and Mesaverde are *lithologic* units — formations whose general rock characteristics persist over great areas but whose composition, thickness, boundaries, and age vary considerably from place to place." Actually the age difference is so great that the Point Lookout Sandstone which occurs well up in the "southern" Mesaverde is the homogenetic equivalent of, but still somewhat older than, the basal unit in the Mesaverde Group in southwestern Colorado and northwestern New Mexico.

VARIABLE RATES OF STRAND-LINE SHIFT - STRATIDYNAMICS

Variation in the rate of trough subsidence during the Cretaceous has been discussed, but there is a related effect which had a direct and profound influence on sedimentation. For every change in rate of subsidence it follows that, other conditions being equal, there would be a change in the rate of strand-line shift. A rapidly subsiding sea margin would result in rapid encroachment of the sea upon the land; and, conversely, a near cessation of sinking would result in: (I) a very slowly shifting shoreline, or (2) if conditions were in balance, a static situation resulting in a vertical buildup of facies.

The stratigraphic units under consideration exemplify the effects of both major and minor changes in the direction of movement of the shoreline. Minor reversals such as regressive movement during a major transgressive phase had the gross effect of slowing down the principal shift and resulted in the local and somewhat irregular accumulation of the various depositional bands. Minor intertonguing relationships such as those observed between the Point Lookout Sandstone and the Menefee Formation north of the San Juan River illustrate this point — in contrast to the same formational boundary south of the San Juan River. In the former area, there is a relative abundance of coal in the comparatively thick paludal facies, and the Point Lookout Sandstone, representing the nearshore and beach deposits, is correspondingly thicker than it is for many miles along the outcrop to the south of the San Juan River. A similar but somewhat larger-scale effect is noted south of the San Juan River in the Menefee-Cliff House relationship.

A major directional change in the migration of the shoreline has been observed to have a significant effect on the sedimentary patterns of deposition. Toward the end of major shift, whether it be transgressive or regressive, there was a slowing down in the rate of shoreline migration as whatever forces were necessary to overcome the prevailing conditions were developing to a sufficient level to reverse the trend. This activity was commonly accompanied by minor reversals in movement and the development of inter-tonguing, but the principal effect resulting from the slowdown is the increase in the extent and thickness of the paludal zone and the corresponding increase in coal.

These conditions can be observed in the vicinity of Gallup where two such major directional changes take place. The lowermost of these, the southwestward (landward) merging and subsequent pinchout of the Lower and Upper Dalton Sandstone Members of the Crevasse Canyon Formation, reveals a corresponding increase in coal content of the Dilco Coal Member in the immediate vicinity and shoreward from the pinchout.

Somewhat higher in the section but at about the same geographic position, the transgressive Hosta Tongue of the Point Lookout Sandstone merges with the regressive main body of the Point Lookout and the combined units pinch out southward. While there is some coal in the Gibson Member north and northeast of this pinchout, it is relatively thin and generally noncommercial.

In the vicinity of Gallup, actually somewhat north of the city, there is a band of well-developed coal in the Gibson and the undivided Gibson-Cleary Coal Members. Most of the major mining camps of past years, Allison, Gibson, Heaton, and Gamerco, and the present-day Pittsburg & Midway Coal Mining Co.'s McKinley mine, are located in this zone of maximum development. There is coal of commercial thickness in the Gibson-Cleary on the south side of Gallup, viz., the Sundance mine, but the area is generally beyond that of the maximum development. Abundant coal is present in the Gibson some distance north of the Gallup area both along the western outcrop area and the eastern outcrop band on the north flank of the Zuni uplift. Above the Point Lookout, the Cleary Member thins to the north and the coal content diminishes. The Point Lookout Sandstone, the nearshore and beach-sand deposit, is correspondingly thin and it is thought that through this middle area, to a position several miles south of the San Juan River, the sea was pushed back from the continent with moderate rapidity.

In general, the rate of lateral shoreline shift can probably be directly attributable to the rate of subsidence of the geosyncline, but it is also possible that the rate of shift might have been affected by the rate of sediment supply and perhaps by variations in the slope of the land surface. Exceedingly rapid lateral shoreline shifts, the type that resulted in the virtual elimination of the intermediate facies, as exemplified in the La Ventana-Cliff House relationship on the east side of the San Juan Basin, are found only in transgressive phases.

A striking example of rapid shoreline shift is found in those strata laid down immediately following the deposition of the La Ventana Tongue of the Cliff House Sandstone in the southeastern part of the basin. In this instance the landward strand-line shift was so rapid as to preclude the development of the transitional environments. As discussed in a subsequent section, there is some evidence to suggest a correlation between minor tectonism and the rapid transgression.

A second example is found in the transgression following the Gallup Sandstone regression in which the coaly facies of the Dilco is in places in direct contact with the silty, sandy shale of the Mulatto Tongue of the Mancos Shale. In this transgression the nearshore and beach deposits are represented by the "stray sandstone" (Sears, Hunt, and Hendricks, 1941, p. 13; Pike, 1947, p. 14), a rather nebulous unit that is present only intermittently along the outcrop and the lower part of the Dalton Sandstone. This latter example may not be an entirely valid illustration of the principle of rapid transgression inasmuch as there is some evidence that closely following this transgression, there was an upward movement of the trough which resulted in the erosion of several hundred feet of beds of late Carlile age (Dane, 1960, p. 46) in the central part of the San Juan Basin. The landward manifestation of this unconformity may coincide with the contact between the Dilco and the Mulatto, and the partial absence of the sand facies may be the result of post-depositional erosion rather than nondeposition due to rapid transgression.

ORIENTATION OF COAL BEDS

If it is assumed that the vegetal matter which has resulted in the major coal deposits was deposited in the paludal areas shoreward from and parallel to the strand line, it is reasonable to infer a control of the coal deposits by the strand line. It is reasonable to assume that the lenticular deposits of the paludal environment will have a long axis, and that this direction is most likely to parallel the strand line. It is obviously not a hard and fast rule, but it does suggest that individual coal beds and lenses are likely to have a linear orientation in the northwest-southeast direction so common to the strand-line direction all of the Cretaceous events in the area. From a practical standpoint, this may be an indication of somewhat greater continuity of beds when viewed or traced in the northwest-southeast direction rather than in the direction normal to the strand line. In other words, the most rapid lateral changes are most likely to occur normal to the strand line.

IMBRICATION AND TIME

Inasmuch as the depositional environment conducive to the accumulation and preservation of the peat layers which eventually were coalified was restricted to a relatively narrow band, it follows that discrete lenses and pods of coal have rather definite and restricted limits. The least dimension is likely to be oriented normal to the shoreline or parallel to the direction of movement of the sea margin. Also, it can be demonstrated that as a shoreline either retreated or advanced, the age of the sediments deposited in the paludal zone will be younger in the direction of shoreline movement. In the case of a regressing shoreline in the San Juan Basin, the deposits within a continuing coal zone will be with only minor exception younger to the northeast. A consideration of the depositional conditions in the paludal band would make it seem unlikely that the integrity of the swamp could be totally preserved as the environment shifted.

The effect then is one of a more or less continuous sedimentary zone transgressing time lines with imbricate lenses of coal becoming progressively younger in the direction of shoreline shift. If the discrete coal lenses are in close enough proximity to one another, the aggregate may be considered a single coal bed with partings. If there is sufficient intervening noncoal sediment, the result is a series of disconnected, usually thin beds. Again, the rate of shoreline shift is a significant factor in the resulting nature of the paludal sediments. During rapid shifts the zone and the coal beds will not only be thinner, but the coal will be much more strung out and discontinuous than if there were a slow and gradual lateral change in conditions.

The progressively younger nature of the sediments in general and the coal specifically in the direction of shoreline movement has a practical application in exploration. If, for example, a series of coal beds is encountered in a drill hole and nothing more is known of the distribution of the coal other than its being in either a transgressive or a regressive sequence, it can be deduced that there is a strong possibility that the higher beds will become better developed and the lower beds will tend to lense out in the direction of shoreline shift. Of course this is not an ironclad rule but it can serve as a guide as to what is most likely to be expected in either direction from the point of observation. It might be added, that to explore in a direction most nearly parallel to the shoreline should provide the greatest chances for continuity — the direction of least change.

DIFFERENTIAL COMPACTION

The variable composition of the sedimentary sequences containing coal and the depth of burial of these sediments have in some instances modified the original sedimentary relationships considerably. The coarser elastic deposits are less susceptible to postdepositional compaction than are the very fine clastic and organic deposits; thus variable vertical proportions of different lithic types can produce distortions in the relationships between the various units.

It is generally acknowledged that coal beds are only a fraction of the thickness of the original organic accumulations and while clay and silt partings are presumed to have been compressed in the diagenetic stage, the amount of compaction is minor as compared to that of the coal. Near the margins of coal swamps it is not uncommon to find the gross thickness of a compound coal bed to increase as the individual coal lenses intertongue laterally and are replaced by predominantly clastic sediments.

Although entirely secondary, the effects of differential compaction can be misleading in the interpretation of coal correlations in both outcrop and well-log studies.

STRUCTURAL MODIFICATIONS

Laramide structural activity has profoundly influenced the availability of the coal to development, the type of mining feasible, and to some degree the rank of the coal. There were, however, minor structural patterns contemporaneous with the deposition of the coal that had a primary effect on the distribution of the coal and associated sediments. It is well established that the Zuni and Defiance highlands were positive in some degree from at least Pennsylvanian time on. It is not reasonable to think that these persistently positive land features did not have some character during the Cretaceous, but it is likely that the positive nature of these elements was slight during this period.

There is no evidence that either the Zuni or the Defiance uplift areas contributed significant quantities of sediment; rather, it is likely that the slight positive character of these areas had the effect of deflecting the shoreline around their margins, causing an actual embayment of significance in the vicinity of Gallup (the present structural configuration in that area is known as the "Gallup embayment"), and providing a slight increase in the slope of the land that would locally inhibit transgression and facilitate regression. Other major structural features on the flanks of the San Juan Basin may likewise have had an incipient effect on Cretaceous sedimentation. There is some evidence that during the final retreat of the sea, as the Cretaceous Period was drawing to a close, new sources of sediment supply were developed to the north and west as the sea was forced to withdraw in a more easterly direction — perhaps even to the southeast as the Nacimiento uplift became a factor.

In the vicinity of Newcomb, New Mexico, south of Captain Tom Wash and east of U.S. Highway 666, there is evidence of considerable structural instability manifested in the upper part of the Menefee Formation. These sediments, deposited late in the Cliff House transgression, exhibit numerous irregular attitudes and truncations that have the appearance of massively scaled crossbedding. The effect may have been very local in extent, or it may have reflected crustal instability heralding the events that were to shortly lead to the final withdrawal of the continental sea from the region.

Local structural anomalies are found in the sediments involved in the massive intertonguing between the Menefee Formation and the Cliff House between Newcomb and the San Juan River. In this area the uppermost Menefee is commonly invaded by swarms of sandstone dikes that range from a fraction of an inch to several feet in width. These dikes are oriented either normal or inclined with respect to the bedding and have lengths ranging from a few feet to several hundred feet. Strata, including the coal beds, are not offset on opposite sides of the dikes but the walls of the dikes often exhibit slickensides with the indicated direction of movement being the same on both walls. The apparent direction of movement is always for the dike walls to have been moved up with respect to the sediments. It might be inferred that the dikes were thus injected from below, but the writer prefers to think that the slickensides reflect the effects of differential compaction of the sediments with respect to the dike material. The direction of emplacement of the sand into these fissures is open to question, but it is likely that these features are the result of isostatic imbalance under more or less local deltaic conditions.

STRATIGRAPHIC UNITS AND EVENTS

The Cretaceous strata in the area of study have been the subject of rather extensive investigation ranging from detailed studies of specific units to broad, regional treatises which have become classics on the subject of intertonguing marine and nonmarine deposits. Although the circumstances of shoreline migration have been given due recognition for the development of the composite geologic conditions, the treatment of the stratigraphy has been the more or less conventional systematic description of the named units. This in itself is difficult inasmuch as the lateral relationships between units are as much a factor as are the vertical relationships. In this section, the writer has attempted to organize the stratigraphic description primarily in order of events and to relate the major facies or sedimentary zones to these occurrences. The primary events are the major transgressive or regressive movements that occurred throughout the period.

In each advance or retreat of the sea, several sedimentary zones and thus several named stratigraphic units are involved, and the degree to which they are present or absent is significant. In order to avoid being unduly cumbersome, the major events are identified by the marginal marine sandstone unit associated therewith.

The conditions of sedimentation which resulted in presence of coal deposits and their peculiar stratigraphic relationships are intimately related not only to the oscillation of the shoreline, but also very directly they reflect the time element involved in the shoreline migrations. The stratigraphic nomenclature for the Cretaceous was developed, quite properly, on the basis of mappable lithologic units, divisions that do not lend themselves conveniently to a discussion of conditions of sedimentation. However, with two stratigraphic diagrams (figs. 6, 7) representing the interpretations of the various past workers and of this writer, hopefully the reader will be able to follow the discussion which is a combination of stratigraphic discussion and geologic history. It should be noted that there has been no attempt to provide uniform coverage for the many units present in the region. By the nature of the report, the emphasis is on the coal-bearing and closely associated units. Also, the extent of the discussion varies between areas, the factors being largely the writer's familiarity with particular areas and the literature available.

DAKOTA SANDSTONE

Beginning in latest Early Cretaceous time, the sea spread westward into the San Juan Basin region. The resulting nonmarine and marine sediments are grouped into the Dakota Sandstone. The thickness of the Dakota varies quite markedly from one location to another owing principally to the irregular surface upon which it was deposited. The thickness of the Dakota reaches a maximum of about 25o feet in the western part of the San Juan Basin, and locally, in the vicinity of the Zuni uplift, the Dakota Sandstone as used by Hunt (1936, p. 40) is absent. The Dakota truncates progressively older rocks southward, and in the Brazos uplift on the east flank of the San Juan Basin, there is evidence that the Dakota Sandstone lies on Precambrian rocks.

The Dakota is quite variable in the region of investigation, but it generally consists of either two or three sandstone units enclosing one or two predominantly nonmarine, coal-bearing shale intervals. The lower sandstone tends to be conglomeratic and the upper sandstone is more likely to be medium to coarse grained. There is coal present at many localities along the Dakota outcrop, but only in southwesternmost Colorado in the vicinity of Cortez (Shomaker, this report), is there a sufficient abundance to constitute potentially valuable strippable-coal reserves.

This initial incursion of the sea was by far the most extensive of any in Late Cretaceous time. The sea margin progressed well beyond the present limits of the San Juan Basin and in the northern, northeastern, and western parts of the basin offshore limy muds (Greenhorn Limestone) were deposited at an interval of about 6o to 90 feet above the Dakota Sandstone, and nearer the shoreline at about this same interval, several broadly distributed sand sheets were spread across the shallow sea floor as manifestations of heavy sediment supply. These sandstone units, probably attributable to the positive nature of the Zuni and Defiance uplifts, vary in number and position in the section, and there are considerable differences of opinion as to their proper strati-graphic assignment. There is little reason to attempt to either explain or resolve this problem in this report.

GALLUP REGRESSION

Following the major incursion of the sea during Dakota and early Mancos time, there was a major regression during which the shoreline apparently proceeded slowly and somewhat irregularly northeastward to the vicinity of the San Juan River. It was during this withdrawal that the lowermost units of the Mesaverde Group were deposited. The major regressive movement was accompanied by several minor transgressive movements in the southern part of the San Juan Basin region. Near Zuni there is a sequence of intertonguing marine and marine transitional deposits assigned by Pike (1947) to the Atarque Member of the Mesaverde and the Horsehead Tongue of the Mancos Shale. The Atarque Member of Pike is present in the extreme southwest corner of the area of investigation. A section measured by Pike (1947, p. 60) in sections 32 and 33, T. ,o N., R. 17 W. indicated his Atarque Member to be 127 feet thick and separated from the lower part of the Gallup Sandstone by 40 feet 0f marine shale assigned to the Horsehead Tongue of the Mancos Shale.

The shoreline apparently fluctuated in this southern portion of the San Juan Basin for a rather long time for, in addition to the Atarque Member of Pike, there is about 500 feet of marine and nonmarine sandstone with subsidiary nonmarine coal-bearing shale intervals intertonguing with marine shale. In their study of the stratigraphy of the Gallup Sandstone on the flanks of the Zuni uplift, Dane, Bachman, and Reeside (1957) noted the deposition of about 200 feet of sediment of this type in the southern part of the Gallup-Zuni embayment and assigned it to the lower part of the Gallup Sandstone. Several thin coal beds have been noted in this lower unit in the hillsides bordering Nutria Creek northeast of Zuni (Kottlowski, this report). The lower part of the Gallup is overlain by shaly sandstone and dark gray shale belonging to the Pescado Tongue of the Mancos. The Pescado is about i 00 feet thick near Pescado Creek.

In the area to the east of the Zuni Mountains, these lowermost sandstone units, the ones corresponding to those assigned to the lowermost Gallup on the west side of the uplift, do not appear in the area of investigation. Twenty or more miles south of the project area, Dane, Wanek, and Reeside (1957) defined a lower part of the Gallup Sandstone having a thickness of 275 feet and lying immediately beneath a marine shale unit which they named the D-Cross Tongue. Northward along the east side of the Zunis toward Mt. Taylor, the lower part of the Gallup breaks down into a series of discontinuous lenses of sandstone. The uppermost Gallup unit, named the Gallego Sandstone by Winchester (1920), is the only unit in the sequence with continuity and, according to Dane, Wanek, and Reeside (1957), it can be traced around the north flank of the Zuni Mountains to within a few miles of Gallup. The Gallego Sandstone, according to these authors, approximates the upper part of the Gallup Sandstone at Gallup, but virtually all of the interval assigned to the lower part of the Gallup on the east and northeast flanks of the Zunis is above the position of the lower part of the Gallup as used on the west side of the mountains in Nutria Creek Valley.

Stratigraphic relationships in this part of the San Juan Basin are complex owing to minor and nonpersistent changes. While a considerable amount of work has been done in this area, the nature of the outcrops, principally their conformity to the configuration of the present Zuni uplift, and the erosion of the rocks over the vast area of the Zuni Mountains, have left some unanswered questions with respect to the details of sedimentation. The writer believes that there is a likelihood that much of this complexity is the result of there having been a slightly positive area closely conforming to the present-day Zuni uplift during most of this sedimentational episode.

A stratigraphic unit that bears mention, although it is of no obvious significance with respect to coal accumulation in the San Juan Basin, is the Juana Lopez Member of the Mancos Shale. The member has been widely known, especially among subsurface geologists, as the "Sanastee" or "Sanostee." It was described by Dane (1966, p. H 1) as being "characterized by ridge-forming hard thin platy layers of orange-brown-weathering calcarenite, which are interbedded with dark-gray noncalcarentic clay shale." The calcarenite is highly cemented and is derived chiefly from oyster and clam shells, worn fish teeth, and bone fragments. The conspicuousness of the Juana Lopez is due to the resistant nature of the calcarenite, but, as Dane (1966, p. H5) pointed out, the dominant lithology is fissile medium dark-gray to black noncalcareous clay shale that weathers light gray and is easily eroded.

The thickness of the Juana Lopez on the east flank of the San Juan Basin ranges from 90 to 135 feet (Dane, 1966, p. H6). The writer (Beaumont, 1954) measured about 90 feet of this unit (although not formally designated as such) on the west side of the basin where the base lies about 500 feet above the top of the Dakota Sandstone. The member is widespread and has been observed and measured by Dane (1966, p. Hz) "from Seboyeta, New Mex., north to Pagosa Springs, Colo., and west to the vicinity of Ship Rock, N. Mex." Dane and the writer also have observed and measured the unit in the southern San Juan Basin where it is 40 to 50 feet thick. In its northern occurrences, Dane (1960, p. 53-55) indicated that the unconformity between beds of Carlile and Niobrara age rests directly on the Juana Lopez Member. The member is recognizable in the subsurface where the highly calcareous nature of some of the beds and presence of several thin bentonite beds gives it distinguishing character.

The presence of crossbedding, ripple-marked surfaces, and possible small-scale scour surfaces (Dane, 1966, p. H5) suggests shallow-water deposition, well within the zone of wave and current action. The abraded nature of the shell, bone, and teeth fragments comprising the calcarenite suggests that sedimentation during the time of deposition of the Juana Lopez had reached a near standstill. Dane (1960, p. 51) wrote that the lithology, wide extent, rather constant strati-graphic position, and paleontologic evidence suggest that it is essentially a time equivalent unit throughout its extent in the San Juan Basin. On the southwest side of the basin the Juana Lopez is thought (Dane, 1960, p. 52) to be equivalent to the basal part of the Gallup Sandstone in the Atarque area, and, to the southeast of the Zuni Mountains, equivalent to the middle to lower part of the Gallup.

In the area of the type locality of the Gallup Sandstone, Sears (1925, p. 25) included one or more commercial coal beds in the formation. Thus the Gallup is not entirely of marine origin by definition. The coal occurs to a small degree in scattered lenses throughout the sequence, but the commercial beds are in the upper 5o to 75 feet and the

Gallup can be considered essentially the basal regressive sandstone of the Mesaverde Group throughout much of the San Juan Basin.

The Gallup Sandstone as used in the northern part of the San Juan Basin, both at the surface and in the subsurface, may include transgressive deposits. There is a possibility (Beaumont, 1957, p. 116) that the upper part of the Gallup section just north of the Chuska Mountains may be a homogenetic equivalent of the transgressive lower part of the Dalton Sandstone. Coal and carbonace0us shale in the middle part of the Gallup in this area and northward may represent the Dilco Member of the Crevasse Canyon Formation.

More recent work (Dane, 1960; Bozanic, 1955) has demonstrated the presence of an unconformity between rocks of Carlile and Niobrara age in the northern part of the San Juan Basin. The relationships suggest that, perhaps for the only time in the depositional history of the Cretaceous, there was an upward bowing of the geosyncline in this area. The extent of the erosion of the Carlile-age sediments is not certain, but it is clear that truncation 0f these strata occurred and that isolated sand bars and channel fills were deposited on the unconformity. The severity of the disturbance which pr0duced the unconformity apparently diminishes shoreward and the record of positive movement is either absent or unrecognized in the southern part of the San Juan Basin. There is a possibility that the shale-on-shale contact between the Dilco Member of the Crevasse Canyon Formation and the overlying Mulatto Tongue of the Mancos Shale in the outcrops bordering the Zuni uplift northeast of Gallup may be the result of a slightly positive related movement in this area. The absence of a sand facies between these units and the presence of a thin discontinuous layer of pebbles may be indicative of minor subaqueous erosion.

During this major regression the paludal environment is represented by the Dilco Coal Member which was named by Sears (1925, p. 17) for coal measures worked in the Dilco mine near Gallup. The Dilco Member, formerly a member of the Mesaverde Formation, is presently assigned to the Crevasse Canyon Formation. The maximum development of the Dilco appears to be in the vicinity of the town of Gallup where it is 240 to 300 feet thick (Sears, 1925, p. 17) and contains as many as nine coal beds from 14 inches to 6 feet in thickness (Sears, 1934, p. 16). Northwestward from Gallup along the Defiance uplift outcrop belt the Dilco interval is recognizable but quite thin and of doubtful commercial significance. As stated previously, the carbonaceous shale and coaly interval associated with the Gallup Sandstone in the Shiprock area may represent the Dilco interval. It is undoubtedly true that these strata have a genetic relationship to the Dilco.

Northeastward from Gallup, the Dilco interval is traceable to the vicinity of Mount Taylor. Northward the unit becomes progressively more sandy and is replaced by marine shale. Coal of commercial potential is almost entirely lacking in the exposures along the Zuni uplift.

"STRAY"-LOWER DALTON TRANSGRESSION

The advance of the sea following the Gallup regression is interpreted on the basis of field relationships either (I) to have been relatively rapid, or (2) to have had the original character of the sediments altered by some measure of tectonic activity. There is generally a lack of transgressive sandstone in this advance. Hunt (1936, p. 47; Sears, Hunt, and Hendricks, 1941, p. I13) noted the presence of a 50-foot thick sandstone separating the Dilco from the Mulatto Tongue in the southwest corner of the Mount Taylor coal field and refers to it informally as the "stray sandstone." Farther southwest, toward Gallup, the transgressive sand facies is represented by the l0wer part of the Dalton Sandstone Member of the Crevasse Canyon Formation. Pike (1947, p. 28) chose to apply the "stray" terminology to a coarse-grained, crossbedded sandstone unit that comprises the upper tripartite division 0f Beaumont's (1957, p. 114) Gallup Sandstone north of the Chuska Mountains.

During this transgression the sea margin advanced to a position just north of the town of Gallup. The Dalton Sandstone is traceable only to this position, but the coal-bearing Dilco extends considerably farther southward and reaches its maximum development near Gallup. It is evident that the upper part of the Dilco is transgressive in nature and, according to relationships established by Sears (5925; 1934, pl. I), there is reason t0 believe that the very uppermost beds assigned to the Dilco in the Gallup area could be considered a part of the next regressive phase.

DALTON REGRESSION

The next withdrawal of the sea from the Gallup area was marked by the deposition of the Dalton Sandstone Member of the Crevasse Canyon Formation, the upper part of the Mulatto Tongue of the Mancos Shale, a small part of the Dilco in the vicinity of Gallup, the Bartlett Barren Member, and the lower part of the Gibson Coal Member of the Crevasse Cany0n Formation. In the vicinity of Gallup the Dalton Sandstone, which consists of both the lower transgressive and the upper regressive phases, has a thickness of about 180 feet and is quite massive. The regressive portion maintains a thickness of about l00 feet for many miles eastward along the fr0nt of the Zuni Mountains, but in the area northeast of Mount Taylor, where a more northerly component of the stratigraphy can be viewed, the Dalton thickens abruptly through a series of tonguing relationships with the Mancos and the overlying nonmarine beds of the Gibson Member.

On the northwest side of Gallup along the Defiance uplift, the Dalton Sandstone relationships are similar in most respects to those along the Zuni front except that the details are not as well known. The southern segment of the upper, regressive part 0f the unit is thin (40 to 45 feet according to Pike, 1947, pl. 2, sec. 30), but the thickness increases to ab0ut l00 feet (Pike, 1947) just south of the Chuska Mountains. There is a considerable amount of sandstone above the Dalton in this area suggesting a shoreline oscillating within rather narrow limits for a considerable period of time. The resulting picture is one of multiple intertonguing between the marginal marine-sand facies and the paludal environment on the one hand and the marginal marine sand and the offshore mud environment on the other. Most of this nearly vertical stratigraphic rise is obscured beneath the Chuska Mountains.

The lower part of the Gibson Coal Member of the Crevasse Canyon Formation was deposited in the marginal swamps accompanying this retreat of the sea. As discussed previously, in the immediate vicinity of Gallup, this depositional phase is probably represented by the uppermost part of the Dilco Coal Member. F0r a considerable distance north and east of Gallup this environment is absent and the floodplain deposits of the Bartlett Barren Member rest on the Dalton, and the absence of the paludal sediments northwest of Gallup suggests a relatively rapid retreat of the sea through this area. In the area where this action began to slow down northward, however, the coal environment appears above the Dalton.

According to Hunt (1936, p. 48) the Gibson Coal Member "passes over to marine shale." The transition is described as taking place "in a very short distance by the introduction of a series of small tongues of marine shale and sandstone within the unit." Hunt also noted that this change is fairly well exposed on the flank of Mesa Chivato, east of Mount Taylor. The corresponding change on the west side of the basin has not been nearly so well documented, but similar relationships are in evidence though hidden from view beneath the Chuska Mountains (Pike, 1947, pl. 2). It would seem that the maximum development of coal in the Gibson theoretically would be in close proximity (on the landward side) to this belt 0f Gibson-Dalton-Mancos intertonguing. There is no direct evidence that this may be the case, but outcrops of the coal in both areas are poor.

HOSTA TONGUE TRANSGRESSION

The Dalton-Gibson regression was a relatively minor withdrawal of the sea, the movement having been on the order of 30 miles. The subsequent Hosta Tongue transgression was correspondingly short in that the advance of the sea was to about the same position as where the previous regression had begun. It should be noted, however, that a considerable thickness of sediment accumulated during this interval. According to Pike (1947, pl. 2) there is about a 550-foot-interval separating the Dalton and the Point Lookout Sandstone. While the sea was advancing southward, the Hosta Tongue of the Point Lookout Sandstone and the upper part of the Gibson Coal Member of the Crevasse Canyon were deposited on the sea margin and landward side, while a portion of the Satan Tongue of the Mancos Shale was being laid down in the offshore environment.

Although the maximum advance of the sea was on a northwest-trending line about ten miles north of Gallup, favorable conditions for the accumulation of coal persisted well into the Gallup area. In this area the coal measures of the Gibson and the overlying Cleary Member of the Menefee Formati0n are not separable. Apparently there was a period of relative shoreline stability at the end of this transgression and preceding the next regression inasmuch as there is a considerable buildup of coal in the paludal zone. The maximum coal development associated with these units occurs in a northwest-trending band that extends from just south of Gallup to the southern margin 0f the Navajo Indian Reservation and includes several major coal-mining camps of earlier days and the present-day activities of the Pittsburg & Midway Coal Mining Co. at its McKinley mine.

POINT LOOKOUT REGRESSION

This withdrawal of the sea marked the most extensive regression prior to the final withdrawal. The nearshore sand deposited during this phase is the Point Lookout Sandstone that can be traced from just north of Gallup northward into southern Colorado. Eastward from the Gallup area, this formation is traceable in the outcrop and the subsurface around the Zuni Mountains and northward along the east flank of the San Juan Basin to about the Colorado line. In the northeastern corner of the San Juan Basin in Colorado, the regressive phase is present but the overall sandy character and the thinness of the Mesaverde Group make it impractical to separate the various subordinate units.

As observed in the outcrops on the western side of the basin, the thickness of the regressive phase of the Point Lookout (excluding the Hosta Tongue) varies somewhat irregularly from II 0 feet in the southern and central areas to 340 feet near the Colorado-New Mexico state line. Along the Zuni front, Sears (1934, p. 49) reported the Point Lookout to be 75 to 85 feet thick. On the east side of the basin Dane (1936, p. 94-95) indicated the Point Lookout to have thicknesses ranging from 55 to 180 feet. Near the Colorado line Dane (1948) measured from l00 t0 240 feet of Point Lookout Sandstone. It is somewhat difficult to compare measurements of this unit by different workers as the varying interpretations of the highly transitional series of interbedded shale and sandstone at the base can have significant effect on the results. However, the regressional phase of the formation is generally thinner in the southern part of its development and thicker to the north to a position where the entire Mesaverde complex is considerably reduced.

The regressive paludal environment is represented by the Cleary Coal Member of the Menefee Formation. The Cleary, named by Beaumont, Dane, and Sears (1956, p. 2157) for an abandoned coal mine two miles west of La Ventana, New Mexico, is recognized as a member of the Menefee on the south, southwest, and southeast sides of the San Juan Basin. Fr0m the vicinity of the San Juan River northward the zone has been distinguished as the "lower coal-bearing member" by Hayes and Zapp (1955). From the vicinity of Gallup eastward along the Zuni uplift, the Cleary Coal Member is poorly exposed across broad flats with only occasional cuestas revealing the nature of the bedrock. Available surface data (Shomaker and Pierce, this report) indicate that the coal in this member is generally thin and lenticular with an occasional bed reaching a thickness of five to seven feet.

Interpretation 0f the logs of several oil tests and three exploratory holes drilled in connection with this project has revealed substantially thicker beds of coal in the subsurface in the Standing R0ck and C0ntinental Divide areas. The actual cored and interpreted coal thicknesses (as much as 22 feet) are far greater than any known outcrop thicknesses; and it is not known whether this disparity in observations reflects crop weathering and/or surficial cover, or whether it is a manifestation of a primary sedimentary condition in which there was a particularly heavy accumulation of organic matter in a narrow belt paralleling the Zuni uplift, but just beyond the line of outcrops. There are insufficient data to properly evaluate this phenomenon in the subsurface, and the particular alignment of data suggesting a trend is buried beneath the Tertiary-capped Chuska Mountains to the west and beneath Mesa Chivato to the east.

Farther north along the western belt of outcrops the Cleary is unimpressive. There are a few scattered thin coal beds which are of little significance. North of the Chuska Mountains, outcrops are poor and very little coal has been observed in this interval. In general the Point Lookout Sandstone is thin and no intertonguing between the Point Lookout and the adjacent formations has been detected. The writer interprets the low coal concentration, the thin Point Lookout, and the lack of intertonguing to signify a relatively rapid retreat of the sea margin through this area with a correspondingly meager development of the various environmental zones.

A few miles south of the San Juan River the Point Lookout begins to thicken and there is a significant tongue development between the P0int Lookout and the Menefee. This tongue, the North Hogback Tongue (Hayes and Zapp, 1955), is indicative of a gross slowing in the rate of regression which is, in fact, accomplished by a minor transgressive movement. There is an accompanying increase in the coal content of the lower coal-bearing member associated with this deceleration. The south end of the North Hogback Tongue of the Point Lookout, representing a minor transgressive movement of the shoreline, occurs about five miles north of the San Juan River. Between this occurrence and the river there is a multitude of small, mostly inactive mines and prospects which have exploited several well-developed coal beds in the lower coal-bearing zone. Several coal-bed thicknesses ranging from seven to ten feet were recorded by Hayes and Zapp (1955) in association with the North Hogback Tongue of the Point Lookout and the corresponding unnamed tongue of the lower coal-bearing zone of the Menefee.

The lower coal-bearing zone is recognizable in the Mesa Verde area (Wanek, 1954) where there are several tongues between the lower coal-bearing member and the Point Lookout Sandstone that, in conjunction with similar intertonguing at the top of the formation, reduce the thickness of the Menefee from about 800 feet near the Colorado-New Mexico boundary to less than 350 feet a few miles southwest of Mancos, Colorado. Eastward toward Durango, Colorado, the lower coal-bearing zone loses its identity as the Menefee Formation is further reduced in thickness, and coal is present throughout the entire interval (Zapp, 1949). About 10 miles northeast of Durango, the Menefee Formation virtually loses its identity through a series of tongues whereby the Menefee interval is converted in an eastward direction to almost entirely sandstone with a few thin scattered lenses of coal. This condition exists eastward from the Pine River (Barnes, 1953) along the north flank of the San Juan Basin where the thickness of the entire undivided Mesaverde sequence is less than 400 feet. While the nearshore and beach sands marking the Point Lookout withdrawal persist for many more miles northeastward, the approximate limit of the paludal zone on the northern side of the basin is near the Florida River northeast of Durango.

On the east side of the San Juan Basin the situation is similar in the Point Lookout-Gibson relationships. The area northward to near Cuba has been mapped in considerable detail (Dane, 1936), but for a distance of about 3o miles north of Cuba very little surface work has been done on the Mesaverde Group. Along this flank of the San Juan Basin the strata are very steeply inclined thus precluding the potential for strippable coal, and, owing to a somewhat wetter climate, the outcrops and thus the stratigraphic relationships are more obscure. Many oil and gas tests have been drilled along the eastern flank, but there are large areas where the frequency of wells is too low to permit detailed correlation. The writer has relied on subsurface data to a large extent in the east-central part of the basin for the construction of the stratigraphic diagram in that area (fig. 7), but there has not been an opportunity to study the well logs to the extent necessary to work out the details of the intertonguing relations.

With regard to the Point Lookout regression on the east side of the basin, the conditions of the shoreline movement would appear similar to those observed on the west side. The Point Lookout Sandstone on the east side is generally thin with respect to thicknesses on the west side of the basin. In the San Miguel Creek dome on the northwest side of Mesa Chivato, on the east flank of Mesa Chivato, and in an outlier of Point Lookout about 12 miles southwest of San Ysidro, Hunt (1936, p. 49) reported the formation to range from 75 to 85 feet thick. Dane (1936, p. 94-95) reported a thickness of 74 feet for the Point Lookout in the southeastern corner of T. 18 N., R. 2 W., but noted the problem of drawing a firm lower boundary owing to the highly transitional relationship of the Point Lookout with the underlying Mancos Shale. If the major part of the transitional beds were included, his maximum thickness at this locality, however, would be only 13x feet. Farther northward, toward Cuba, New Mexico, Dane reported greater thicknesses ranging up to 200 feet in T. 19 N., R. r N. and 180 feet southeast of Cuba. These surface observations are corroborated by subsurface data. The thickness of the sandstone reaches about 250 feet near Cuba, but farther northward the formation thins somewhat and becomes quite shaly.

In the southern part of the area mapped by Dane (1948) in the northeastern San Juan Basin, the Point Lookout Sandstone was described as a thin- to massive-bedded, buff to white sandstone transitional downward into the Mancos Shale and having a thickness of 17o to 240 feet. Near the Colorado-New Mexico state line, Dane reported the Point Lookout to be about r 00 feet thick. In southernmost Colorado, Wood, Kelley, and MacAlpin (1948) did not attempt to differentiate the various units of the Mesaverde and reported the unit to thin from 365 feet on the Piedra River, about 18 miles west of Pagosa Springs, to thin sandstones and shales indistinguishable from the overlying and underlying units a few miles northeast of Pagosa Springs.

The coal-bearing Cleary Member of the Menefee Formation is present in some degree of development above the regressive Point Lookout Sandstone from the southeast part of the San Juan Basin northward almost to the state line. Only a few miles north of the Monero coal field where coal-bed thicknesses up to seven feet have been measured (Shomaker, this report), the paludal environment terminates abruptly, much as it does to the east of Durango, near the Florida River.

In the southern part of the area, Dane (1936, p. 96) reported that the Cleary Member is a fairly distinct unit west of the Rio Puerco and less distinct eastward and northward. The thickness of the Cleary varies from about 250 to 300 feet (Hunt, 1936, p. 49; Dane, 1936, p. 96) and individual coal beds are generally less than four feet. At several localities bed thicknesses reach six and seven feet, but in most instances these thicker coal units are interrupted by several shale partings such as at the Cleary mine (section 31, T. 19 N., R. 1 W.), the locality for which the member is named. There is a rather gradual decrease in the coal content of the nonmarine sequence upward in the section, and most of the significant coal occurs in the lower 100 feet. Apparently the coal rapidly diminishes northward as Dane (1936, pl. 54) reported no coal more than two feet thick north of T. 19 N. The entire sequence of nonmarine beds, the Cleary at the base and both the barren and the coal-bearing parts of Allison above, is reduced in thickness quite rapidly, from an estimated 1,800 feet in the southeastern corner of the basin to less than 250 feet near Cuba. The major part of this reduction is due to the northward replacement of the upper several hundred feet of Allison beds by sandstones assigned to the La Ventana Sandstone.

Northward from Cuba along the east flank of the basin, the Cleary-Allison sequence is involved in the steep dips marginal to the Nacimiento uplift. This situation, coupled with poor exposures, has discouraged detailed study of the coal and stratigraphic relationships. In the area mapped by Dane (1948) between T. 26 N. and the Colorado state line, the entire Menefee interval, 250 feet or less in thickness, was mapped as "Gibson," the unit which has been changed to "Cleary" (Beaumont, Dane, and Sears, 1956). Application of the term "Cleary" to this entire sequence is somewhat misleading as the interval probably contains both regressive and transgressive coal deposits indistinguishable from one another except in terms of relative position. Shomaker (this report) has judiciously assigned the entire interval to the Menefee Formation, thus avoiding the Gibson (Cleary)-Allison implication.

The presence of minable coal in the Monero-Lumberton area and the abrupt termination of the coaly sequence a short distance to the northeast of this coal field present a situation analogous to that observed between the relatively abundant coal of the Menefee Formation in the vicinity of Durango and the correspondingly abrupt termination of the Menefee east of Durango. Relating these two areas in this manner provides a strand-line direction of N. 60° W., well in keeping with other Cretaceous trends. In the Durango area where much more detailed coal and general stratigraphic data are available (Zapp, 1949), the coal beds in the terminal area of the Menefee are not individually thick but comprise a relatively large amount of the total interval (17.7 percent at Zapp's locality 62). This would suggest relatively static conditions in this area with minor oscillations and considerable clastic sedimentation during the inertial period prior to the final landward advance of the sea.

CLIFF HOUSE TRANSGRESSION

The sea, having withdrawn to the northern margin of the area now occupied by the San Juan Basin, began a final advance to the south which was marked by a considerable number of minor regressions and consequent intertonguing. This transgressive period resulted in the deposition of the Cliff House Sandstone and its La Ventana Tongue representing the nearshore and beach environment and coal-bearing paludal deposits assigned to the upper part of the Menefee Formation. As with the lower units in the Mesaverde Group, this sedimentary phase is best documented on the west side of the San Juan Basin. The transgression involves a considerable stratigraphic rise in the Cliff House. The overlying Lewis Shale, representing the offshore deposits, is about 1,800 feet thick and pinches out southward as the transgressive Cliff House merges with the succeeding regressive sandstone, the Pictured Cliffs Sandstone. At the base, the Cliff House intertongues with the underlying Menefee Formation, and in a series of step-like progressions, the Menefee thickness increases from about 120 feet near Durango, Colorado to more than 2,500 feet near Newcomb, New Mexico, a distance of about 75 miles.

In the Durango area, Zapp (1949) noted possible intertonguing at two localities, one immediately east of the town and the other near Hesperus, Colorado, that raised the base of the Cliff House 5o and 75 feet, respectively. The latter tongue thickens the Menefee to an extent that it is possible to separate the lower and upper coal-bearing zones. One of the most prominent and extensively mined coals in the Menefee appears immediately below the Cliff House Sandstone in the interval of this tongue. The bed, mined extensively along Hay Gulch for a distance of four miles, reaches thicknesses of 6.5 to 7.0 feet. In the Durango area the Cliff House has an average thickness of 325 feet and is composed of "irregular to lenticular ledges of hard fine- to medium-grained calcareous sandstone enclosed in softer argillaceous, fine-grained sandstone, mudstone, and silty shale" (Zapp, 1949). Zapp also pointed out that the Cliff House becomes finer grained eastward in the area of his investigation.

Somewhat farther westward on the northwest flank of the San Juan Basin, in the Mesa Verde area, Wanek (1954) recorded further stepping up of the Cliff House in two closely associated tongues. The lower is known as the "lower tongue" and the upper is designated the Barker Dome Tongue. The thickness of the Cliff House is 345 feet near the east edge of Mesa Verde National Park (Barnes, Baltz, and Hayes, 1954) and also on the La Plata River close to the New Mexico-Colorado line. *Between* the Colorado line and the San Juan River, Hayes and Zapp (1955) described three tongues between the Cliff House and the Menefee. They named the Cliff House tongues southward in progressively higher position, the Barker Dome, the Cholla Canyon, and the Beechatuda Tongues. These three units step up the base of the Cliff House nearly 30o feet. In this same interval the Cliff House increases in thickness from an estimated 120 feet to about 750 feet at the San Juan River through the process of lateral gradation with the Lewis Shale.

Coal beds are intimately related to each of these tongues between the Cliff House and the upper coal-bearing member of the Menefee, but the greatest abundance of upper Menefee coal is developed in the interval above the Beechatuda Tongue where at one locality the beds contain 19 feet of relatively clean coal. The coal in this zone dwindles southward until there is only one thin bed of coal exposed in the Mesaverde hogback between the San Juan and Chaco Rivers, and the interval immediately below the Cliff House is essentially barren for the next ten miles. At this position, about ten miles south of the San Juan River, the lower, massive sandstone of the Cliff House, the unit that is so conspicuous as the backbone of Hogback Mountain, begins to thin noticeably. In a short distance it pinches out and is completely replaced by the Chaco Tongue of the Menefee Formation. This intertonguing raises the base of the Cliff House about 300 feet in a single step.

The Chaco Tongue of the Menefee represents a significant regression in the major Cliff House transgression, and coal beds are abundant in the interval. The Chaco Tongue can be traced northward along the back side of Hogback Mountain for about eight miles, and there is evidence of coal throughout this distance. A section measured by Shomaker and Lease (personal communication) revealed three coal beds 11, 5.5, and 21 feet thick, in this tongue on the east side of Hogback Mountain. In the southward projection of the Chaco Tongue beyond the pinchout of the Hogback Mountain Tongue, the writer has measured from 32 to 38 feet of coal in seven to ten beds. Southward through a succession of unnamed tongues the Cliff House continues to rise until in the vicinity of Newcomb, New Mexico, the Menefee Formation is about 2,500 feet thick and the overlying Lewis Shale is reduced to a feather-edge.

The maximum landward extent of the offshore mud facies represented by the Lewis Shale is to be found in the bluffs six to seven miles east of Newcomb. The nearshore and beach-sand facies carries farther southwestward, but erosion of these sediments precludes tracing them to their ultimate transgressive position. It may be that somewhere in the extensively covered thick sequence of nonmarine strata preserved in the flanks of the Chuska Mountains there are remnants of the undivided Cliff House and Pictured Cliffs Sandstones.

The intertonguing between the Cliff House and the Menefee Formation is much more clearly defined than the equivalent phenomenon occurring between the Cliff House and the Lewis Shale. As a transgressive deposit, the Cliff House tends to be composed largely of thin sandstone units interbedded with marine shales — the more massive beach-type deposits being largely absent. It is presumed that the mechanics of transgressive deposition tend to dissipate the more massive sand accumulations before they are buried. There are some striking massive sand units within the Cliff House such as that which forms the bulk of the Hogback Mountain Tongue but in most instances these massive sandstone beds can be attributed to the minor regressive phases that interrupted the major transgressive movement. There are intervals along the expanse of Cliff House outcrop from the San Juan River southward where tongues of Lewis-like marine shale rest directly on or are very close to the Menefee. These shale units can be held in the strictest sense to be tongues of the Lewis and, thusly, to separate the Menefee from the Cliff House. The writer, however, prefers not to make this fine distinction but to consider these interruptions of the sand phase a normal consequence of transgressive deposition.

The coal development in the upper coal-bearing member of the Menefee on the west side of the San Juan Basin is s0mewhat erratic because of the frequent intertonguing and the subsequent stratigraphic climb of this zone. Laterally along the outcrop the coal occurrences can be characterized by saying that there are areas of moderately thick coal accumulation alternating with areas of relative barrenness. In each instance the coal concentrations can be related to the intertonguing and the changing rate of shoreline migration.

On the east side of the San Juan Basin the outcrops related to the Cliff House transgression have not been as th0roughly studied. On casual examination, what is known of the east flank of the basin does not seem to parallel the stratigraphy of the west side. Although the state of knowledge of the two areas is not comparable, comparison of the Cliff House stratigraphy on the west side with that on the east side reveals many points of similarity. The west-side outcrops are oriented more nearly normal to the direction of greatest change and thus the east-side outcrop band with its oblique orientation to the presumed strand-line direction provides an illusionary effect that the same events occurred over a greater interval.

For reasons discussed in the paper that realigned the Cretaceous nomenclature of the San Juan Basin (Beaumont, Dane, and Sears, 1956), the transgressive sandstone deposited during this episode is known as the La Ventana Tongue of the Cliff House Sandstone throughout most of the east side of the basin. Beginning in northernmost New Mexico, where the transgressive phase can first be distinguished from the remainder of the Mesaverde, the Cretaceous sea apparently transgressed landward at about the same rate as on the west side of the basin, but the thickness of sand appears to be somewhat less. Dane (1948) measured between 30 and 80 feet of La Ventana in the northeast part of the basin and noted the transitional nature of this sand facies with both the overlying Lewis Shale and the underlying Menefee. A short distance to the east of Dane's map near Chama, New Mexico, Muehlberger (1967) found similar conditions in the Mesaverde except that he measured n 0 feet of sandstone above a 14-foot-thick siltstone-and-shale interval that contains coal fragments. The shaly interval is in turn underlain by massive sandstone. This "notch" on the cliff face may represent the wedge-edge of the Menefee Formation in which case the overlying n 0 feet could be appropriately assigned to the La Ventana Sandstone.

For a considerable distance south of the mapping of Dane (1948) and Muehlberger (1967) there is virtually nothing published on the Mesaverde Group, but there are several oil tests that penetrate this part of the section basin-ward. Whereas the Point Lookout shows rather strongly on most well logs, the Cliff House is in many instances a weak unit — difficult to distinguish from the Menefee. In T. 26 N., R. 3 W. there is about 110 feet of weakly developed La Ventana sand, but in T. 25 N., R. r E. it is difficult to delineate more than 20 feet of section at the top of the Mesaverde interval on the well log as being La Ventana. This irregularity persists southward and there is a general thickening of the Menefee interval suggesting intertonguing between the La Ventana Tongue and the Menefee. The wide spacing between oil tests and the difficulty of distinguishing between marine and nonmarine sandstones on the logs preclude directly establishing this intertonguing relationship, but this area appears to be analogous with the better documented area on the west side of the San Juan Basin. In a distance of 25 miles, the thickness of the interval from the base of the Menefee to the top of the La Ventana Tongue increases from 425 feet on the north to 635 feet. The log records are too vague to allow for firm conclusions, but it would appear that there is an upper coal zone in the Menefee, the Allison coal of Dane (1936).

Observations along the outcrops near Cuba indicate considerable variation in the thickness of the La Ventana. Renick is reported (Dane, 1936, p. 101) to have measured 37 feet at a locality a few miles southeast of Cuba, and Dane (1936, p. 109) reported it to be absent in a section only a few miles to the south. However, he suggested that this observation, made in an area of sharp structural flexing, may be due to faulting. In about the vicinity of Señorito, New Mexico, the La Ventana Tongue begins to thicken quite dramatically toward the south. In T. 19 N., R. 1 W. Dane (1936, p. 08) remarked that this thickness includes a considerable amount of marine shale and that the upper part is probably more than half shale, but nevertheless, a few miles farther south, Dane estimated the total thickness of the La Ventana to be about 900 feet. Just as abruptly as the greatly expanded La Ventana comes into existence from the north, it grades in a southerly direction into a correspondingly increased thickness of nonmarine Allison beds. Thus the expanded La Ventana terminates in the surface exposures and for a distance of ten miles to the south there is no nearshore and beach deposit separating the paludal zone from the offshore muds.

The massive accumulation of the La Ventana Tongue forms a band only 12 miles wide, a situation which is interpreted to indicate a relatively long period of balance between subsidence and sedimentation in this relatively limited area in the southeastern part of the San Juan Basin. Whatever conditions might have prevailed during this time of sand accumulation must have been suddenly disturbed to allow the shoreline to advance rapidly across the swamp and floodplain deposits that had been accumulating just shoreward from the strand line. A sudden shoreward shift of the strand line provides a reasonable explanation of the direct superposition of the Lewis Shale on the Allison Member and fits the concepts of stratidynamics.

South of Cuba, where it underlies the La Ventana Tongue, the upper coal zone of the Allison Member consists principally of a single persistent coal bed that reaches a maximum thickness of nine feet (Dane, 1936, p. 98). Dane's (1936, pl. 39) map showed this bed to be present from the central part of T. 20 N., R. 1 W. southward along a sinuous outcrop to the southern edge of T. 18 N., R. 2 W., a distance of about 16 miles. The thickness of the bed varies considerably in this distance but if this bed does indeed have a lateral extent of this magnitude, it is remarkable in the Mesaverde Group. According to Dane, the bed is traceable beyond the southern limit of the La Ventana Tongue.

In the area of lateral gradation between the La Ventana and the Allison, thin coal beds are said (Dane, 1936, pl. 39), to be present in considerable abundance, but in this stratigraphic interval of about 900 feet none are reported to have any substantial thickness. The writer notes that surface burning 0f the coal is extensive in this area and Dane (1936, p. 150-151) remarked that "tracing and correlating these beds is difficult."

An oil test in section 17, T. 19 N., R. 4 W. appears to penetrate the zone of lateral gradation between the La Ventana Tongue and the Allison Member. In the 580 feet of strata that can be assigned to the La Ventana interval, there are three distinct sandstone sequences separated by two shaly intervals. The lower shaly interval, beginning about 120 feet above the base and having a thickness of 190 feet, contains several electrical log curve configurations that suggest two moderately thick coal beds. The lower of these is about 12 feet thick, and the upper, which contains two major partings, is about 24 feet thick. The upper shale sequence also appears to contain some coal.

One would anticipate that the conditions providing for an essentially vertical buildup of the marginal marine sands would also produce circumstances favorable to extensive deposits of vegetal material on the landward side. If minor oscillati0n of the shoreline occurred during this period of sedimentation, these paludal deposits would appear to alternate with the beach and nearshore deposits. As previously noted, Dane (1936) did record the presence of numerous coal beds in this interval, but the thickness and frequency do not really substantiate this theory. The above interpretation of subsurface data would seem to be somewhat more in accord with this idea.

A phenomenon that may have played a part in the sudden landward shift of the sea at this time may be recorded in the continental beds on both sides of the basin. Southeast of Newcomb, New Mexico, the writer has observed in the fluvial beds underlying the upper coal zone of the Menefee evidence of crustal instability in the form of minor intraformational unconformities. Numerous, and apparently erratic in their orientation, these interruptions in the normal sedimentary process take the form of large-scale truncations of sets 0f strata of mixed lithic types. The effect produced is that of mammoth crossbeds, and it surely represents local crustal instability that possibly was accompanied by sudden sealevel changes and accompanying strand-line shifts.

Dane (1936, p. 96) apparently noted a similar situation on the southeast side of the basin where he described the upper part of the Allison as consisting "chiefly of gray structureless clay with a few beds of white or gray sandstone which. . . . cut across the general bedding at low angles for hundreds of feet." Whether or not the writer and Dane are describing the same conditions is uncertain without further field work, but the locations for both observations are on an approximate depositional strike and in about the same stratigraphic position. Although a sudden major shift is not indicated on the west side, it is conceivable that the effect of a disturbance whose manifestations are recorded over an 80-mile distance could have been significant.

Southward and westward beyond the terminus of the La Ventana Tongue and beyond the area in which the Allison and Lewis are in contact, the final stages of this transgression are represented by a sandstone sequence several hundred feet thick that tongues rather abruptly northward into the Lewis Shale. This conspicuous unit has been traced northwestward into the Cliff House Sandstone of the western San Juan Basin. The Cliff House in this southern part of the San Juan Basin forms the backbone of the northwest-trending linear feature, Chacra Mesa, from which it received its former name (Dane, 1936, p. i 0 I). Dane recognized the possibility that his "Chacra sandstone" was continuous with the type Cliff House, but chose to call it by a separate name until the relationship could be definitely established.

The Cliff House on Chacra Mesa attains thicknesses of 290 to 360 feet (Dane, 1936, p. 102-107), and contains lenses or tongues of carbonaceous material and coal in its southerly exposures. It is suspected that the development and the preservation of Chacra Mesa is closely associated with the maximum sedimentary development of the Cliff House Sandstone. Dane (1936, p. 103) noted "that the appearance of. . . .coal in the Chacra sandstone represents the beginning of a change of the marine Chacra sandstone to continental beds toward the southwest, where they have been now removed by erosion." Speer (this report) notes that the frequency of well data now makes it possible to confirm Dane's suspicion that this segment of the Cliff House merges laterally into the marine Lewis Shale to the northeast.

The thick development of Cliff House Sandstone on Chacra Mesa represents accumulating sediments during the waning moments of this major transgression with a slowing rate of shoreline migration. There are very limited carbonaceous deposits beneath the Cliff House of Chacra Mesa which can perhaps be accounted for by the relative rapidity with which the shoreline shifted from the La Ventana position to the Chacra Mesa position. It would seem likely that some rather extensive coal deposits formerly existed in the area from which the sediments are now eroded to the southwest, a situation analogous to that existing in the Gallup area beyond the pinchout of the Point Lookout Sandstone.

It is fairly certain that the Cliff House of this area is entirely transgressive inasmuch as a small inlier of Lewis Shale and Pictured Cliffs Sandstone is preserved in a fault block close to the edge of the southwest Chacra Mesa escarpment. But it is also evident fr0m the 83-foot thickness of the Lewis Shale at the above-mentioned inlier that this position was close to the feather edge of the Lewis. In any case, the maximum advance of the sea during this transgression was certainly short of any previous major transgressive movement.

PICTURED CLIFFS REGRESSION

This episode in the Cretaceous depositional history marks the final withdrawal of the sea from the area of the San Juan Basin. In addition to the marginal marine and sand facies represented by the Pictured Cliffs Sandstone, other units associated with this regression are the coal-bearing Fruitland Formation representing the paludal environment, the barren continental shales and sandstones of the Kirtland Shale, and the offshore mud facies represented by the upper part of the Lewis Shale.

As might be expected at the close of an epoch and the decay of the Cretaceous geosyncline, conditions of sedimentation become more complex, and the patterns and trends that had prevailed through the accumulation of several thousand feet of sediment underwent modification. The final regressive movement began somewhat to the southwest of the northwest-trending band of Cliff House-Pictured Cliffs outcrops, and from this trend it can be ascertained that the initial retreat was along a northwest-trending line that approximates the prevailing trends of earlier episodes. There are indications, however, that in addition to the southwestern source area, an additional area (or areas) of sediment supply developed somewhere to the north. There is considerable disagreement among the various workers as to: (I) whether or not there was, in fact, a northern source, and (2) if there were two sources, what the relationships were between the two depositional lobes. The Pictured Cliffs Sandstone has been described (Dane, 1936, p. 112-113) as absent or very thin in the outcrops on the east side of the basin. Absent or not, the formation thins markedly in that area both from the south and the north, and there is an indication that a secondary source of sediments was developing during this time. This writer, however, believes that the predominance of sedimentation was from sources to the south and along a shoreline retreating to the northeast.

Along the southeast-trending band of outcrops of the Pictured Cliffs Sandstone and Fruitland Formation in the southern part of the area, the Pictured Cliffs is not particularly thick at any point of observation and thins very noticeably to the point of being questionably present along the east side of the basin. The Fruitland Formation, however, is well developed for a distance of about 70 miles from the Burnham area on the west to near Star Lake on the southeast. Eastward and northward from Star Lake the Fruitland is recognizable but loses much of its thickness and coal content in a short distance.

The investigations of Bauer and Reeside (1921) and Dane (1936) delineated the Fruitland Formation and the individual coal beds in this southern area about as well as could be done considering the problems of access, the necessity to construct their own base maps, and the quality of the exposures. Their maps and sections do not, however, portray the true nature of the Fruitland coal as it has been revealed through drilling. Whereas Bauer and Reeside reported one to six individual beds having thicknesses ranging up to 12 feet but averaging closer to four feet, examination of drill-hole logs reveals at least one bed having a thickness of 3o feet (Shomaker, this report) and several other beds in the same sequence aggregating nearly another 30 feet. It is generally recognized that outcrop measurements of coal are likely to be somewhat reduced from the true thickness as determined by measurements in drill holes behind the crop. In the case of the Fruitland in the southern outcrop belt, there seems to be a greater than normal disparity between the two types of measurements, which suggests that thicker coals lie slightly downdip from the present band of outcrops. Although the Pictured Cliffs is relatively thin, there are many indications of intertonguing and minor reversals in the direction of shoreline movement, and an anomalously thick section of sandstone in this interval was reported by Baltz (1962, p. 49). Enough data are available to show that lateral changes in individual coal beds are both frequent and in places spectacular. In general, the Fruitland coal in this southern area is high in mineral content with ash values ranging from 8.5 to 35.1 percent (Shomaker, this report). The ash is largely in thin discrete shale and siltstone partings and may be indicative of frequent interruptions of the normal swamp conditions. On the whole, the Fruitland coal beds throughout the San Juan Basin are somewhat dirtier than the coal in the various Mesaverde units.

Along the east side of the San Juan Basin the Pictured Cliffs Sandstone thins until the zone is represented by a thin sandy shale and thin sandstone beds at the top of the Lewis, and the Fruitland Formation and the overlying barren Kirtland Shale are reduced to 126 feet (Baltz, 1962, p. 59). Although apparently present in some degree throughout the eastern flank of the San Juan Basin, the coal beds in the Fruitland of this area are thin and are erratic in their distribution.

On the southwest and west side of the Fruitland outcrop area there has been rather extensive coal exploration and development owing to the abundance of coal and the low pitch of the strata. The writer has conducted drilling programs for Public Service Co. of New Mexico on leases near Bisti, immediately east of the Navajo Indian Reservation boundary, where the Fruitland has been found to contain three and possibly four coal beds of commercial potential through an interval of about 180 feet. In the area investigated, the basal coal bed is the most widely distributed and is essentially in immediate superposition on the Pictured Cliffs. This bed ranges from a feather-edge to 15 feet in thickness and averages 7.9 feet in thickness throughout the area. A medial coal bed lies 45 to 95 feet above the lower bed and has a thickness ranging from three to 16 feet, averaging 9.5 feet. Ten to 50 feet above this second principal bed, there is a relatively thin bed averaging less than four feet thick; and about 160 feet above the top of the lower bed, there is an upper coal that has a maximum thickness of nine feet in the outcrop. This bed has several partings and splits into two units eastward.

Immediately west of the Public Service Co. of New Mexico's Bisti property, El Paso Natural Gas Co. and Consolidation Coal Co. jointly hold large Fruitland coal reserves. In this area there are six coal beds considered to have potential for mining. All of the beds are not present everywhere; the average thicknesses range from five to 15 feet.

From the El Paso-Consolidation lease northward to the San Juan River valley, a distance of about 25 miles, the Fruitland Formation is on a lease belonging to Utah Construction and Mining Co. This is the site of the Navajo mine from which the Utah Construction and Mining Co. produced six million tons in 1970. Mining operations were initiated at the north end of the lease and to time of publication only about the northern five miles had been developed. Utah has delineated nine minable beds which become progressively younger toward the north (Tom Gambill, personal communication). At the south end of the lease they estimate on the basis of preliminary drilling that there are nine minable beds. Northward, however, the lower beds pinch out until at the north end of the lease there is but one definitely commercial bed and one of questionable value.

The base of the principal bed at the north end, bed 8, is a few feet above the Pictured Cliffs whereas at the south end of the lease the coal thought to be bed 8 or its stratigraphic correlative is about 13o feet above the Pictured Cliffs Sandstone. Examination of well logs in this general area reveals the stepping-up of the Pictured Cliffs in this northward direction and a corresponding rise in the Fruitland Formation.

In a distance of about two miles on the south side of the San Juan River and immediately east of the Navajo mine, the Pictured Cliffs increases in thickness from 107 to 236 feet in a northward direction. The formation also rises stratigraphically approximately 130 feet in this same distance.

Throughout much of the west side of the San Juan Basin, the top of the Pictured Cliffs is marked by a dense fossil oyster bed. At a locality now within the Utah Construction and Mining Co. lease, the writer observed minor intertonguing relationships between the Pictured Cliffs and the Fruitland in which the oyster-bearing sandstone alone was involved and tongued out northward.

North of the San Juan River, the Pictured Cliffs and the Fruitland continue their northerly outcrop trend for about six miles at which point the formations are deflected eastward and caught up in the steep dips of the northeast-trending Hogback monocline. Through this area and northeastward to the Colorado state line, Hayes and Zapp (1955) mapped four "shoreline" events in the deposition of the Pictured Cliffs. Each "shoreline" is thought to indicate a pause in the retreat of the sea and perhaps minor advances. They indicated a northward rise in the Pictured Cliffs-Fruitland contact of about 280 feet in a distance of 14 miles. In this same interval Hayes and Zapp reported the Pictured Cliffs to thin from 390 to about 190 feet.

From about the San Juan River northward for seven miles to the Ute Mountain Indian Reservation boundary the Fruitland coals have been explored in detail. A single basal bed of coal predominates in the southern part of the area where it ranges from a maximum thickness of about 19 feet to about a foot at one drill-hole location near the El Paso Natural Gas Co. pipeline. This bed, known as the "main bed" in the Western Coal Co. lease area, consists of a series of imbricate lenses separated by silty, sandy bentonitic partings. All but one of the lesser component coal lenses tongue out northward near the pipeline, and the detail of drill-hole data makes it possible to ascertain that the aggregate reduction from 16 to three feet in the "main bed" occurs in a distance of about 1,500 feet along a slightly sinuous east-west trend. There is a gradual increase in the thickness of the various components of the "main bed" northward. About 2.5 miles south of the Ute Mountain Indian Reservation boundary, a thin but persistent shale parting begins to thicken in a northward direction and eventually separates the two principal splits by about eight feet near the northeast corner 0f the Western Coal Co. lease. The aggregate maximum thickness of this coal in the northern part of the lease also is about 19 feet.

A lesser seam of coal lies from 90 to 130 feet above the top of the "main bed" from the bluffs on the north side of the San Juan River valley into the Ute Mountain Indian Reservation. This upper bed attains a thickness of six feet and averages about 4.5 feet, and, like the "main bed," it is thinned to less than 2.5 feet near the pipeline.

The area in which both of these coal beds are thin has caused the writer to speculate as to the cause. The several component lenses of coal comprising the "main bed" are reduced in thickness and with one exception pinch out toward this "want" area from both the south and the north. It can be demonstrated that this phenomenon is a primary sedimentary feature and not the result of removal by secondary channeling. There is at least one instance in which the elimination of one of the lesser coal tongues could be interpreted as due to channeling, but on the whole, the loss of coal is sedimentary and not erosional. The area of thin coal may represent the site of a stream or river which passed through and discharged sediment into the swamp and thus inhibited the accumulation of organic matter. The deposits in this interval of reduced coal thickness consist of greater than normal concentrations of sandstone in proportion to shale and siltstone.

Whether or not these conditions persisted through the deposition of more than a hundred feet of additional sediments to affect the upper coal bed is not readily apparent; the reduced thickness in the same general area of this upper bed may be purely coincidental. The breadth of the area in which detailed data are available is too narrow to draw conclusions with respect to the trend of the postulated drainageway, but the sharp east-west trend of the northward reduction of the "main bed" coupled with some broad isopachous trends in the coal suggest, at least locally, a more northerly component of strand-line trend than had earlier been experienced in the Cretaceous.

Coal continues to be present northeastward along the Fruitland exposures in the Hogback monocline and younger and higher beds continue to replace the older beds. About 13 miles southwest of the Colorado state line, Hayes and Zapp (1955) recorded the beginning of a rapidly expanding bed of coal that continues into southern Colorado. Although interrupted by numerous partings, this bed reaches thicknesses in the outcrop of more than 38 feet (Hayes and Zapp, 1955). In the subsurface Peabody Coal Co. found the bed to be more than 35 feet thick. Toward the southern end of this bed, it is about 90 feet above the Pictured Cliffs Sandstone, but at the Colorado state line it is immediately above the Pictured Cliffs, a "shoreline" event or intertonguing of the Pictured Cliffs having occurred in the intervening area. This thick coal bed has been traced with a moderate degree of certainty for a distance of about six miles into southern Colorado (Barnes, Baltz, and Hayes, 1954). Throughout most of this distance it maintains a thickness of between 25 and 28 feet.

Coal occurs at several horizons through an interval of about 275 feet about four miles southwest of the Colorado state line, which in effect delineates the thickness of the Fruitland Formation.

In southernmost Colorado, the Fruitland continues to be rich in coal, but except for limited circumstances, the dip of the strata from about the south end of the Ute Mountain Indian Reservation northeastward along the Hogback monodine is too steep to allow the Fruitland coal beds to be considered for stripping (Beaumont and Speer, this report). In a section of the Fruitland measured by Barnes, Baltz, and Hayes (1954) six miles north of the state line, these authors reported 67.2 feet of coal in a 24i-foot-thick section of the Fruitland, a rather high density of 27.5 percent coal. A few miles farther northeast, they reported a stratigraphic rise of 63 feet for the top of the Pictured Cliffs and abundant coal to the north end of their investigative area, about six miles south of Durango.

Near Durango, the basal coal in the Fruitland is named the Carbonero bed. For a distance of about a mile this bed attains a thickness of about 8o feet, of which only the lower 40 feet is of any potential value (Zapp, 1949). This maximum occurrence is immediately landward from a thick Pictured Cliffs tongue that, according to Zapp, splits the Carbonero coal. The lower split can be traced intermittently within the Fruitland tongue counterpart of the Pictured Cliffs tongue for about five miles to the east side of the Florida River valley. The upper split can be traced with reasonable certainty northeastward above the Pictured Cliffs tongue for about three miles where it appears to split into lesser units (Zapp, ,949). To the south, the Carbonero bed thins rapidly. The lower part is entirely replaced by shale and sandstone within a mile of the area of maximum development.

If Zapp's conclusion to the effect that the Carbonero bed is split by a tongue of the Pictured Cliffs Sandstone is correct, the massiveness of the Carbonero coal immediately to the landward side of the intertonguing may be attributable to there having been nearly continuous deposition of vegetal matter under very stagnant shoreline conditions in a limited area during the deposition of the transgressive Pictured Cliffs tongue. This is an excellent illustration of the stratidynamic principle. The Pictured Cliffs is shown by Zapp to rise about 110 feet in this event.

The Pictured Cliffs-Fruitland outcrop bands continue through an area of poor exposures eastward across the north end of the San Juan Basin with occasional outcrops revealing beds, particularly in the basal portion, ranging up to nearly 17 feet in thickness (Zapp, 1949; Barnes, 1953). The Fruitland Formation has a thickness of about lo0 feet, and, in general, there is a diminution of coal in the formation eastward across the north end of the basin. Just about coincident with the La Plata-Archuleta county line the Fruitland-Pictured Cliffs outcrop belt swings southeastward and there is a slight increase in coal content in the Fruitland for the next several miles (Barnes, 1953). Although Barnes did not show any specific intertonguing between the Fruitland and the Pictured Cliffs, he did acknowledge the probable presence of this occurence through the 16 miles or so of outcrop he mapped in the Los Pinos coal field. Barnes pointed out a general decrease in grain size in the Pictured Cliffs Sandstone eastward across his area, and there is a decrease in its thickness from 230 feet to 125 feet (Wood, Kelley, and MacAlpin, 1948) in a distance of about four miles.

The above completes the area of specific coal investigation undertaken by the U.S. Geological Survey in northern New Mexico and southern Colorado. While not specifically concerned with coal, Wood, Kelley, and MacAlpin (1948) recorded its presence in the Fruitland interval, one bed being reported to be about 15 feet thick. These authors stated that in the area of their investigation, the Pictured Cliffs Sandstone is 140 to 160 feet thick in the central and western portions, thins to 90 feet in the Klutter Mountains, and is thin or absent on the San Juan River, a few miles north of Pagosa Springs. They showed graphically a marked decrease in the thickness of the undifferentiated Kirtland Shale and Fruitland Formations from 830 feet on Squaw Creek (N. T. 34 N., R. 5 W.) to 120 feet on the north flank of the Klutter Mountains (T. 33 N., R. 1 W.), a distance of about 30 miles.

Southward for a distance of nine miles into New Mexico, Dane (1946, 1948) mapped the Pictured Cliffs Sandstone and the Fruitland Formation. The Pictured Cliffs is a readily mappable unit having a thickness of about 100 feet near the state line, but, according to Dane, it grades laterally southward into Lewis Shale and is indistinguishable from the Lewis although there are marine sandstone beds which may be equivalent to the Pictured Cliffs present for several miles beyond the point where he ceased mapping the unit. Dane's experience with the Fruitland is similar to that with the Pictured Cliffs Sandstone. He carried the Fruitland southward to about the same latitude as where he terminated mapping of the Pictured Cliffs. He (1946) indicated the thickness of the Fruitland to range from 85 to 175 feet and showed scattered coal of no particular consequence in the basal part of the formation.

An important aspect of Dane's (1946) investigation was his conclusion that the Pictured Cliffs "as it crops out in the northeastern part of the San Juan Basin, is distinctly older than the closely similar unit exposed in the southwestern part." However, in the preceding paragraphs the development of the Pictured Cliffs from its southwesternmost occurrences northward along the west side of the basin and northeastward to the Durango area shows that the Pictured Cliffs-Fruitland contact rises stratigraphically through the entire distance. From a few miles south of the San Juan River, on the west side of the San Juan Basin, north to the Durango area, this contact rises about 580 feet on the basis of one electric log and the several stratigraphic rises previously discussed.

The Fruitland Formation is the youngest Cretaceous unit in the San Juan Basin to contain coal of consequence. It represents primarily the paludal depositional environment and is overlain by the Kirtland Shale which represents the subsequent continental facies. The Kirtland Shale, as the lithologic designation would imply, consists principally of shale but it also contains soft sandstone and siltstone beds in varying abundance. According to Bauer and Reeside (1921, p. 172) the Kirtland has a maximum thickness of 1,180 feet on Hunter Wash, in the southwest part of the outcrop area. The formation thins eastward to essentially a featheredge along the eastern side of the San Juan Basin.

The Kirtland is divided into lower and upper shale units separated by the Farmington Sandstone Member which is well exposed as a hard, brown, cliff-forming sandstone in the bluffs near Farmington, New Mexico. The Farmington Sandstone ranges in thickness from 0 to 480 feet and is considered to be of fluviatile origin (Reeside, 1924, p. 22). The unit appears on the northern rim of the basin on the western edge of Archuleta County, reaches a maximum development north of Farmington, and thins to a vanishing point in southeastern San Juan County.

The Kirtland is divided into lower and upper shale units in the San Juan Basin, but inasmuch as the highest coal-bearing unit of significance in the region is the Fruitland Formation, neither these younger nonmarine Cretaceous deposits nor the overlying Tertiary rocks are dicussed.

Strippable Coal Resources of Fields and Areas

Descriptions of the individual coal fields and coal area are grouped stratigraphically, beginning with coals in the Dakota Sandstone (abbreviated Kd), then coals in the Mesaverde Group (Kmv), and finally coals in the highly productive Fruitland Formation (Kf). In some chapters, the minor coal beds in the Dakota Sandstone are described with the overlying Mesaverde Group. For designations of some areas, the Mesaverde Group is subdivided into the Crevasse Canyon Formation (Kcc), and the Menefee Formation (Kmf), and the Menefee into the "upper part" (Kmfu) and the Cleary Member (Kmfc). The designation "K" applied to the Pagosa Springs area refers to all rocks of Cretaceous age.

The boundaries of the various fields and coal "areas" set **up** for this report (fig. 8) are for the most part natural geologic and physiographic divisions, but locally township and range lines or other arbitrary boundaries have been used. This division of the coal fields and coal areas is unlike any previous designations, which were of relatively large areas, too generalized, or were vaguely bounded. Future development of the strippable and deep coal resources of the San Juan Basin probably will result in further subdivision of the coal areas.

A considerable amount of repetition in the stratigraphic descriptions of the fields and coal areas is utilized so that each section can be read separately. The amount of detail or of generalization varies greatly because of different approaches by the various geologists that investigated the coal areas, and because mainly only low-sulfur strippable coal beds are emphasized. Within reports of coal areas, each township is discussed if relevant, the strippable areas are described and are shown on township maps, coal quality is noted with particular attention to sulfur and ash content, and the results of our exploratory drilling are given.

CORTEZ DAKOTA AREA

by John W. Shomaker

SUMMARY

Known occurrences of coal have been extended by surface reconnaissance and the drilling of three test holes to yield a reserve estimated at 158.8 million tons. Of that total, about 148.8 million tons (119.3 million of which are covered by less than 15o feet of overburden) lie in an area of about 3o square miles between the towns of Cortez and Mancos. The remaining part of the estimated reserve underlies the southwestern part of T. 37 N., R. 16 W., northwest of Cortez. The coal is of high-volatile C bituminous rank, and is noncoking. Sulfur content is consistently less than 0.7 percent.

INTRODUCTION

The Cortez Dakota area comprises the region of outcrop of the Upper Cretaceous Dakota Sandstone in Montezuma County, Colorado. The area (fig. 9) is bounded on the west by the Utah state line, on the north by the Montezuma-Dolores county line, and on the east and the southwest by the outcrop of the Mancos Shale. Coal has been mined from the Dakota Sandstone on a small scale for many years.

This evaluation of strippable coal reserves is based on field examination, open-file reports by the U.S. Geological Survey, data provided by the Empire Electric Association of Cortez. three test holes drilled by the New Mexico State Bureau of Mines and Mineral Resources, and other published maps and analyses. Data are very sparse, particularly in the area west of Cortez, and it is still not possible to determine with certainty whether large coal reserves exist.

In the Cortez area the Dakota Sandstone is largely white to yellow-brown crossbedded quartz sandstone, interbedded with gray sandy shale, carbonaceous shale, and coal. Distribution of coals in the section is rather erratic and the carbonaceous shales often change laterally to coals in short distances. The principal coal, at least in the area east of Cortez, lies near the middle of the section beneath a fairly thick sandstone and averages about three feet in thickness, although in places it is 81/2 or 9 feet thick. Other thinner and less continuous coals occur both above and below. The Dakota is overlain by olive-gray to black marine shales of the Upper Cretaceous Mancos Shale and is underlain by variegated shales assigned to the Lower Cretaceous Burro Canyon Formation.

Northeast of Cortez the Dakota Sandstone forms an even southwest-sloping upland cut by deep canyons along its southern and western margins. The overlying Mancos Shale has been stripped off leaving a relatively smooth dip slope. Northwest of Cortez, the Dakota forms very gently rolling plains, bounded on the northeast by the Dolores River Canyon and on the southwest by rugged canyons tributary to McElmo and Montezuma Creeks. A few low rounded hills on the generally flat surface are outliers of the Mancos Shale.

The coal is of high-volatile bituminous A, B, or C rank (U.S. Bureau of Mines, 1937). Analyses of coal from the Montezuma No. z mine, about three and one-half miles east of Cortez, are probably representative. There the as-received heating value ranged from 11,58o to 13,65o Btu per pound. Ash ranged from 4.8 to 16.z percent and sulfur content ranged from 0.5 to 0.7 percent. These analyses along with those of coal cores recovered during the New Mexico State Bureau of Mines and Mineral Resources drilling program appear in Table **1.**

DESCRIPTIONS OF TOWNSHIPS

T. 32-34 N., R. 17-20 W.

In these townships the Dakota Sandstone is exposed in arroyos and on considerable areas of relatively flat surface south and west of Ute Mountain. There are few places where more than 3o or 4o feet of section can be measured. Thin discontinuous coal beds which grade rapidly into gray shales are quite common, but no beds of commercial thickness were found. No reserves were estimated.

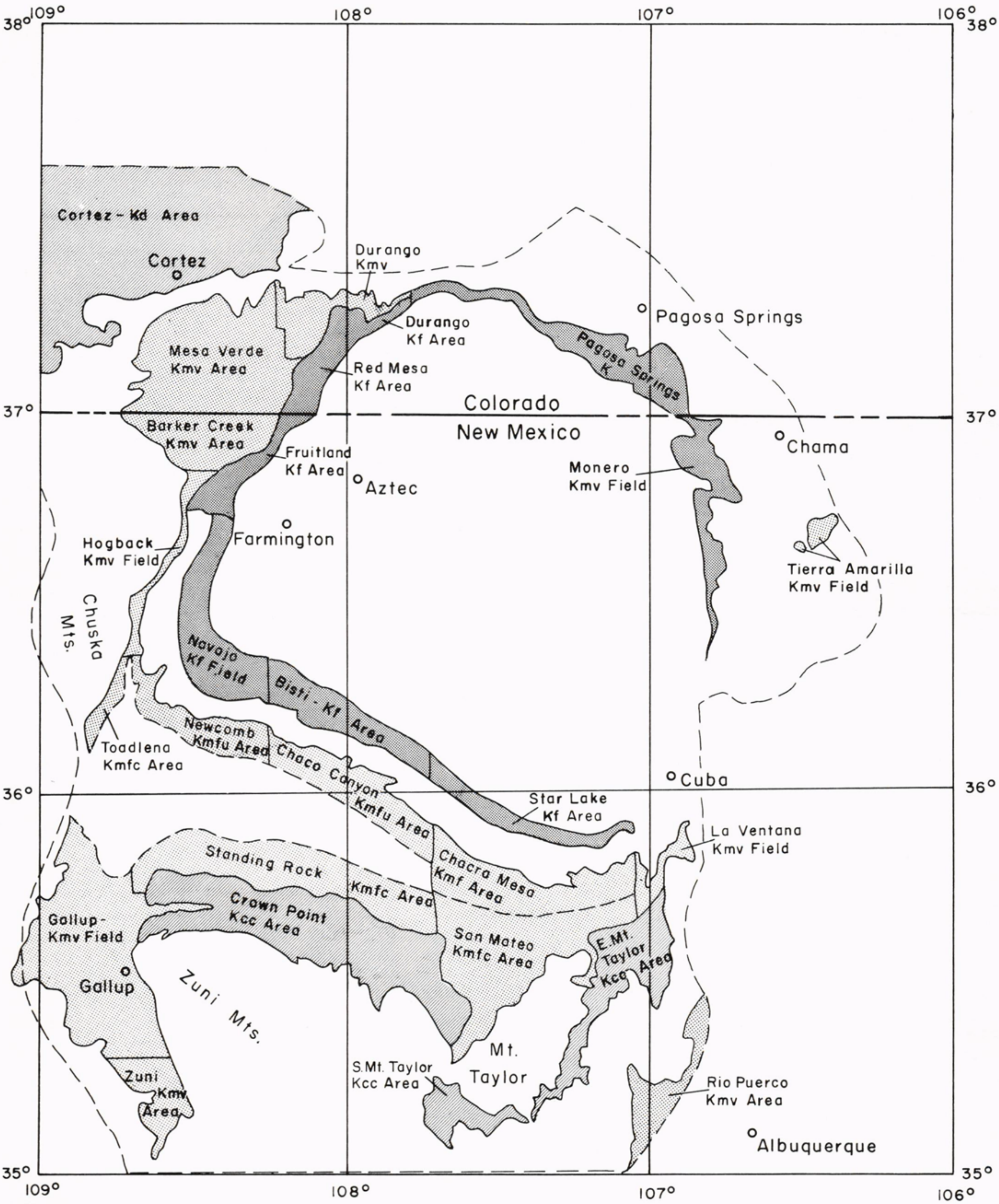

Figure 8
FIELDS AND AREAS OF STRIPPABLE LOW-SULFUR COAL IN SAN JUAN BASIN

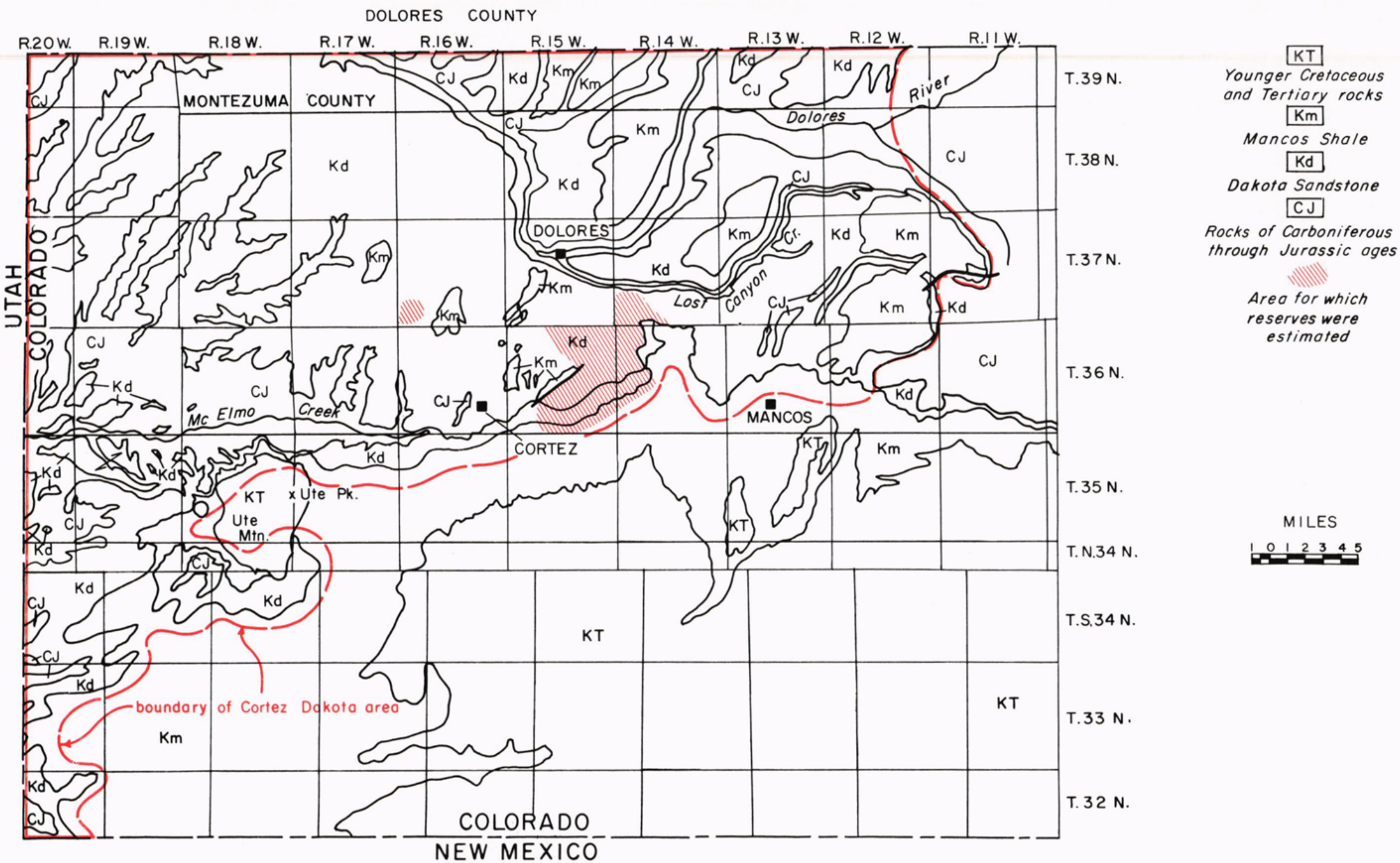

Figure 9

Map showing Cortez Dakota area and areas of estimated strippable reserves

T. 35 N., R. 15 W.

In this township the Mancos Shale and younger rocks are exposed. Though the Dakota Sandstone crops out just north of the north line of the township, the coal sequence probably is too deeply buried to be of commercial value.

T. 35 N., R. 16-20 W.

McElmo Creek Canyon runs nearly along the northern line of this tier of townships. The Dakota Sandstone crops out in McElmo Canyon and in its tributary canyons. Several nearly complete sections of the Dakota Sandstone were measured in the canyon but no coal of commercial thickness was found.

T. 36 N., R. 12, 13 W.

The Dakota Sandstone is exposed in parts of both of these townships, particularly in the deeper canyons. No coal has been reported from either township and none was found during this investigation. Dense timber and brush preclude a thorough examination.

T. 36 N., R. 14 W.

The Dakota Sandstone crops out over an area of about six square miles in the eastern part of the township and about five square miles along the western boundary. The eastern area is almost flat and very heavily covered with timber and brush. No coal was found. In the western part, on the other hand, sections of the Dakota are fairly well exposed and a number of measurements were made. In section 6, 4.1 feet of coal were measured and in section 7 more than 5 feet. New Mexico State Bureau of Mines test hole No. 8 was drilled in the northeast corner of section 18 and 7.3 feet of coal were recovered at a depth of 75 feet. The same coal bed was measured in the southeast corner of the section, where it was at least 3.5 feet thick. Based on these measurements and the measurements nearby in T. 36 N., R. 15 W., a reserve of about 16.4 million tons can be estimated with some assurance. If these data are extrapolated farther east in the township beneath the cover of Mancos Shale, the total reserve for the township beneath less than 150 feet of overburden can be extended to 48.9 million tons, and an additional reserve beneath 150 to 250 feet of overburden of 24.2 million tons can be estimated. The overburden would consist of alternating 20- to 40-foot beds of sandstone and shale.

T. 36 N., R. 15 W.

A small reserve of good quality coal has been known in this area for many years. In 1955 the Empire Electric Association of Cortez drilled about 60 holes in sections 21, 22, 27, and 28, and from this drilling a reserve of approximately 4.3 million tons was calculated. All of this coal lay in one bed ranging from 3.5 to 13 feet in thickness and beneath less than 56 feet of overburden. This area of investigation was extended in a U.S. Geological Survey open-file report (Cullins and Bowers, 1965). In this report a rough estimate of the original reserve in the same main coal bed in sections 21, 22, 23, 27, and 28 indicated about 0.5 million tons of coal. This figure was based on an 80-percent recoverability factor so that actual original reserves in place regardless of recoverability would have been about 13.1 million tons. All of this coal was beneath less than 90 feet of overburden.

For the present study, the area was extended even farther based on additional surface measurements and on New Mexico State Bureau of Mines test hole No. 9 drilled (fig. 10) in the northwest quarter of section 12 in which the main bed was about seven feet thick. The position and thicknesses of the main bed were also extrapolated southward from the original area of investigation into sections 32, 33, 34, and 35 in which the Dakota is covered by alluvium. A total reserve of about 55.7 million tons was estimated, of which about 50.4 million tons would be under less than 150 feet of overburden. It should be recognized that this figure includes coal in measured, indicated, and inferred categories and that much of the coal in the inferred category was estimated on the basis of sparse data.

The topography of the area is well suited for stripping, and the overburden consists of alternate beds of sandstone and shale. Unfortunately, much of the surface is occupied by irrigated farm land so that acreage for a stripping operation would be expensive. Furthermore, the thickness of the coal is rather erratic and the dip, though it averages around 3 degrees, may reach 14 degrees locally.

T. 36 N., R. 16 W.

Except for outcrops of the Jurassic Morrison Formation and the Lower Cretaceous Burro Canyon Formation in the bottoms of some of the drainages, the Dakota Sandstone occurs over the entire township. Several thin coals were measured, particularly in the area immediately northwest of Cortez, but none of commercial thickness were discovered.

T. 36 N., R. 17 W.

The Dakota Sandstone caps the generally flat surface between several deep canyons in this township. Sections were measured in several of the canyons which probably do cut the coal-bearing zone, but no coal of commercial thickness was discovered.

T. 36 N., R. 18-20 W.

Only isolated remnants of Dakota Sandstone between canyons occur in this township. Due to the difficulty of access no sections were measured, but even if coals of commercial thicknesses were found the areas would be too small to be of significance.

T. 37 N., R. 12, 13 W.

The Dakota Sandstone covers extensive areas between deep canyons in these two townships. There are occasional indications of coal in the canyon walls but due to the extremely thick brush cover no extensive investigation was done,

T. 37 N., R. 14 W.

In this township the Dakota Sandstone caps the broad, relatively fiat uplands between the canyons of Lost Canyon

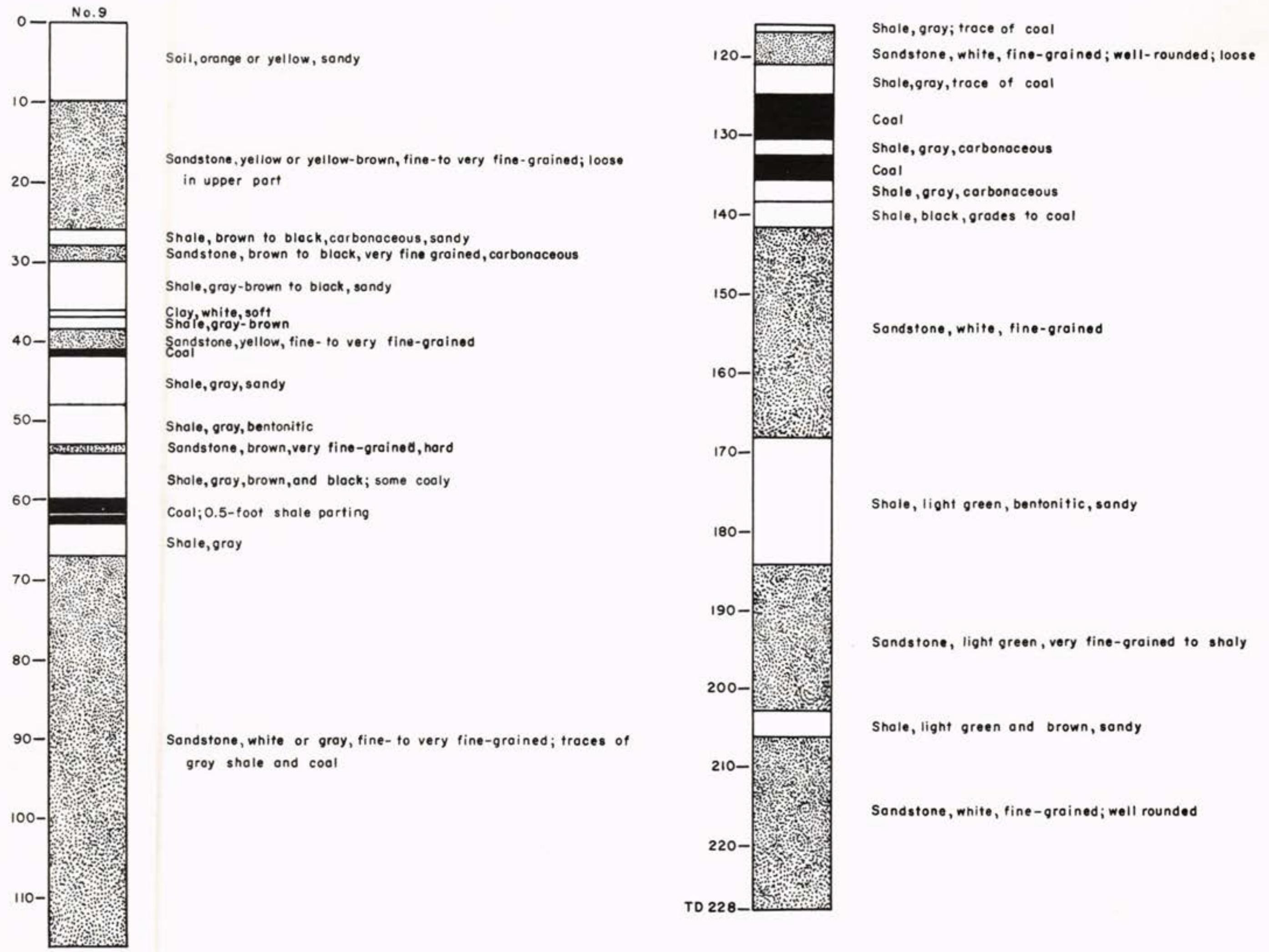

Figure 10

Graphic log of test hole No. 9, NW¼NE¼NW¼ section 12, T. 36 N., R. 15 W., Montezuma Co., Colo. Logged by R. C. Lease

Creek and the Dolores River. There are numerous coal outcrops and abandoned adits in the upper parts of the canyon walls. The area south of Lost Canyon is contiguous with the coal fields described in T. 36 N., R. 14 W., and an isolated measurement of 4.5 feet in section 31 of T. 37 N., R. 14 W. indicates that the thickness of the main coal bed is still significant in this area. By extrapolation it would appear that some 20 million tons might be strippable in this township beneath an overburden thickness of less than 150 feet.

T. 37 N., R. 15 W.

This entire township is underlain by the Dakota Sandstone except for the canyons of the Dolores River and Lost Canyon Creek. Based on the work of the U.S. Geological Survey (Cullins and Bowers, 1965) in T. 36 N., R. 15 W., it would appear that the thickness of the main Dakota coal bed is less than three feet over most of the southeastern part of this township. The thickness of the bed may be greater in the western part of the township; during the present study a bed 3.5 feet thick was measured in section 33. Thus it may be that minable reserves exist in the western part of the township but too few data are available to make an estimation.

T. 37 N., R. 16 W.

The Dakota Sandstone is at the surface throughout this township except for a few small hills which are outliers of the overlying Mancos Shale. A small abandoned mine in section 31 probably indicates a coal bed several feet thick. New Mexico State Bureau of Mines test hole No. ro (pl. 4-A) drilled (fig. 11) in the SW1/4 of section 32, penetrated a 4-foot coal bed at a depth of 76 feet, a 5-foot coal bed at a depth of 132 feet, and a bed about 3 feet thick at a depth of 158 feet. It would appear likely that a small reserve (on the order of 5 to i o million tons) might exist in the southwestern corner of this township. A far larger amount of strippable coal may be present but it could be found only by a rather extensive drilling program. Unfortunately all the coal pen-

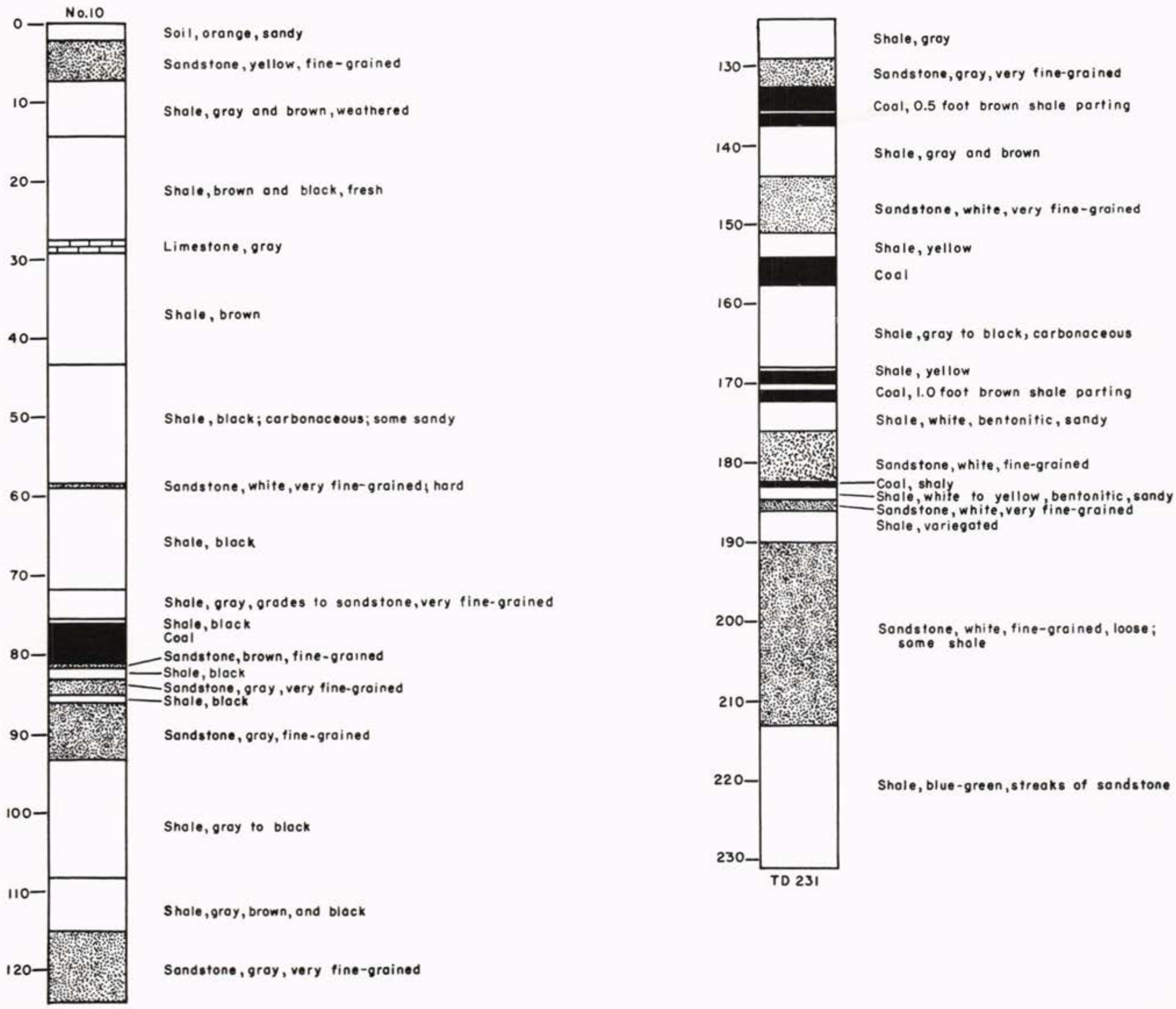

Figure 11

Graphic log of test hole No. 10, SW¼SW¼ section 32, T. 37 N., R. 16 W., Montezuma Co., Colo. Logged by R. C. Lease

etrated in test hole No. 10 lay below the ground-water table and mining of such a reserve would be difficult.

T. 37 N., R. 17-20 W., T. 38 N., R. 15-20 W., and T. 39 N., R. 15-20 W.

Because of similar geology (Finley, 1951) and topography, these townships are discussed together. The Dakota Sandstone forms a broad, gently rolling surface deeply incised from the southwest by deep canyons and on the northeast by the deep canyon of the Dolores River and its tributaries. Coal beds crop out in numerous localities in this area and in at least one place reach a thickness of over six feet. In other localities, however, nearly complete measured sections of the Dakota Sandstone contain no coal. The few oil and gas tests that have been drilled in the area are of little value from a coal exploration point of view because the coal zone, if present, lies so close to the surface that surface casing generally penetrates it; thus the electric logs do not begin until below the coal zone.

Detailed geologic mapping in the canyons that dissect the Dakota Sandstone may reveal thickness trends in the coal that can be projected into the area where no outcrops are available; then drilling could determine whether reserves of any consequence exist. The relatively thick and persistent coal bed east of Cortez suggests that such coal deposits are possible, and this large area northwest of Cortez should not be written off as a coal prospect.

GALLUP MESAVERDE FIELD

by Robin C. Lease and John W. Shoinaker

The Gallup coal field is part of a northwesterly trending outcrop of the Mesaverde Group in western McKinley County, New Mexico (fig. 12). The topgraphy of the area

TABLE 1. ANALYSES OF COAL SAMPLES FROM CORTEZ DAKOTA AREA

LOCATION	KIND OF SAMPLE	CONDITION[1]	SAMPLE NO.	LABORATORY NUMBER[2]	PROXIMATE, PERCENT: MOISTURE	VOLATILE MATTER	FIXED CARBON	ASH	ULTIMATE, PERCENT: HYDROGEN	CARBON	NITROGEN	OXYGEN	SULFUR	ASH	HEATING VALUE: BRITISH THERMAL UNITS PER POUND	FORMS OF SULFUR: SULFATE	PYRITIC	ORGANIC	FUSIBILITY OF ASH, °F: INITIAL DEFORMATION TEMP.	SOFTENING TEMP.	FLUID TEMP.	REMARKS
SE¼ NE¼ Sec. 29, T. 36 N., R. 15 W.	tipple	1	Y-397	C-28505	6.8	33.3	54.0	5.9	—	—	—	—	0.5	—	12,860	—	—	—	2910+	—	—	Montezuma mine; 1″ slack.
		2			—	35.7	58.0	6.3	—	—	—	—	0.6	—	13,800							
		3			—	38.1	61.9	—	—	—	—	—	0.6	—	14,730	—	—	—				
SE¼ NE¼ Sec. 29, T. 36 N., R. 15 W.	tipple	1	3971	C-28504	7.7	32.0	56.8	3.5	5.5	74.8	1.2	14.4	0.6	3.5	13,190	—	—	—	2850	2900	2910	Montezuma mine; 1″ lump.
		2			—	34.6	61.7	3.7	5.1	81.1	1.3	8.2	0.6	3.7	14,290							
		3			—	36.0	64.0	—	5.3	84.2	1.4	8.5	0.6	—	14,850							
SE¼ NE¼ Sec. 29, T. 36 N., R. 15 W.	tipple	1	5833	E-58658	6.6	30.6	49.9	12.9	—	—	—	—	0.7	—	11,930	—	—	—	2790	2910+	—	Montezuma mine; 1½″x0 coal; Hardgrove grindability index = 58; free-swelling index = 1½.
		2			—	32.8	53.4	13.8	—	—	—	—	0.8	—	12,780							
		3			—	38.1	61.9	—	—	—	—	—	0.9	—	14,820							
SE¼ NE¼ Sec. 29, T. 36 N., R. 15 W.	tipple	1	6089	E-58657	4.8	33.9	56.5	4.8	5.5	76.5	1.3	11.3	0.6	4.8	13,650	—	—	—	2760	2890	2910+	Montezuma mine; 1½″ lump.
		2			—	35.6	59.4	5.0	5.2	80.4	1.3	7.5	0.6	5.0	14,340							
		3			—	37.5	62.5	—	5.5	84.7	1.4	7.7	0.7	—	15,100							
SE¼ NE¼ Sec. 29, T. 36 N., R. 15 W.	tipple	1	4565	F-44727	5.0	29.8	49.0	16.2	—	—	—	—	0.6	—	11,580	—	—	—	2910+	—	—	Montezuma mine; 1½″x0 coal; Hardgrove grindability index = 59; free-swelling index = 1.
		2			—	31.4	51.5	17.1	—	—	—	—	0.6	—	12,200							
		3			—	37.8	62.2	—	—	—	—	—	0.7	—	14,700							
SE¼ NE¼ Sec. 29, T. 36 N., R. 15 W.	tipple	1	4567	F-44726	5.5	30.5	52.7	11.3	—	—	—	—	0.5	—	12,400	—	—	—	2910+	—	—	Montezuma mine; 1½″ lump.
		2			—	32.3	55.7	12.0	—	—	—	—	0.5	—	13,120							
		3			—	36.7	63.3	—	—	—	—	—	0.6	—	14,900							
NE¼ NE¼ NE¼ Sec. 18 T. 36 N., R. 14 W.	Core, test hole No. 8	1	8254	J-63511	3.5	19.1	31.0	46.4	3.1	40.2	0.5	9.5	0.33	46.4	6,810	—	—	—	2910+	—	—	Equilibrium moisture = 3.75%; Hardgrove grindability index = 59; free-swelling index = 1.
		2			—	19.8	32.1	48.1	2.8	41.6	0.5	6.7	0.35	41.8	7,060	—	0.13	—				
		3			—	38.2	61.8	—	5.4	80.2	1.0	12.7	0.66	—	13,590							
SW¼ Sec. 23, T. 36 N., R. 16 W.	channel	1			8.1	32.3	45.4	14.2	4.7	60.3	1.0	19.2	0.6	14.2	10,440	—	—	—	—	2980	—	Cortez mine.
		2			—	35.1	49.5	15.4	5.2	65.6	1.1	13.1	0.6	15.4	11,350							
		3			—	41.5	58.5	—	4.9	77.5	1.3	15.6	0.7	—	13,420							
"1½ miles southeast of Cortez"	channel	1			4.8	34.6	42.3	18.3	4.9	59.9	1.1	8.2	7.6	18.3	11,070	—	—	—	—	2130	—	Mowry mine.
		2			—	36.3	44.5	19.2	4.5	63.0	1.2	4.2	7.9	19.2	11,630							
		3			—	45.0	55.0	—	5.6	77.9	1.5	5.2	9.8		14,400							

[1]Condition: 1, as received; 2, moisture-free; 3, moisture- and ash-free
[2]Analyses by U.S. Bureau of Mines

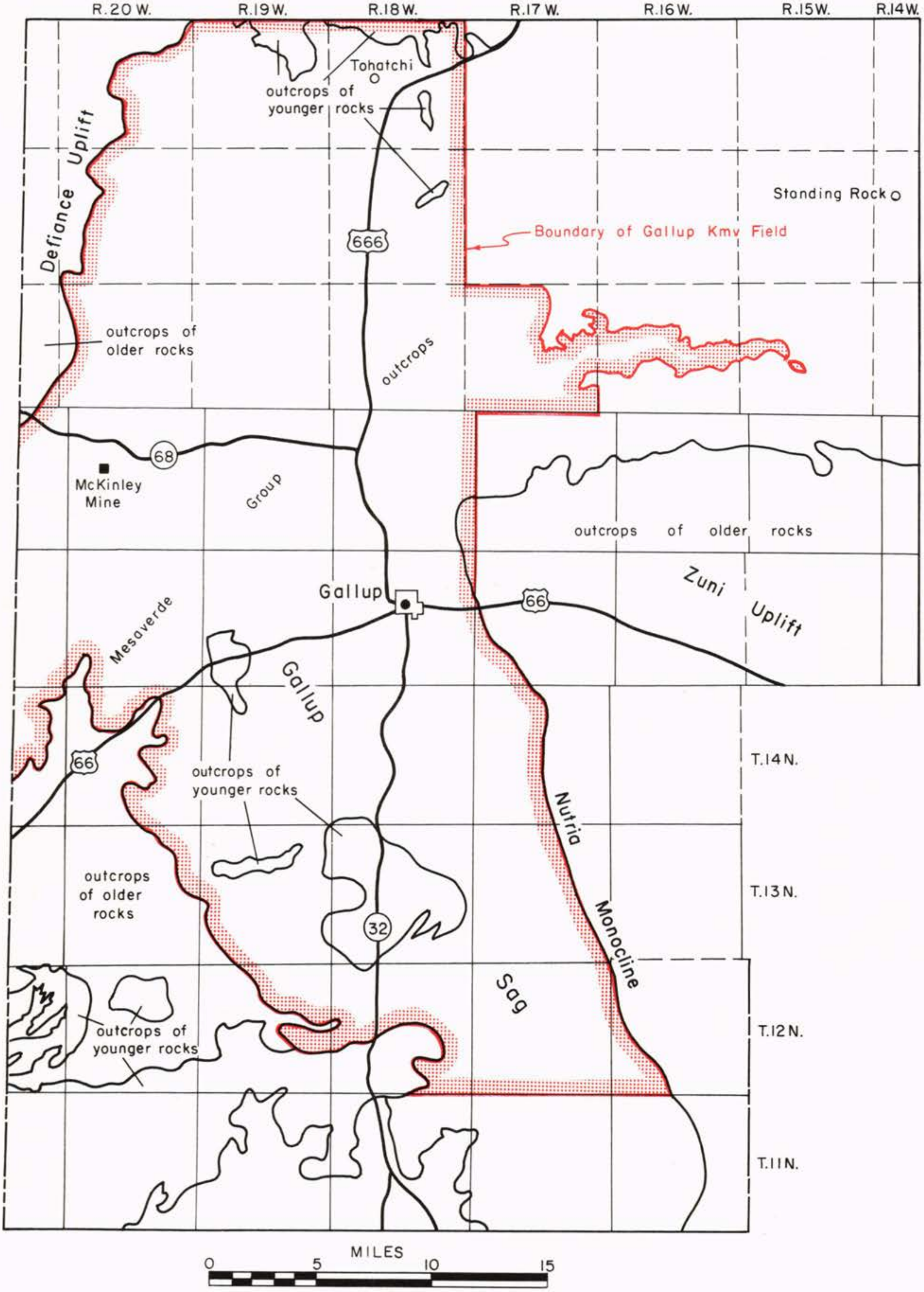

Figure 12
INDEX MAP OF GALLUP MESAVERDE FIELD

is characterized by mesas and tablelands. The climate is arid with little or no surface waters.

Mining began in the 1880's because of the close proximity of the coal outcrops to the mainline of the Atchison, Topeka, and Santa Fe Railway. Other early customers were the copper smelters in southern Arizona. Peak production from the underground mines was about 825,00o tons in 1920; underground mining on an important scale continued until 1951 when the Navajo No. 5 mine ceased operations.

Large-scale strip mining began in mid-1961 when the Pittsburg and Midway Coal Mining Co. opened its McKinley mine (pl. 4-B). The impetus and main customer for the renewed mining is the Arizona Public Service Co.'s coal-fired Cholla electrical generating plant at Joseph City, Arizona. In 1969 this mine produced 440,808 tons of coal and in 197o it produced 385,40o tons; it has the potential for substantially greater production.

GEOLOGIC SETTING

The Gallup coal field is in a southwestern extension of the San Juan Basin known as the Gallup sag. The strata within the sag are relatively flat lying and approximately 6,30o feet thick. It is bounded on the east and west by the basinward-dipping monoclines of the Zuni and Defiance uplifts respectively (fig. 12). Several gently dipping anticlines are found in the south-central part of the sag. Surface mapping shows a few faults trending north-south and some trending east-to-northeast. Underground mining has revealed numerous local faults of limited displacement.

Strata cropping out in the Gallup sag are the Mancos Shale, sandstones, shales, and coals of the Mesaverde Group, and various Tertiary shales and sandstones. The adjacent Zuni and Defiance uplifts have outcrops of Dakota Sandstone, and shales and sandstones of the Morrison, Summerville, and Entrada Formations of Jurassic age. The Triassic sequence below the Jurassic rocks consists of the massive sandstone beds of the Wingate Sandstone underlain by the shales, sandstones, and siltstones of the Chinle and Moenkopi Formations. Permian strata exposed are the San Andres Limestone and the DeChelly Sandstone.

Late Cretaceous time in northern and central New Mexico was marked by repeated movements of the sea from the northeast to the southwest with resulting parallel depositional trends. The oscillating shorelines were accompanied by landward swamps in which coal-forming organic material was deposited.

The thickness and areal extent of the coals appear to have been directly affected by the duration of "shoreline stand-stills." Regionally the major coal lenses are to the landward and trend parallel to the most stable shorelines. Areas that had rapid shifts of shorelines have thin coals. The southern pinchout of several sandstone units (pl.) suggests that the Gallup coal district was in a landward position for substantial periods during Mesaverde Group depositional time (Beaumont, 1968).

COAL-BEARING STRATA

Coal-bearing strata occur in the Dakota Sandstone and the Mesaverde Group in the southern San Juan Basin. The coals of the Dakota are thin, poor in quality, and uneconomic for mining in the Gallup coal field.

Mesaverde Group

The Mesaverde Group in the Gallup Coal Field is divided into four formations as follows:

Menefee Formation
- Allison Member
- Cleary Member

Point Lookout Sandstone

Crevasse Canyon Formation
- Gibson Member
- Bartlett Member
- Dalton Sandstone Member
- Dilco Member

Gallup Sandstone

Commercial coal beds of the Mesaverde Group occur in the Gallup Sandstone, the Dilco and Gibson Members of the Crevasse Canyon Formation, and the Cleary Member of the Menefee Formation. The coals in the Crevasse Canyon and Menefee Formations are the best developed. All of the coals in the Gallup coal field are lenticular and do not show more than one or two miles of continuity (Sears, 1925). The intervals between beds and the thickness of the partings also are quite variable.

Coals in the Gallup Sandstone have been mined for short periods in the Mentmore area west of Gallup. The coals are local lenses in the shales separating the three main sandstone beds of the Gallup. Underground mining and field work have shown these coals to be of limited areal extent; no strippable coal reserves have been calculated for the Gallup Sandstone.

The Dilco Member of the Crevasse Canyon Formation is gradational with the underlying Gallup Sandstone, is 240 to 30o feet thick, and contains five important coal beds. The thickest and the most extensive bed is the Black Diamond coal which ranges from 3.5 feet to over five feet in thickness and is of good quality. The strata between coal beds are lenticular sandstone and shale units of continental origin.

In the southern San Juan Basin, the Point Lookout Sandstone separates the coal-bearing members of the Crevasse Canyon and Menefee Formations. To the southwest in the Gallup sag, the Point Lookout Sandstone is absent and the coal-bearing strata of the Gibson and Cleary Members merge into a single unit (fig. 13). In this chapter the combined Gibson and Cleary Members unit is referred to as the Gibson Member.

The Gibson Member of the Crevasse Canyon Formation is 150 to 175 feet thick with five commercial coal beds. The coals, and the shale and sandstone units separating them, are highly lenticular and difficult to correlate. The principal mining areas in the Gibson Member are north and west of the town of Gallup (Sears, 1925, pl. 1). In the southern part of T. 17 N., R. 17 W., the lower part of the Gibson Member has a coal bed 12 feet thick, the thickest known coal bed in the Gallup coal field. Other commercial coal beds are three to six feet thick and of good quality.

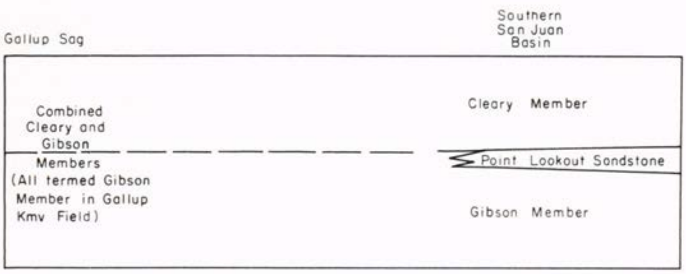

Figure 13
DIAGRAMMATIC CROSS-SECTION OF GALLUP MESAVERDE FIELD

COAL QUALITY

As indicated by the selected representative analyses in Table 2, the coals of the several coal-bearing formations in the field are quite similar. They are generally of high-volatile C bituminous rank, with fairly low ash content (ten percent or less for most samples on an "as-received" basis) and low sulfur content. Sulfur content of the Gibson Member and Gallup Sandstone coals is commonly 0.6 percent or less, and that of Dilco Member coal is generally less than 1.5 percent. No successful coking analyses are known.

TOWNSHIP DESCRIPTIONS

T. 12 N., R. 16 W. and T. 12 N., R. 17 W.

The Dilco Member crops out over nearly all of T. 12 N., R. 17 W.; a capping of the Bartlett Member covers it in about two square miles along the northern line of the township, and the Gallup Sandstone is exposed beneath the Dilco in small patches in sections 31 and 33. In T. 12 N., R. 16 W. the Dilco is exposed over about eight square miles between the sharp fold of the Nutria monocline and the western boundary of the township. A persistent coal bed crops out across the northern half of T. 12 N., R. 17 W. and two beds lower in the stratigraphic section crop out in sections 28 and 29, but none maintain minable thickness over a significant area.

Two coal beds in the Gallup Sandstone crop out just south of sections 31 and 32 of T. 12 N., R. 17 W., and thus underlie virtually all of that township; in one place one of the beds reaches a gross thickness of 4.1 feet, but in general the beds are less than three feet thick. No reserve estimates seem warranted.

T. 12 N., R. 18 W.

This township is not included on any published map showing outcrops of coal beds, and no field investigation was done for this project. The Dilco Member outcrop does occupy most of the eastern and northern parts of the township and the same persistent bed found in T. 12 N., R. 17 W. doubtless is present, but there is little likelihood that it is of sufficient thickness to be minable. The Gallup Sandstone crops out in sections 6, 7, and 8, and 17 to 20, and undoubtedly contains some coal. Though the coal beds in the Gallup are not often of strippable thickness for very great distances along the outcrop, it is possible that beds are thick enough in this area to provide some strippable coal; field examination is justified.

T. 12 N., R. 19 W.

The Gallup Sandstone crops out over about 12 square miles of the northeastern part of the township. Scattered observations indicate the presence of coal beds, but none over three feet thick.

T. 13 N., R. 17 W.

The Dilco Member crops out in the southeast and southwest corners, but the sequence exposed is apparently too high in the stratigraphic section to contain coal. The Gibson Member underlies most of the central and northwestern parts of the township, and contains some coal. Only scattered observations were made, but no coal beds thicker than three feet were found.

T. 13 N., R. 18 W.

The Dilco Member and the Gibson Member are both present in the township. The former is exposed in the southeastern part and underlying the entire township, and the latter underlies the northeast quarter. A few observations revealed no coal of strippable thickness in either unit. However, more field work is warranted in this township and in T. 13 N., R. 17 W.

T. 13 N., R. 19 W.

The Gallup Sandstone crops out over nearly all of the southern half of the township, and underlies the balance. The Dilco Member is exposed over the northern half of the township. No beds over three feet thick were found.

T. 14 N., R. 17 W.

The Dilco Member is exposed in sections 3 through 6, and 9 and 10, west of the Nutria monocline. South of section 10, the entire thickness of the Dilco is part of the mono-dine, and though it crops out in a continuous band to the southern edge of the township, the dip is too steep to permit stripping. In section 9, a bed averaging about six feet in thickness is being stripped in the Sundance mine (pl. 4-C); the reserves have not been determined by drilling, but surface measurements indicate that the strippable portion does not extend over more than one or two square miles in a band trending northwestward from the center of section 9. The reserves estimated for this stripping area are included in an overall figure for the entire field to avoid revealing specific information about individual properties.

The Gibson Member is exposed over about 7.5 square miles in the west-central part of the township. Coal beds were measured at several places in sections 21, 22, and 28 but none exceeded three feet in thickness. Several measurements of an apparently continuous bed in section 24 of T. 14 N., R. 18 W. revealed coal 3.0 to 3.8 feet thick; the proximity to the western edge of T. 14 N., R. 17 W. sug-

TABLE 2. REPRESENTATIVE ANALYSES OF COAL SAMPLES FROM GALLUP MESAVERDE FIELD[1]

LOCATION	KIND OF SAMPLE	PROXIMATE, PERCENT: CONDITION[2]	LABORATORY NUMBER	MOISTURE	VOLATILE MATTER	FIXED CARBON	ASH	ULTIMATE, PERCENT: HYDROGEN	CARBON	NITROGEN	OXYGEN	SULFUR	ASH	HEATING VALUE: BRITISH THERMAL UNITS PER POUND	REMARKS
Sec. 9, T. 14 N., R. 17 W.	delivered coal 1½" x 0	1	I-30855	12.5	38.3	42.5	6.8	—	—	—	—	0.6	6.8	11,390	Dilco Member; "as received" analysis calculated from dry coal analysis.
		2	—	—	43.7	48.5	7.8	—	—	—	—	0.7	7.8	13,020	
SE¼ SE¼ SE¼ Sec. 9, T. 15 N., R. 18 W.	tipple sample 3" lump	1	—	11.4	40.3	40.5	7.7	—	—	—	—	0.7	7.7	11,420	Dilco Member; "as received" analysis calculated from dry coal analysis. Ash softening temperature 2910°F.
		2	—	—	45.5	45.8	8.7	—	—	—	—	0.8	8.7	12,890	
SW¼ Sec. 32, T. 16 N., R. 18 W.		1	—	11.9	37.2	43.0	7.9	5.9	63.6	1.1	21.0	0.5	7.9	11,290	Gibson Member; composite.
		2	—	—	42.3	48.8	8.9	5.2	72.2	1.3	11.8	0.6	8.9	12,820	
		3	—	—	46.4	53.6	—	5.7	79.3	1.4	12.9	0.7	—	14,080	
T. 16 N., R. 20 W.		1	—	14.7	34.6	43.2	7.6	5.3	60.6	1.0	24.9	0.6	7.6	10,680	Gibson Member; "as received" analysis calculated from dry coal.
		2	—	—	40.5	50.6	8.9	5.1	71.1	1.2	13.0	0.7	8.9	12,500	
SE¼ SE¼ SE¼ Sec. 20, T. 15 N., R. 19 W.	channel sample	1	19213	12.7	36.4	43.4	7.47	5.78	64.18	1.10	20.75	0.72	7.47	11,230	Myers bed, Gallup Sandstone.
		2	—	—	41.7	49.7	8.56	5.01	73.52	1.26	10.83	0.82	8.56	12,870	
		3	—	—	45.7	54.3	—	5.48	80.40	1.38	11.84	0.90	—	14,070	
McKinley mine	tipple	1	—	15.20	—	—	7.95	—	—	—	—	0.42	—	10,637	Typical analysis of coal produced from McKinley mine. Provided by Pittsburg and Midway Coal Mining Co.
Sec. 8, T. 15 N., R. 18 W.	mine	1	32274	14.4	38.8	40.8	6.0	6.1	62.6	1.2	23.6	0.5	—	11,110	Composite analysis of 32272 and 32273.
		2	—	—	45.3	47.6	7.1	5.3	73.1	1.4	12.6	0.5	—	12,970	
		3	—	—	48.7	51.3	—	5.7	78.7	1.5	13.5	0.6	—	13,950	
NW¼ Sec. 12, T. 15 N., R. 18 W.	mine	1	A46585	10.0	37.3	46.3	6.4	6.2	66.2	1.2	18.6	1.4	—	11,890	
		2	—	—	41.4	51.5	7.1	5.7	73.6	1.3	10.8	1.5	—	13,210	
		3	—	—	44.6	55.4	—	6.1	79.2	1.4	11.7	1.6	—	14,220	
Sec. 24, T. 15 N., R. 18 W.	mine	1	A89052	13.0	37.4	45.3	4.3	6.2	66.1	1.2	21.7	0.5	—	11,810	
		2	—	—	43.0	52.1	4.9	5.5	75.9	1.4	11.8	0.5	—	13,570	
		3	—	—	45.2	54.8	—	5.8	79.8	1.4	12.5	0.5	—	14,270	
Sec. 28, T. 15 N., R. 18 W.	mine	1	A89051	11.1	37.3	44.8	6.8	6.0	65.2	1.2	20.1	0.7	—	11,600	Composite analysis of A89048 to A89050.
		2	—	—	42.0	50.3	7.7	5.3	73.4	1.3	11.5	0.8	—	13,050	
		3	—	—	45.4	54.6	—	5.8	79.5	1.4	12.5	0.8	—	14,130	
SW¼ NE¼ Sec. 16, T. 15 N., R. 19 W.	mine	1	A11470	10.9	40.7	42.3	6.1	6.0	65.1	1.1	21.1	0.6	—	11,810	Composite analysis of A11467 to A11469.
		2	—	—	45.6	47.5	6.9	5.4	73.1	1.3	12.6	0.7	—	13,260	
		3	—	—	49.0	51.0	—	5.8	78.5	1.4	13.6	0.7	—	14,240	
SE¼ Sec. 21, T. 15 N., R. 19 W.	mine	1	19213	12.7	36.5	43.3	7.5	5.8	64.2	1.1	20.9	0.7	—	11,230	
		2	—	—	41.8	49.6	8.6	5.0	73.5	1.3	10.8	0.8	—	12,870	
		3	—	—	45.7	54.3	—	5.5	80.4	1.4	11.8	0.9	—	14,070	
SW¼ NW¼ Sec. 22, T. 15 N., R. 19 W.	mine	1	19221	15.4	38.2	41.3	5.1	6.3	63.0	1.1	23.6	0.9	—	11,130	
		2	—	—	45.1	48.9	6.0	5.4	74.4	1.3	11.8	1.1	—	13,160	
		3	—	—	48.0	52.0	—	5.7	79.2	1.4	12.5	1.2	—	14,000	
SW¼ SE¼ Sec. 33, T. 16 N., R. 18 W.	mine	1	32342	13.2	37.7	41.2	7.9	5.9	62.0	1.0	22.7	0.5	—	10,920	Composite analysis of 32338 to 32341.
		2	—	—	43.5	47.3	9.2	5.1	71.4	1.2	12.5	0.6	—	12,580	
		3	—	—	47.9	52.1	—	5.6	78.6	1.3	13.9	0.6	—	13,850	
NW¼ Sec. 35, T. 16 N., R. 18 W.	mine	1	32378	15.3	38.2	42.0	4.5	6.2	63.0	1.2	24.7	0.4	—	11,070	
		2	—	—	45.1	49.6	5.3	5.3	74.3	1.4	13.2	0.5	—	13,060	
		3	—	—	47.6	52.4	—	5.6	78.4	1.4	14.1	0.5	—	13,790	
NW¼ (projected) Sec. 22, T. 17 N., R. 17 W.	mine	1	A46443	11.3	35.6	42.6	10.5	6.2	60.9	1.1	20.6	0.7	—	10,830	Tohatchi Indian School mine.
		2	—	—	40.2	48.0	11.8	5.6	68.7	1.2	12.0	0.7	—	12,220	
		3	—	—	45.6	54.4	—	6.3	77.9	1.3	13.7	0.8	—	13,850	

[1] Analyses by U. S. Bureau of Mines.
[2] Condition: 1, as-received; 2, moisture-free; 3, moisture- and ash-free.

gests that some coal of strippable thickness may be present in sections 19 and 30 of that township. In any case, the topographic relief would dictate that any reserve would be limited to hundreds of thousands of tons in sinuous hillside bands. Detailed field mapping, and perhaps a test hole in the northern half of section 20 would be worthwhile.

T. 14 N., R. 18 W.

The Gibson Member crops out in a sinuous pattern across the township, underlies most of the northern two tiers of sections, most of the southern two tiers, and about four square miles in the west-central part. Coals were measured at thicknesses between 3.0 and 3.5 feet at several points in section 3, but apparently correlative beds nearby were less than three feet thick. Two beds, one consistently 3.0 to 3.8 feet thick and the other somewhat thinner, were mapped for short distances in section 24. The thicker bed may represent a reserve of few hundreds of thousands of tons disposed in a sinuous pattern along the flanks of the steep ridges. Measurements of the Aztec coal bed in the area to the north (in T. 15 N., R. 18 W.) adjoining sections 3, 10, and 11 indicate that it may be of strippable thickness over a small area in those sections.

T. 14 N., R. 19 W.

The Gallup Sandstone is exposed in the core of the Torrivio anticline in the central part of the township, and is surrounded by outcrops of the Dilco Member. No coals thicker than three feet were measured in the Gallup Sandstone by Sears (1925) in the area just north of this township. Two beds just over three feet thick were measured by Sears in the Dilco in section 34 of T. 15 N., R. 19 W., so that a strippable thickness may exist in one or more very small areas of T. 14 N., R. 19 W. No reserves were estimated.

T. 14 N., R. 20 W., and T. 14 N., R. 21 W.

The Gallup Sandstone and overlying Dilco Member crop out in the eastern half and along the north line of T. 14 N., R. 20 W. and over about one-half of the partial township T. 14 N., R. 21 W. No observations were made, and no data regarding coal were found in the literature.

T. 15 N., R. 17 W.

The Dilco Member crops out over about 41/2 square miles in the southwest corner of the township. Measurements made during the present study, along with data in Sears (1925), indicate that a small area in sections 29 and 32, slightly less than one square mile, may be underlain by one coal bed of strippable thickness. The measured thicknesses are z.3, 2.5, 6.7, and "5 to 6" feet.

T. 15 N., R. 18 W.

This township, centered on the town of Gallup, was the heart of the coal field during the days of active underground mining. The Dilco Member is exposed in the area south and east of Gallup, and underlies the entire township except for small outcrops of Gallup Sandstone in sections 15, 22, 26, and 27, and a minor area in sections 1 and 12 in which the Gallup Sandstone and older rocks crop out in the Nutria monocline. The Gibson Member crops out in a north-south band only a few hundred feet wide just west of the center of the township, and in an irregular band up to a mile wide in sections 19, 30, and 31. The Gibson underlies most of the west half of the township.

South of the Rio Puerco, the Dilco Member contains only two beds (the Black Diamond and a slightly higher unnamed bed) which contain coal of strippable thickness for a distance of more than a few thousand feet along the outcrop. The Black Diamond and higher beds are present beneath only insignificant areas east of a line north and south through Gallup, but crop out near the western limit of the area shown as Dilco Member (Kcd) on Plate 1 and to the west are present in the subsurface. Thicknesses of the Black Diamond bed and of the higher bed mentioned are 2.5 to 6.8 feet as measured along the outcrop by Sears (1925), but, unfortunately, the thicker coal is caught up in the steep west flank of the Gallup anticline and dips too steeply for stripping (ten degrees and more at the outcrop). Near the southeast corner of the township, dips are within stripping range but the coal is less than three feet thick. Drill holes in section 34 (Sears, 1925) indicate that the thick coal section does not persist downdip.

North of the Rio Puerco, the Black Diamond is the only Dilco bed that is consistently of strippable thickness for more than half a mile along the outcrop, and even it probably contains little or no strippable reserves owing to the ruggedness of the topography and the fact that much of the best coal was mined out during the period of active underground mining. West of Gallup, both north and south of the Rio Puerco, the Dilco Member is at too great a depth to be strippable.

In the eastern flank of the syncline that parallels the western limb of the Gallup anticline, the Aztec bed of the Gibson Member is of strippable thickness in most measured sections (Sears, 1925). Two drill holes in section 29 (Ebasco, 1960) showed thicknesses of 4.1 and 6.3 feet for a bed which may be correlative with the Aztec, and surface measurements in section z8 indicate 2.9 to 4.4 feet; the thickest overburden in either section is probably less than 150 feet. To the north, south, and west in sections 20, 21, and 30 through 33, surface measurements and drilling data indicate that the coal may be too thin to strip mine. Reserves estimated for the area in sections 28 and 29 (see pl. 1) are included in the general total for the Gallup field. Farther north within the syncline, north of section 21, the coal lies at too great a depth to be strippable.

Outcrops of the Gibson Member along the northern boundary of the township include several beds of strippable thickness, but none are present beneath a significant area of this township.

T. 15 N., R. 19 W.

The Gallup Sandstone and the Dilco Member are exposed in both the eastern and western flanks of the Torrivio anticline, in the western half of the township, and the Gibson Member is exposed in a narrow belt across the northeastern quarter. Of six measurements of the Gallup Sandstone (Myers or Richards) coal beds made by Sears (1925), only one section contained more than three feet of coal.

In section 6, surface mapping indicates that the uppermost Dilco bed (Dilco 1) and a bed 2o to 3o feet below it (Dilco 2) are of sufficient thickness to be strippable beneath about one-half square mile. The reserves calculated for the area, and continuations of it in adjoining townships, are included in the general reserve total for the field. Five Dilco beds reach strippable thickness at one point or another on the outcrop in sections 16, **21,** and **22,** but the only bed which is persistently more than three feet thick (the Dilco 4) is so low in the stratigraphic section that it is deeply buried less than a mile from the outcrop. The Dilco 4 bed has not been mined in the past, and presumably some small quantity of coal could be stripped near the outcrop. Dilco beds exposed south of the Rio Puerco in sections 27 and 28 do not appear to be consistently thick enough for stripping.

Drilling by the Gallup American Coal Co. in the earlier days of underground mining indicated that the uppermost bed of the Gibson Member is consistently thick enough for stripping beneath somewhat more than four square miles in sections **2,** 3, and 10 through 14 (Sears, 1925, and Ebasco, 196o). Thicknesses along the outcrop are much less, never reaching three feet; this may indicate abrupt shoreward thinning of the coal lens near the present outcrop. The possibility exists for a small strippable reserve, and an estimate of the tonnage present is included in the total for the field.

T. 15 N., R. 20 W. and T. 15 N., R. **21** W.

The entire thicknesses of the Gallup Sandstone, Dilco Member, and Gibson Member are present in the two-township area (pl. 1). Except for a possible small area of strippable Dilco coal in the east half of section 1 of T. 15 N., R. **20** W. and a few isolated measurements yielding slightly more than three feet of coal in both the Dilco and the Gibson Members, no evidence of strippable coal was found.

T. 16 N., R. 18 W.

All coal-bearing units of the Mesaverde Group are present beneath virtually the entire township, but are involved in the Nutria monocline near the east edge of the township and thus are either too steeply dipping or too deeply buried beneath all but the southernmost part. In sections 33, 34, and 35, the Gibson Member contained numerous coals of strippable thickness, but most of the coal that was originally available at strippable depths has been mined out. In section 32, and in the area north of sections 33 and 34, dips are very steep and place the Gibson coals below stripping reach.

T. 16 N., R. 19 W.

The Gibson Member crops out in sections 30, 31, 32, and 33, and contains one bed which may be strippable in those sections plus parts of sections 34 and 35. This is an extension of the reserve discussed under T. 15 N., R. 19 W. In the remainder of the township the Gibson is too deeply buried to yield strippable coal.

T. 16 N., R. 20 W.; T. 16 N., R. **21** W.; T. 17 N., R. 19 W.; T. 17 N., R. 20 W.; and T. 17 N., R. **21 W.**

These five townships contain the McKinley mine lease of the Pittsburg and Midway Coal Mining Co. The lease covers approximately 32,000 acres, and includes five rather irregular beds in the Gibson Member (more properly the combined Gibson and Cleary Members of the Crevasse Canyon and Menefee Formations, respectively. See the discussion of stratigraphy in the introductory paragraphs). The beds vary greatly in thickness, ranging from **2 to 15** feet (Coal Age, 1966), and are characterized by rolling structure and many erratic partings. Mining began in mid 1961; the coal is shipped by rail to the Cholla plant of Arizona Public Service Co. at Joseph City, Arizona.

Strippable reserves for the five townships are estimated to be 25o million tons in the 10- to 150-foot category and 180 million tons in the 150- to 250-foot category. These estimates are included in the total reserve figures for the field as given under "Coal Reserves."

T. 17 N., R. 15 W.; T. 17 N., R. 16 W.; and T. 17 N., R. 17 W.

In these townships the following convention has been applied to simplify the definitions of the Gallup field and the Crownpoint area: coal above the Point Lookout Sandstone (i.e., in the Cleary Member of the Menefee Formation) and coal in the combined Gibson Member-Cleary Member (of the Crevasse Canyon and Menefee Formations, respectively), which is simply termed the Gibson Member in this report and is recognized where the intervening Point Lookout Sandstone is absent, are included in the Gallup field. Coal in the Gibson Member of the Crevasse Canyon Formation is included in the Crownpoint area. Coals of the Gallup Sandstone and of the Dilco Member of the Crevasse Canyon Formation, as they occur in these townships, are considered part of the Crownpoint area.

In T. 17 N., R. 15 W., Cleary Member beds cover about two square miles in sections 16, 17, 18, 19, and **21** (Sears, Hunt, and Dane, 1936). Two to four coal beds are present, and at least one is strippable (ranging in thickness from 3.9 to 5.5 feet) over about 200 acres in two patches. Overburden is less than 5o feet thick.

Cleary Member beds occupy about eight square miles of T. 17 N., R. 16 W., lying on a long flat-topped ridge in sections 13 through 24. Coal beds are numerous but generally thin (less than 2.5 feet for the most part) and extremely lenticular. New Mexico State Bureau of Mines and Mineral Resources test hole No. 3 was drilled (fig. 14) in the NE1/4NW1/4NE1/4 section **21** to a depth of 297 feet to test the Cleary Member and the upper, more favorable part of the Gibson Member of the Crevasse Canyon Formation. No coal of strippable thickness was found in either unit.

In T. 17 N., R. 17 W. both the Cleary Member and the combined Gibson-Cleary unit are recognized, because the Point Lookout Sandstone, which to the east separates the Gibson and Cleary, pinches out near a line drawn from the northwest corner to the southeast corner of the township.

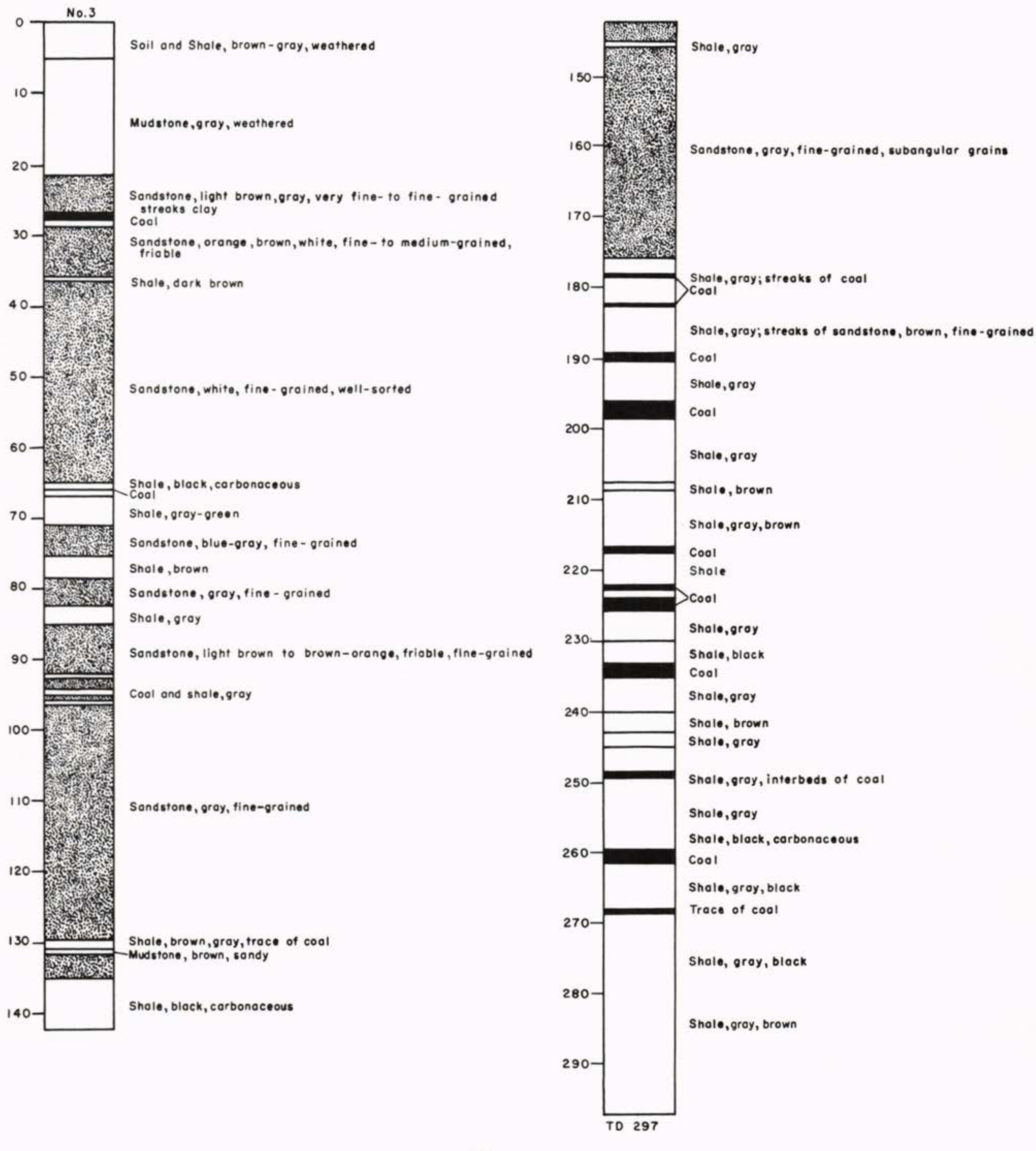

Figure 14

GRAPHIC LOG OF TEST HOLE No. 3, NE¼NW¼NE¼ SECTION 21, T. 17 N., R. 16 W., McKINLEY Co., N.M. LOGGED BY W. H. PIERCE

The combined unit is well over 30o feet thick and contains as many as 14 erratically distributed, lenticular coals, most of which are less than three feet thick. Within two miles of the Point Lookout Sandstone pinchout, two beds, one near the top of the Gibson-Cleary and the other near the bottom, thicken abruptly. The lower bed reaches an 11- to 12-foot thickness and can be followed over perhaps three square miles in the deep canyons in sections 14, 15, 22, 23, z6, and 27. It is everywhere overlain by 200 feet or more of overburden, and northeastward of the Point Lookout pinchout, more and more of the overburden is massive sandstone. The thick development of the upper bed, up to 12.5 feet in two "splits," is apparently confined to a small area in sections 23, 26, 27, and 28. Probably only slightly more than a square mile can be considered strippable; in that area, overburden is generally less than 100 feet.

T. 17 N., R. 18 W.; T. 18 N., R. 18 W.; T. 19 N., R. 18 W.

In these townships, the coal-bearing units are doubtless too deep for stripping.

T. 18 N., R. 19 W.; T. 18 N., R. 20 W.; T. 19 N., R. 19 W.; T. 19 N., R. 20 W.

All of the formations in which coal is found near Gallup are exposed within this four-township area. According to Allen and Balk (1954), coal of "commercial" thickness (3o inches or more) is restricted to the Gibson and Cleary Members. They measured coal up to six feet thick, but found that the coal beds everywhere dip more than five degrees, with an average dip of perhaps 15 degrees.

COAL RESERVES

In order to protect the confidentiality of individual reserves, the Bureau's estimates for areas underlain by strippable coal in the Gallup field have been totalled to yield an aggregate for the entire field. The total includes coal in proven, indicated, inferred, and speculative categories, and much of the total is in small, scattered patches. The estimate is 295 million tons in the 10- to 150-foot overburden category, and 201 million tons in the 150- to 250-foot category. In some areas, the estimate is limited to coal that can be won at a stripping ratio of 10:1 or better and in some areas no ratio limitation was applied.

MESA VERDE, DURANGO, AND BARKER CREEK MESAVERDE AREAS

by John W. Shomaker

The Mesa Verde, Durango, and Barker Creek areas were combined in one brief report for the purposes of this study because of very similar geologic conditions and general lack of strippable coal potential. The areas lie along the northwestern edge of the San Juan Basin, and are all bounded on their east or southeast sides by the Hogback monocline (fig. 15). In general, younger rocks crop out to the east and older rocks to the west of the three areas. All of the coal considered occurs in the Menefee Formation, which overlies the Point Lookout Sandstone and is overlain by the Cliff House Sandstone. The three formations are in the Upper Cretaceous Mesaverde Group.

Coal has been mined by underground methods since the 1870's in various parts of all three areas, particularly in Hay Gulch, in Coal Gulch, near Hesperus, along the northern rim of Mesa Verde, and near Durango. Coal is still being mined on a much reduced scale in all of these localities except the rim of Mesa Verde.

MESA VERDE MESAVERDE AREA

Within the Mesa Verde Kmv area, coal occurs in the upper coal member and lower coal member of the Menefee Formation, a part of the Mesaverde Group. A geologic map (with stratigraphic sections) by Wanek (1954) covered the part of the area west of 108° 20' W. Long. Evaluation of stripping coal reserves in that area was done almost entirely by examination of the Wanek map. East of o8°20' W. Long., the evaluation was made by field examination.

The upper coal member contains only discontinuous beds, rarely of strippable thickness, and is absent in the northern part of the area. The lower coal member contains more coal, although in highly lenticular beds, but its outcrops are in most places on steep canyon walls so that only very narrow bands of strippable areas can be outlined under the criteria used in the study. The greater part of the area, particularly east of the Mancos River, is covered by a thick cap of the Cliff House Sandstone which masks the Menefee Formation and is an effective barrier to strip mining.

No reserves were calculated for the Mesa Verde Kmv area.

DURANGO MESAVERDE AREA

In general, the coal beds in the Durango Kmv area occur sporadically throughout the Menefee Formation, but with their major development within 100 feet of the top of the formation. The area is partly covered by a detailed geologic map, with stratigraphic sections (Zapp, 1949), from which most of the coal evaluation was made.

Except for outcrops on the walls of canyons, the Menefee Formation is everywhere covered by the massive Cliff House Sandstone. Thus the overburden is nearly all sandstone, and it is nearly everywhere more than 25o feet thick. In the Hay Gulch area, where coal sections have been measured in mines, the overburden is about 25o feet thick at the rims of the canyons and thicker away from the rims; in the Coal Gulch area overburden thicknesses are even greater, partly because the minable coal beds are somewhat lower in the Menefee Formation.

No significant strippable reserves were found in the Durango Kmv area.

BARKER CREEK MESAVERDE AREA

The Menefee Formation of the Mesaverde Group contains coal in two stratigraphic zones in this area, one comprised of the upper 25o feet and the other of the lower 100 feet (Hayes and Zapp, 1955). As much as 19.2 feet of coal is known to occur in the upper zone and as much as 17.3 feet has been measured in multiple beds of the lower zone. Unfortunately, in every part of the area the Menefee Formation is either involved in the Hogback monocline, where it dips too steeply to permit stripping, or is overlain by thick beds of the Cliff House Sandstone.

The sections measured by Hayes and Zapp beneath the cover of Cliff House Sandstone indicated that the individual coal beds of the upper zone are generally not of strippable thickness and are rather erratically distributed through the zone. The coals of the lower zone are poorly exposed in the area away from the Hogback, but in none of the exposed sections does a single bed exceed 2.4 feet.

No strippable reserves were calculated for the Barker Creek Kmv area.

COAL QUALITY

A large number of analyses are available in the published literature; many are listed in U.S. Bureau of Mines Tech-

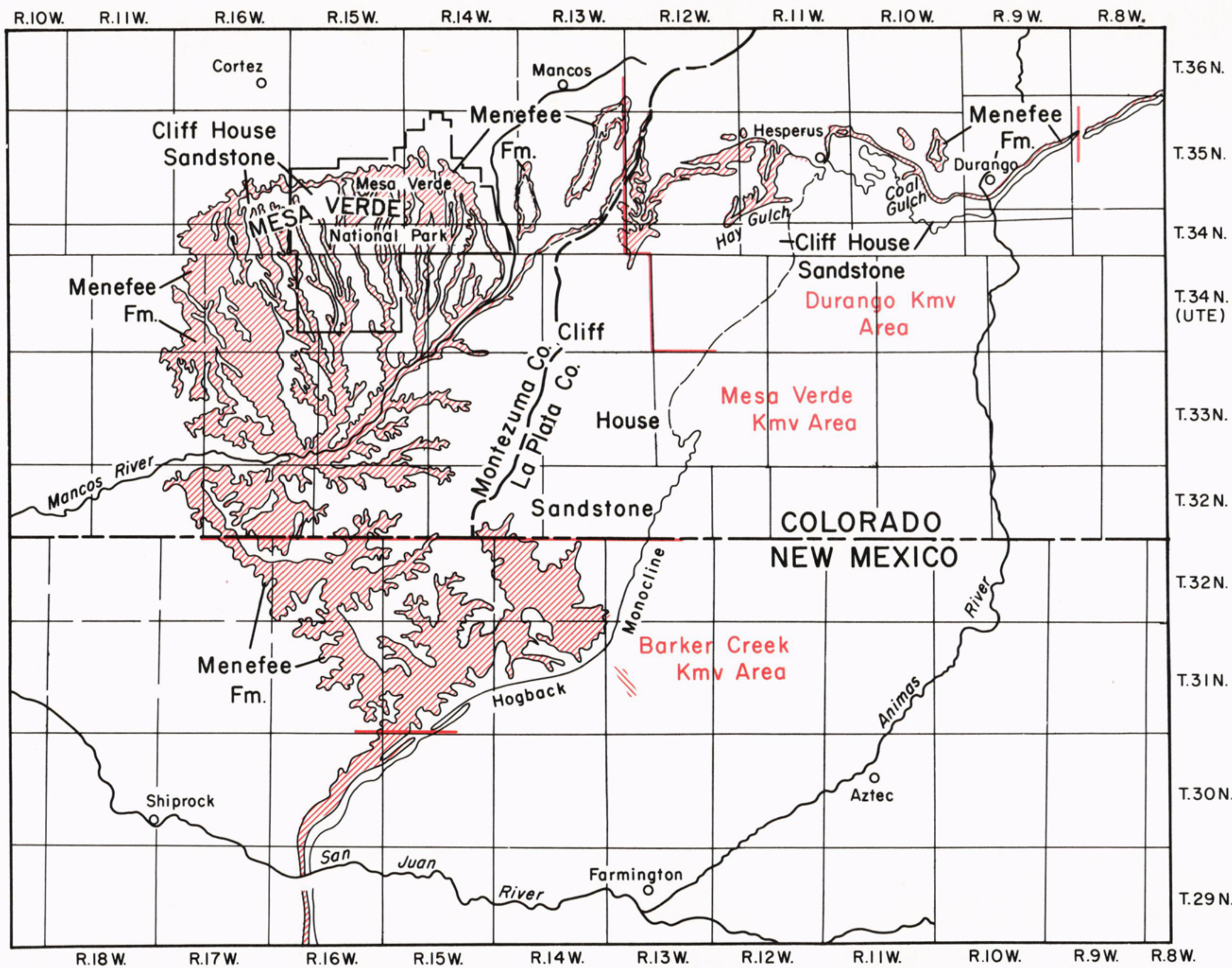

Figure 15

Map showing Durango, Mesa Verde, and Barker Creek Mesaverde areas and outcrops of Menefee Formation and Cliff House Sandstone nical Paper 574 (1937). The coals are typically of high-volatile bituminous B or C rank, with as-received heating values ranging from 12,500 to more than 14,00o Btu, ash content of I o percent or less, and sulfur content generally less than 1.0 percent. Sulfur content is erratic in some areas, owing to the presence of the sulfur in irregular pyrite or marcasite veins.

HOGBACK UPPER MENEFEE AREA

by Robin C. *Lease*

The Hogback Kmfu area is a northerly trending outcrop of Menefee Formation and Cliff House Sandstone in the northwestern San Juan Basin (fig. 16). It is bounded on the north by T. 3o N. and on the south by T. 26 N.

The Menefee Formation has two coal zones in the Hogback area: a poorly developed lower Menefee coal zone just above the Point Lookout Sandstone and an upper Menefee coal zone associated with the base of the Cliff House Sandstone. The coals in the lower Menefee coal zone range in thickness from a few inches to 11.3 feet and are best developed near the San Juan River.

The upper Menefee coal zone is near the base of and locally intertongues with the Cliff House Sandstone. Aggregate coal thickness ranges from 2.5 to 38.3 feet and occurs in as many as I o separate beds. The individual beds are quite lenticular and locally thicken to as much as 22 feet. Several small underground mines have been operated periodically for local use.

The area is structurally part of the eastward-dipping Hogback monocline. Dips range from approximately 10 degrees in the south to as much as 38 degrees in the north along the San Juan River (Beaumont and O'Sullivan, 1955).

Dips appreciably greater than eight degrees are too steep for strip mining with existing techniques. The area appears to have a substantial amount of coal reserves, but these are uneconomic for strip mining owing to the steep rate of dip. No stripping coal reserves have been calculated.

TOADLENA UPPER MENEFEE AREA

by Robin C. *Lease*

The area of this investigation (fig. 17) is about 5o miles north of Gallup and 1 1/2 miles west of the Two Gray Hills Trading Post. Coal exposures are in a small northern tributary of Captain Tom Wash. An east-west paved highway (two miles to the north) and an extensive network of dirt roads provide good access to the area.

The Toadlena area (parts of T. 23 N., Rs. 18 and 19 W., and T. 24 N., R. 19 W.) lies along the eastern edge of the Chuska Mountains in a region of mesas dissected by east-flowing streams. The climate is arid and vegetation is characterized by grass, sage, and woodland of juniper and piñon. Surface water is not plentiful and ground-water supplies have had little development.

The area is immediately east of the Defiance monocline and south of the Tocito dome. Structural strike is to the northeast and dips are 4 to 12 degrees to the southeast with an apparent decrease from west to east.

Strata cropping out in the area are in the Mesaverde Group of Late Cretaceous age. The Point Lookout Sandstone caps the mesas along the northern flank of the area and the softer rocks of the Menefee Formation form the stream-cut tablelands of the central part. Widespread landslide deposits, terrace gravels, and alluvium cover the southern edge.

The only known coal exposures are in the upper Menefee Formation. They are in beds 1.5 to 2.5 feet thick which characteristically occur in pairs with 1 to 2 feet of shale parting. These coals are in most places capped and underlain by 5 to Io feet of brown shale.

The thinness of coal beds, their partings, and the amount of overburden are critical factors in determining the economics of strip mining. Outcrop evidence indicates that these coals are of insufficient individual thickness and projection of structural dips places the coals at angles and depths unfavorable for strip mining.

NEWCOMB UPPER MENEFEE AREA

by John W. Shomaker

SUMMARY

The Newcomb area is an outcrop of the upper part of the Upper Cretaceous Menefee Formation. There are numerous coals of irregular thickness and limited areal extent; in several localities, coals of minable thickness may occur over significant areas, and in one area, in T. 24 and 25 N., R. 17 W., a reserve of 77.8 million tons has been estimated. The coal is of subbituminous A or B rank, with sulfur content generally less than 1.0 percent.

INTRODUCTION

The Newcomb upper Menefee (Kmfu) area is that area of outcrop of the upper part of the Menefee Formation along the Chaco River between a point about the mouth of Captain Tom Wash and the eastern boundary of the Navajo Indian Reservation, and including outcrop areas of younger rocks to the extent that coal-bearing Menefee strata might underlie them at strippable depth (fig. 17).

Generally speaking, the coal beds in the area are associated with a sequence of tan to white sandstones near the top of the Menefee Formation and in the overlying Cliff House Sandstone. The structure in the area is such that the topography is dominated by sandstone-supported cuestas which face west in the northwestern part and turn to a southward-facing position in the eastern part, with strata dipping generally toward the Chaco River at every point. The topography is much modified, particularly in the area east of Coyote Wash, by the effect of burning of the coal beds. Where the shales and sandstones are baked by the burning, myriad isolated hills and irregular ridges are formed by erosion.

The coal beds themselves, though abundant, are lenticular and irregularly distributed both areally and in the stratigraphic section. Evaluation of the coal deposits was done through use of published maps (O'Sullivan, 1955; Beaumont and O'Sullivan, 1955), oil well logs, and by field examination of outcrops and drilling of test holes.

Coal of the Menefee Formation was sampled at three shallow pits, and in two core holes drilled by the New Mexico

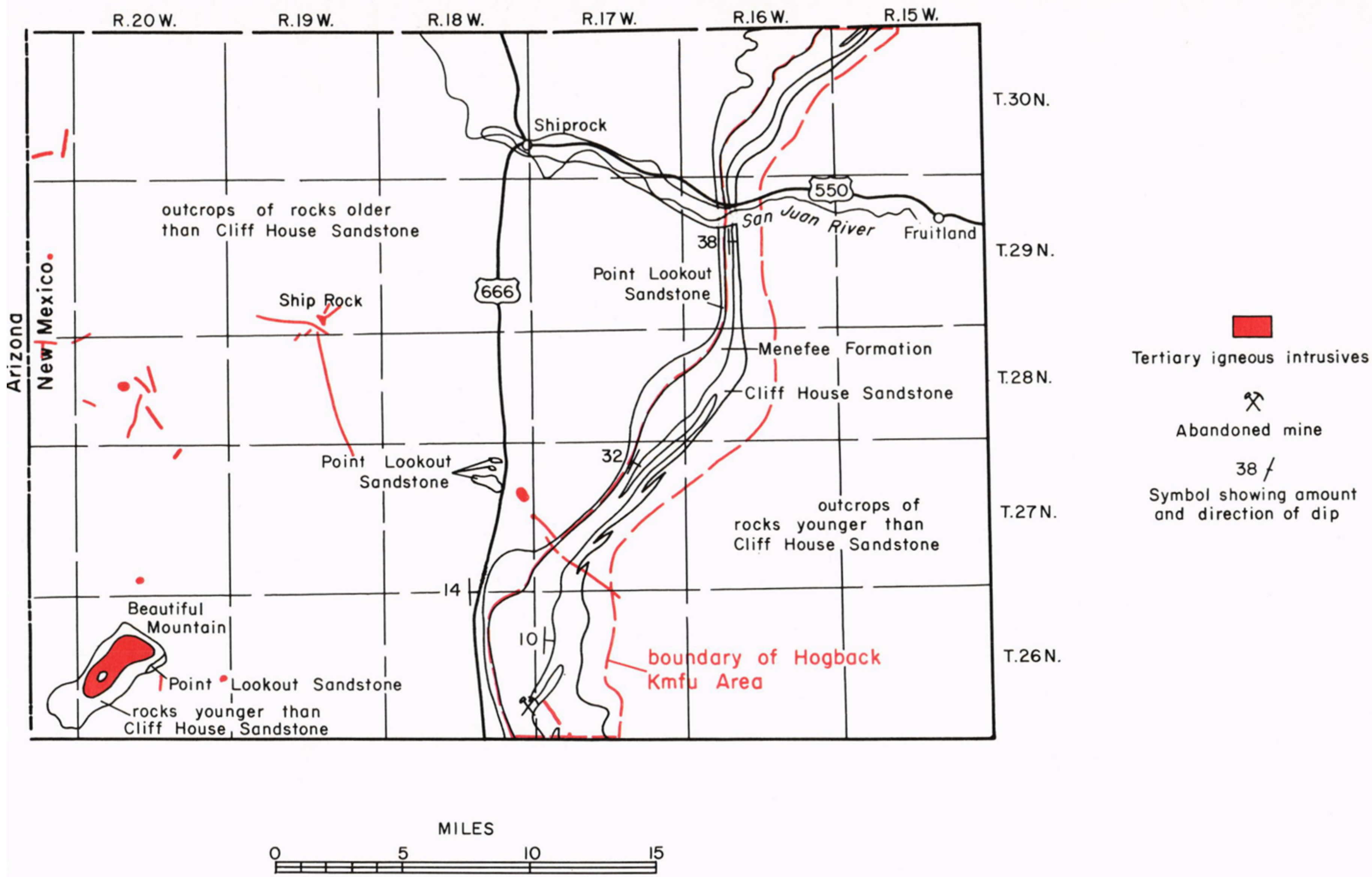

Figure 16
Index map of Hogback Upper Menefee area

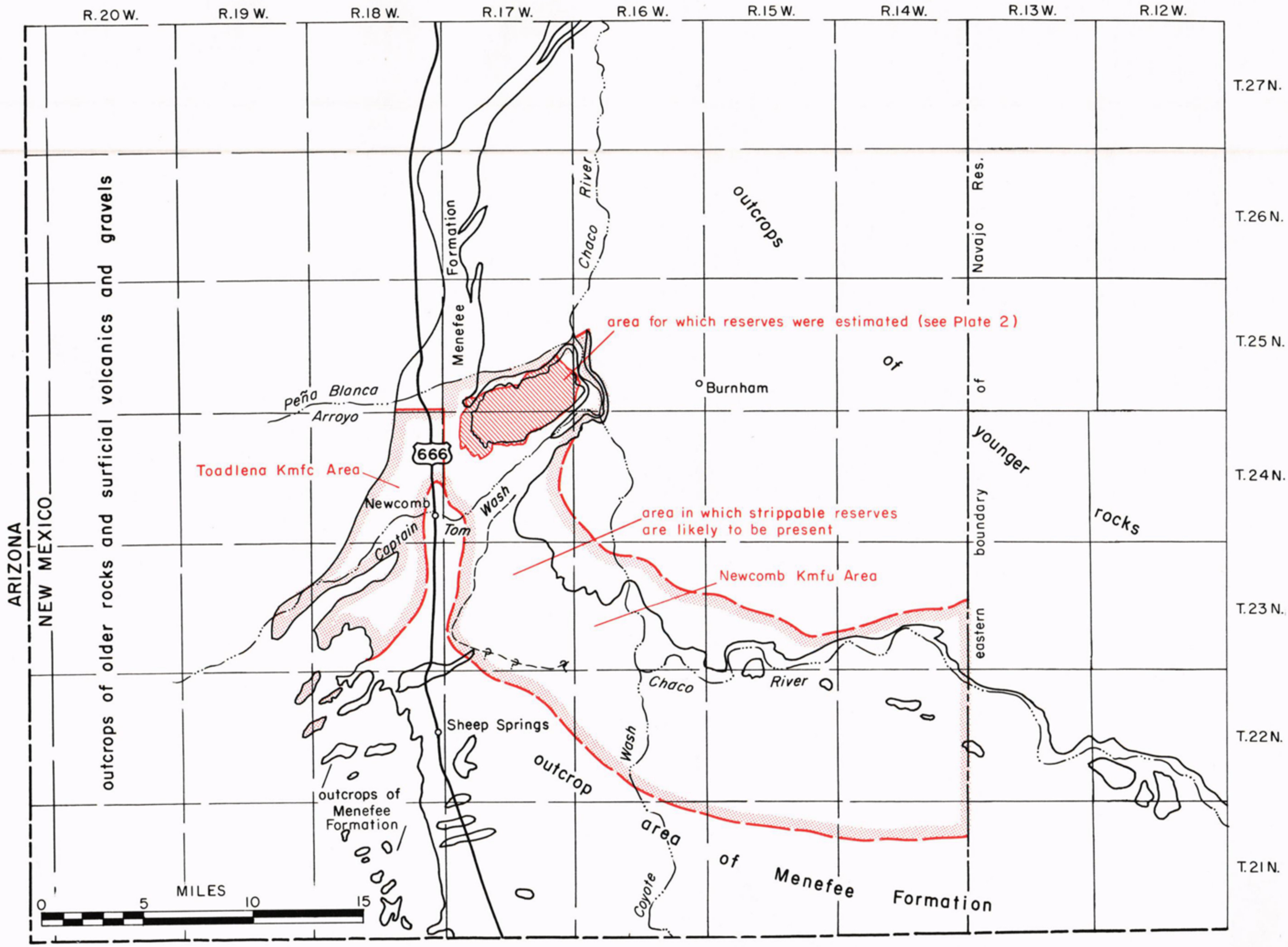

Figure 17

INDEX MAP OF TOADLENA AND NEWCOMB UPPER MENEFEE AREAS

State Bureau of Mines and Mineral Resources. Full proximate and ultimate analyses were determined by the U.S. Bureau of Mines coal laboratory in Pittsburgh. The coal was found to be of subbituminous A rank for relatively unweathered samples. The analyses are tabulated in Table 3.

T. 21 N., R. 14 W.; T. 21 N., R. 15 W. No coal-

bearing rocks were found in these townships.

T. 22 N., R. 14 W.

Shales and sandstones of the Menefee Formation occupy the entire township except for a few acres of Cliff House Sandstone outcrop in section 1. In the northeastern part of the township (sections 1-5, 8-16, 22-26), a number of coal beds are exposed, some of significant thickness. The coals are commonly burned on the outcrop, and that, coupled with the rough topography resulting from extensive dissection of the strata and from the effect of the burning, makes correlation of the coals difficult. However, the coals appear to be highly lenticular and of limited and irregular areal extent. Furthermore, the thicker coals are generally high in the section, near the base of the Cliff House Sandstone, and are thus present only in the highest hills and mesas.

A possible exception may be the beds exposed in the White Rock mine in section 31 of T. 22 N., R. 13 W.; here two beds 3.1 and 6.6+ feet thick are separated by a parting about 2.8 feet thick. These beds can be traced about 1,000 feet northwestward, almost to the east line of T. 22 N., R. 14 W., where they are covered. If they do continue, and their thicknesses remain fairly constant, a small reserve (5-10 million tons) may be present in sections 24 and 25 of T. 22 N., R. 14 W.

T. 22 N., R. 15 W.

Most of the township is underlain by upper Menefee Formation coal-bearing strata but only in a small mesa in section 1 were coal beds of minable thickness discovered.

T. 22 N., R. 16 W.

Upper Menefee Formation coal beds underlie most of the northern half of the township, and several very lenticular coal beds were measured. At only two places, one at the center of the east edge of section 5 and the other in the northeast quarter of section 2, were beds thicker than three feet measured, and the beds thinned markedly a short distance from the point of measurement in both cases. The possibility remains but there is no proof that thicker coals exist below the beds that are exposed.

T. 22 N., R. 17 W.

Though the coal-bearing part of the upper Menefee Formation occupies the northeast part of the township, no coal outcrops of any significance were found. It is possible that some reserves are present, but none were indicated by surface examination.

T. 23 N., R. 14 W.

The coal-bearing Menefee sequence crops out over the township south of the Chaco River, and at the base of the steep bluff of Cliff House Sandstone along the north side of the Chaco. Measurements of coal beds just below the base of the Cliff House in SW1/4 section 24 (4.9 feet) and in NE1/4 section 30 (8.7 feet in two beds) indicate that a fairly important coal zone is present at this horizon. The outcrops can be traced for only short distances and no drilling data are available, but there is at least potential for a reserve of as much as several tens of millions of tons beneath less than 50 feet of overburden if the coal is continuous and of minable thickness between the two outcrops. A test hole should be drilled in the northeast corner of section 20 to a depth of about 400 feet to determine whether the zone continues eastward and downdip.

T. 23 N., R. 15 W.

As in T. 23 N., R. 14 W., the Menefee coal measures crop out over most of this township south of the Chaco River and in a narrow band at the base of the Cliff House Sandstone bluffs north of the river. No coal of minable thickness was found, but if the normal northwestward depositional trend prevails, the coal zone mentioned in T. 23 N., R. 14 W. may exist downdip from the outcrop beneath a cover of Cliff House Sandstone, Lewis Shale, and Fruitland Formation. Only drilling would reveal whether a strippable reserve is present.

T. 23 N., R. 16 W.

The upper Menefee Formation is exposed throughout the western half of the township and in much of the southeast quarter. No Menefee coal of significant thickness was found in surface examination, but it is possible that the deeper beds penetrated in test hole No. 5 (in section 2 of T. 23 N., R. 17 W.) would be found thick enough and shallow enough to be minable in the western half of the township.

T. 23 N., R. 17 W.

The coal-bearing sequence of the upper Menefee Formation forms a low, irregular west-facing cuesta whose crest trends slightly west of south from the northeast corner of section 5 to the south edge of section 19. The gentle topography of the dip slope east of the crest is all underlain by the coal-bearing sequence, as is most of the southern third of the township (i.e., south and east of section t9).

Numerous coal-bed measurements (pl. 2) indicate that there are many thin beds of very limited extent along the outcrop. The thickest bed measured was only 3.9 feet thick, and it could be traced only a few hundred feet. However, the situation presented by test hole No. 5 drilled (fig. 18) by the New Mexico State Bureau of Mines in the southwest quarter of section 2 was quite different. In the test hole, a bed 6.8 feet thick was encountered at 97 feet and that bed can be correlated with a probable coal about 7.0 feet thick at 88 feet in an abandoned well about 3,100 feet west. Between the two holes, it would be reasonable to estimate about two million tons, and it seems likely that additional drilling would reveal a small but significant reserve.

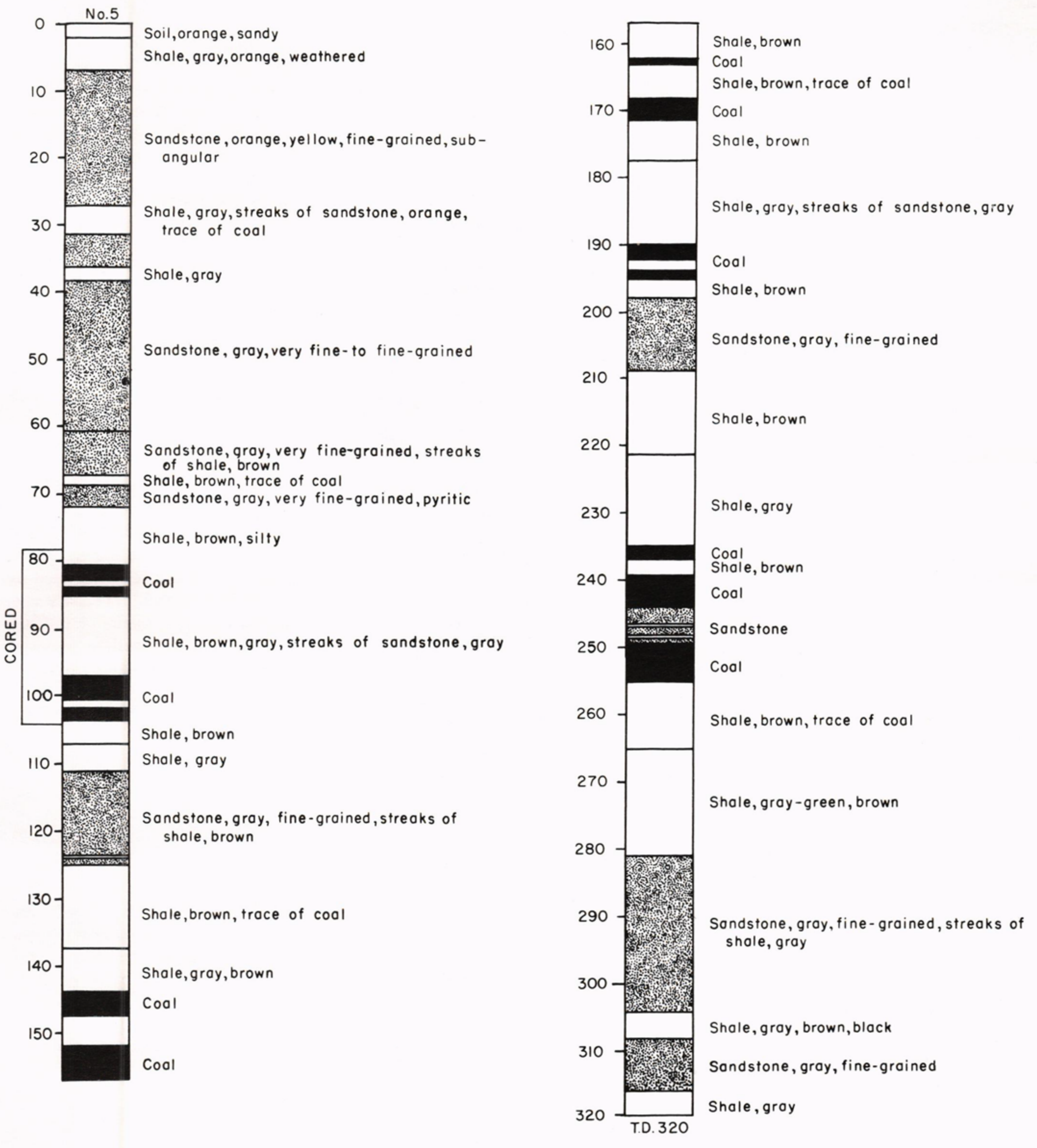

Figure 18

Graphic log of test hole No. 5, NW¼SW¼SW¼ section 2, T. 23 N., R. 17 W., San Juan Co., N.M.
Logged by R. C. Lease

The quality of the coal as determined from the core taken in test hole No. 5 is on an as-received basis, moisture 18.5 percent, volatile matter 27.7 percent, fixed carbon 31.1 percent, and ash 22.7 percent. Sulfur is 0.54 percent, with 0.66 percent on a moisture-free basis, including 0.11 percent pyritic sulfur. Btu on a moisture-free basis was 9,410 per pound.

The coals cored in test hole No. 5-A were of better quality, containing 13.0 to 10.7 percent ash, 15.8 to 17.4 moisture, 31.6 to 31.5 percent volatile matter, 39.6 to 40.4 percent fixed carbon, and 1.17 to 1.4 percent sulfur. The sulfur percentages are higher than most coals at these horizons in this part of the San Juan Basin.

T. 24 N., R. 16 W.

The coals of the upper Menefee Formation underlie the entire township and are probably beneath less than 150 feet of overburden in the northwest corner. It is very likely that the strippable reserve described in T. 24 N., R. i 7 W. extends into sections 5 and 6 of T. 24 N., R. 16 W., but no data are available to confirm that it does.

The results of drilling (test hole No. 5) in section 2 of T. 23 N., R. 17 W. indicate that the southwestern part of T. 24 N., R. 16 W. may be underlain by strippable coal as well, but it would be for the most part in the 150- to 250-foot overburden category.

Extensive strippable reserves in the Fruitland Formation are described in the section dealing with the Navajo Kf Field.

T. 24 N., R. 17 W.

The upper Menefee Formation coal measures underlie about 1 i square miles in the southeastern part of the township and about 61/2 square miles in the north-central part of the township (see pl. 2). In the southeastern area, I1 measurements were made; coal thickness ranged from 1.0 to 5.5 feet in several lenticular beds. However, based on the New Mexico State Bureau of Mines test hole No. 5 in section 2 of T. 23 N., R. 17 W., which penetrated a 6.8-foot bed of fair coal, it would seem that this area has some promise.

In the north-central area of the township, the coal-bearing rocks underlie (in ascending order) the Cliff House Sandstone, a thin wedge of Lewis Shale, and a remnant of the Pictured Cliffs Sandstone, all of Late Cretaceous age. Two short dikes of probable Tertiary age intrude the section. Three outcrop coal measurements and two subsurface measurements (in New Mexico State Bureau of Mines test hole No. 5A in section 36 of T. 25 N., R. 17 W. and in the J. H. Lawrence No. i Navajo oil test) indicate a continuous bed four to about eight feet thick under 4,190 acres. If an average thickness made up of these measurements plus three additional outcrop measurements on an apparently correlative bed in T. 25 N., R. 17 W. is considered representative, then a reserve of about 38.4 million tons can be estimated; of that amount about 4.4 million tons would lie beneath more than 150 feet of overburden. Several other coals of minable thickness, both deeper and shallower, were encountered (fig. 19) in the New Mexico State Bureau of Mines test hole No. 5A, and several deeper minable coals are also indicated by the electric logs of the Lawrence oil test. From these considerations, it would appear that this area has definite stripping-coal potential.

The quality of the coal is doubtless similar to that sampled in sections 27 and 36 of T. 25 N., R. 17 W. (see table 3). Overburden would consist of interbedded soft gray and brown shale and very fine-grained gray sandstone. The sandstone beds are quite hard, but are not likely to be more than 4o feet thick.

T. 2.5 N., R. 16 W.

The coals of the upper Menefee Formation underlie the entire township, and are probably minable in parts of sections 3o and 31. Though no direct evidence of minable coal was found, it is reasonable to suppose that the strippable reserve delineated in T. 24 N., R. 17 W. and T. 25 N., R. 17 W. extends into that area. The coals either are beneath the broad channel of the Chaco River or are covered by too great a thickness of younger rocks throughout the remainder of the township.

The extensive reserves of strippable coal in the eastern half of the township are described in the section dealing with the Navajo Kf Field.

T. 25 N., R. 17 W.

The coal measures of the upper Menefee Formation underlie the Cliff House Sandstone in most of the eastern half of the township, and in most of the area south of Peña Blanca Arroyo (the northern limit of the Newcomb area).

Three outcrop measurements and New Mexico State Bureau of Mines test hole No. 5A, together with data in T. 24 N., R. 17 W., indicate a possibly continuous bed of minable thickness beneath some 4,275 acres. The coal bed is overlain by the Cliff House Sandstone, the Lewis Shale, and the Pictured Cliffs Sandstone and has been intruded by a dike and a small intrusive neck of probable Tertiary age. Using an average of all thickness measurements of the bed in both townships, a reserve of about 39.4 million tons can be estimated, of which about 1.9 million is covered by more than 150 feet of overburden. The overburden consists of soft gray and brown shale and fairly hard, very fine-grained sandstone.

The coal was sampled in an open cut in section 27, and in test hole No. 5A. The analyses are shown in Table 3.

CHACO CANYON UPPER MENEFEE AREA

by Robin C. Lease

The Chaco Canyon upper Menefee area is a northwestward-trending area of Menefee Formation outcrop in the southern San Juan Basin (fig. zo). It is bounded on the southeast by R. 8 W. and on the northwest by the Navajo Indian Reservation boundary (T. 22, 23 N., R. 14 W.). In terms of coal beds there are two areas of interest: the South Chaco Canyon National Monument subarea and the La Vida Mission subarea.

SOUTH CHACO CANYON NATIONAL MONUMENT SUBAREA

This subarea extends from R. 8 W. on the southeast to the northern end of Chacra Mesa in Chaco Canyon National Monument (sections 25 through 28, T. 21 N., R. 10 W.). Topographically, the subarea is a series of high northwestward-trending mesas and valleys. The higher mesas have sparse forests of piñon and juniper while the valleys are grasslands. All drainage is intermittent and trends to the northwest and southeast.

The mesas are generally capped by the Cliff House Sand-

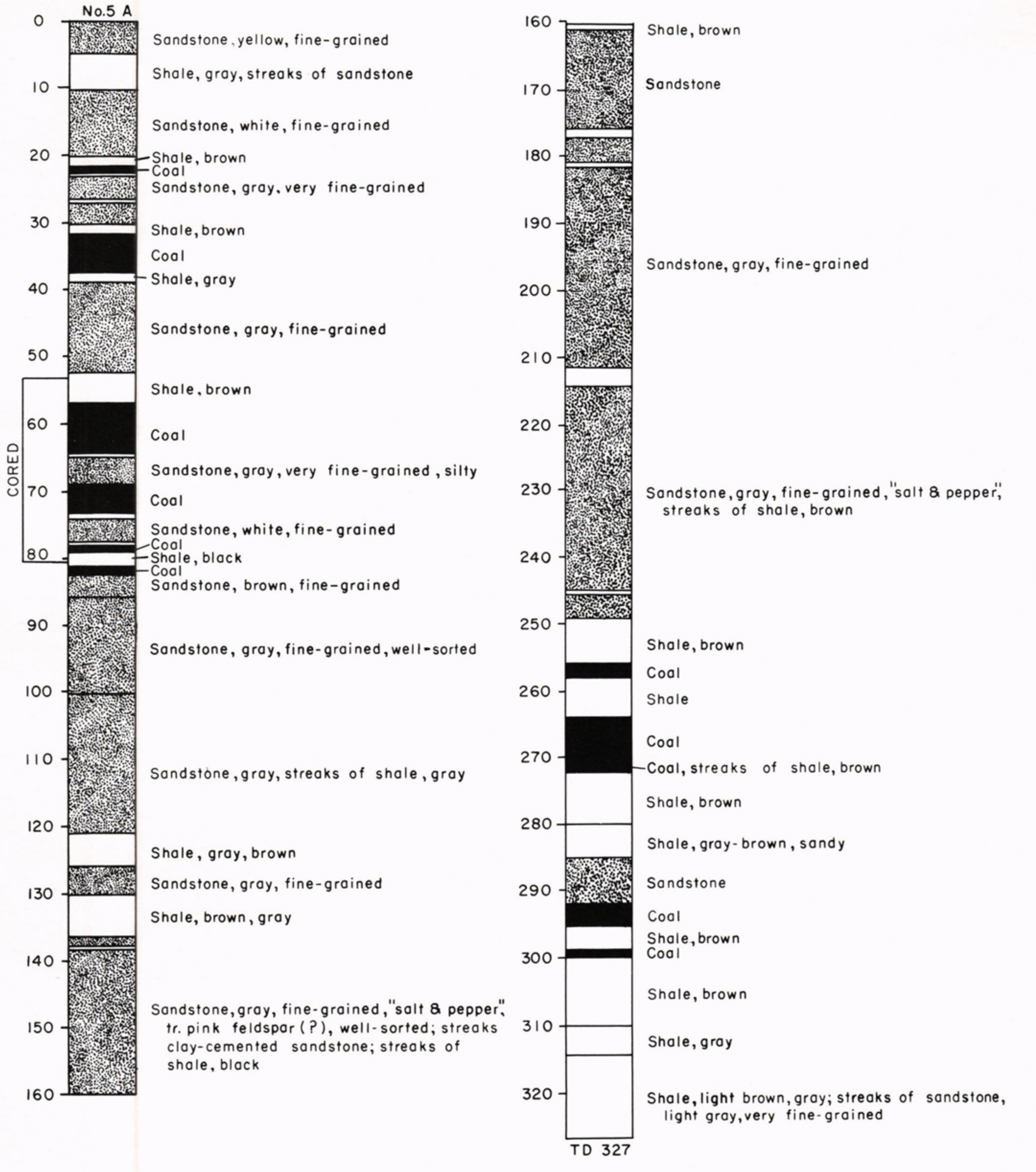

Figure 19

GRAPHIC LOG OF TEST HOLE No. 5A, SW¼SW¼ SECTION 36, T. 25 N., R. 17 W., SAN JUAN Co., N.M.
LOGGED BY R. C. LEASE

stone and underlain by the Allison Member of the Menefee Formation. All of the coals found are adjacent to the Allison Member-Cliff House Sandstone contact. This contact is midway up the southwestern cliff face of the mesas and thus is not present on the plains to the southwest. Owing to the northeastward regional dip, this contact is not visible on the northeastern sides of the mesas.

The upper part of the Allison Member is a series of shales

TABLE 3. ANALYSES OF COAL SAMPLES FROM NEWCOMB UPPER MENEFEE AREA

LOCATION	KIND OF SAMPLE	CONDITION[1]	SAMPLE NO.	LABORATORY NUMBER[2]	MOISTURE	VOLATILE MATTER	FIXED CARBON	ASH	HYDROGEN	CARBON	NITROGEN	OXYGEN	SULFUR	ASH	HEATING VALUE, BRITISH THERMAL UNITS	SULFATE	PYRITIC	ORGANIC	INITIAL DEFOR-MATION TEMP.	SOFT-ENING TEMP.	FLUID TEMP.	REMARKS
NE¼ SE¼ SW¼	channel,	1	954	J-52142	17.4	35.5	40.5	6.6	6.3	59.0	1.3	26.2	0.6	6.6	10,410	0.05	0.10	0.45	2910+	—	—	Noncaking. Coal may have been
Sec. 27, T. 25 N.,	open pit	2			—	43.0	49.1	7.9	5.2	71.4	1.5	13.3	0.7	7.9	12,600	0.06	0.12	0.55				slightly weathered.
R. 17 W.		3			—	46.7	53.3	—	5.7	77.6	1.7	14.2	0.8	—	13,680	0.07	0.13	0.59				
SW¼ NE¼ NW¼	channel,	1	877	J-51245	19.1	33.4	40.7	6.8	5.6	54.8	1.1	30.8	0.9	6.8	9,280	0.37	0.04	0.53	2520	2570	2620	Noncaking. Coal probably
Sec. 9, T. 22 N.,	open pit	2			—	41.3	50.3	8.4	4.3	67.7	1.4	17.0	1.2	8.4	11,470	0.45	0.05	0.64				weathered.
R. 14 W.		3			—	45.1	54.9	—	4.7	73.9	1.5	18.6	1.3	—	12,520	0.49	0.06	0.70				
SW¼ NE¼ NE¼	channel,	1	882	J-51246	15.3	33.9	42.7	8.1	5.8	59.1	1.2	24.8	1.0	8.1	10,310	0.04	0.20	0.72	2690	2740	2790	
Sec 2, T. 22 N.,	open pit	2			—	40.1	50.3	9.6	4.9	69.8	1.4	13.2	1.1	9.6	12,180	0.04	0.24	0.85				
R. 16 W.		3			—	44.3	55.7	—	5.4	77.1	1.5	14.7	1.3	—	13,470	0.05	0.26	0.94				
SW¼ SE¼ SW¼	core, test	1	5A-A	J-61758	15.8	31.6	39.6	13.0	5.8	55.6	1.1	23.3	1.2	13.0	9,700	—	—	—	2570	2620	2690	Equilibrium moisture = 16.41%;
Sec. 36, T. 25 N.,	hole No.	2			—	37.5	47.1	15.4	4.8	66.0	1.3	11.1	1.4	15.4	11,510	—	0.71	—				Hardgrove grindability index =
R. 17 W.	5A	3			—	44.3	55.7	—	5.7	78.0	1.5	13.2	1.6	—	13,610	—	—	—				55; free-swelling index—non-caking.
SW¼ SE¼ SW¼	core, test	1	5A-B	J-61759	17.4	31.5	40.4	10.7	6.0	55.6	1.1	25.2	1.4	10.7	9,730	—	—	—	2730	2780	2830	Equilibrium moisture = 16.91%;
Sec. 36, T. 25 N.,	hole No.	2			—	38.1	48.9	13.0	4.9	67.3	1.3	11.8	1.7	13.0	11,780	—	1.10	—				Hardgrove grindability index =
R. 17 W.	5A	3			—	43.8	56.2	—	5.6	77.4	1.5	13.5	2.0	—	13,540	—	—	—				58; free-swelling index—noncaking.
NW¼ SW¼ SW¼	core, test	1	5-A	J-61757	18.5	27.7	31.1	22.7	5.5	43.9	0.9	26.5	0.5	22.7	7,660	—	—	—	2910+	—	—	Equilibrium moisture = 15.98%;
Sec. 2, T. 23 N.,	hole No. 5	2			—	34.0	38.2	27.8	4.3	53.9	1.0	12.3	0.7	27.8	9,410	—	0.11	—				Hardgrove grindability index =
R. 17 W.		3			—	47.2	52.8	—	5.9	74.7	1.4	17.1	0.9	—	13,030	—	—	—				64; free-swelling index—non-caking.

[1]Condition: 1—as received, 2—moisture-free, 3—moisture- and ash-free.
[2] Analyses by U. S. Bureau of Mines Pittsburgh Laboratory.

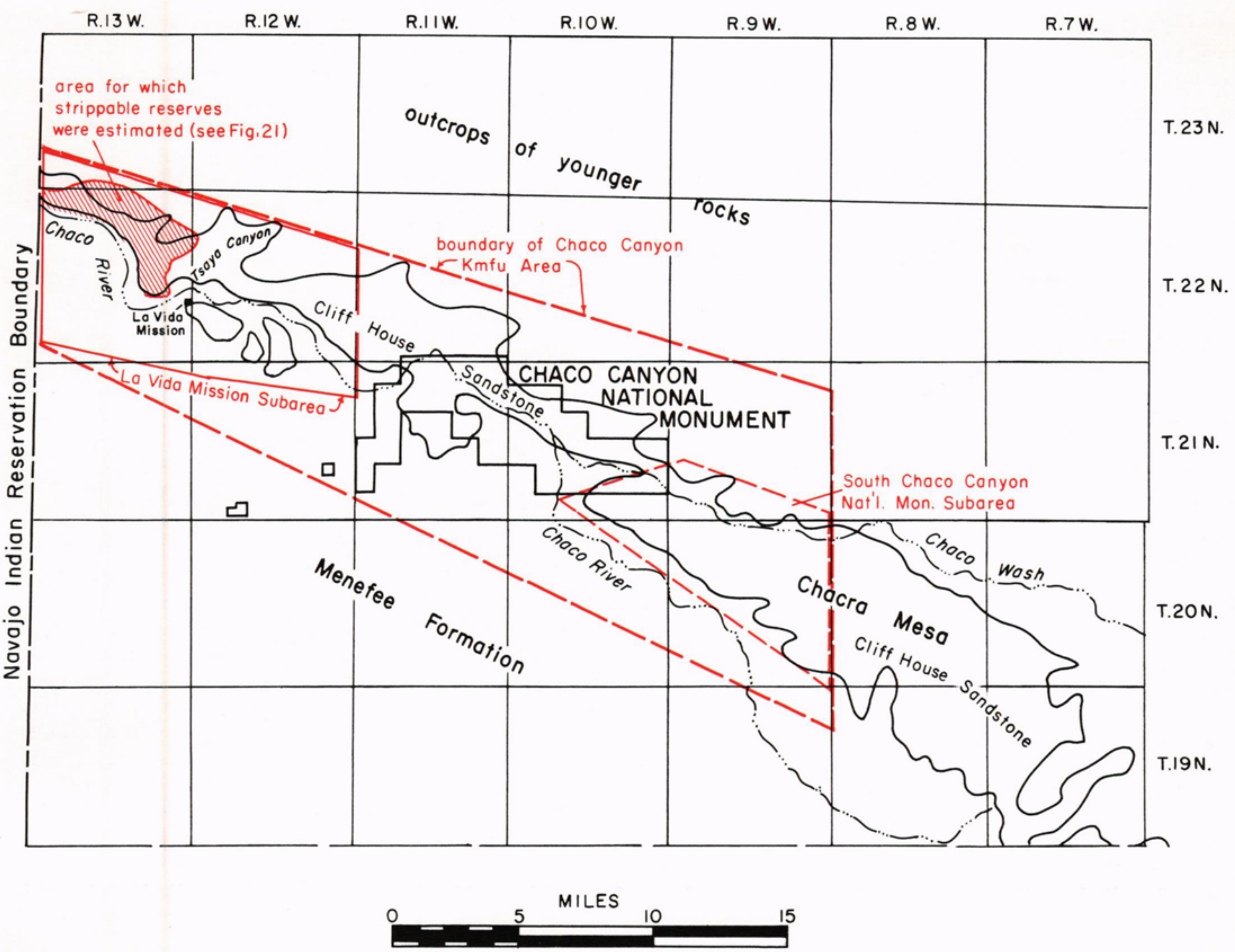

Figure 20
Index map of Chaco Canyon Upper Menefee area

and thin sandstones that in most places include several thin coals. South of the National Monument these coals are fairly continuous but they vary rapidly in thickness from less than an inch to approximately 2.5 feet. A few highly lenticular coal deposits are found in the base of the Cliff House Sandstone. These coals range in thickness from a few inches to 6.5 feet and contain greatly varying amounts of shale.

T. 20 N., R. 9 W.

The western escarpment of Chacra Mesa crosses the southwestern corner of this township. A 2.0- to 2.6-foot-thick coal occurs near the top of the Allison Member. No strippable-coal-reserve estimates were made owing to the excessive overburden and insufficient thickness of the coal.

T. 20 N., R. 10 W.

The western face of Chacra Mesa crosses sections 1, 2, and 3 of this township. The Allison Member coals are similar to those in R. 9 W. except in the southeastern part of section 2. Here a lenticular upper Allison Member coal bed thickens to 5.5 to 6.2 feet for several hundred feet and then grades rapidly into a sandstone to the southeast. This unusually thick coal zone appears to be a lens that thins rapidly to 2.0 to 2.5 feet to the northwest. The limited extent of this thickening and the excessive overburden of Chacra Mesa make this coal uneconomic for strip mining.

T. 21 N., R. 10 W.

Chacra Mesa has its northern terminus in the southeastern corner of this township. The upper Allison Member coals at this locality are quite similar to those to the southeast and range in thickness from a few inches to 2.4 feet. A 6.5-foot-thick coal lens is found in the base of the Cliff House Sandstone along the southwestern side of Chaco Canyon in the NE1/2NW1/4 of section 36. The coal is very sandy and grades into the basal Cliff House Sandstone 20 yards to the northwest. A 1.4-foot-thick coal was found near the top of the Allison Member a short distance downslope from the lens.

The only coal analyses available are from the abandoned Pueblo Bonito mine (section 14, T. 20 N., R. 11 W.) which is now inside Chaco Canyon National Monument. These analyses are shown on Table 4 and were made by the U.S. Bureau of Mines (1936).

LA VIDA MISSION SUBAREA

The La Vida Mission subarea (fig. 21) is bounded on the west by the Navajo Indian Reservation and on the east by R. II W. It is marked by broad, grass-covered mesas bordering the Chaco River. A number of deep tributary canyons along the river provide excellent exposures of the Cliff House Sandstone and of the upper Menefee Formation.

Coal in the La Vida Mission subarea is associated with the shale beds separating tongues of the Cliff House Sandstone. Regional dip is to the northeast and north and consequently the lower Cliff House Sandstone-upper Menefee Formation contact is best exposed to the west along the reservation boundary. Two main shale and coal zones crop out along the river; both coals appear to be broad lenticular deposits and grade laterally into sandy shales.

T. 21 N., R. 12 W.

An erosional outlier of the Cliff House Sandstone caps the mesa in section 3 on the south side of Chaco River, where the Allison Member-Cliff House Sandstone contact shows a considerable amount of burned coal clinker. In the SE1/4 NW1/4 of the section a coal zone 3.o to 4.2 feet thick was measured. This coal is apparently correlative with the lower coal in Tsaya Canyon to the northwest discussed under T. 22 N. No coal reserve was calculated due to the sparsity of coal outcrop.

T. 22 N., R. 13 W.

Strata of the Menefee Formation crop out in the township south of Chaco River and interfinger with the Cliff House Sandstone along the north side of the river. The lower coal zone is exposed in sections i 3 and 24 in Tsaya Canyon and in sections 25 and 31 south of the river. At the mouth of Tsaya Canyon the lower coal is seven feet thick and of good quality in several abandoned mines. About 0.7 mile to the northeast, the lower coal is lenticular and is locally six feet thick. This lenticularity, together with the change to a sandy coal, suggests that the exposures are near the northeastern depositional limit of this lens of the lower coal. Exposures to the east along the north bank of Chaco River are poor but indicate a pinchout of the lower coal.

On the mesa immediately south of La Vida Mission School, the lower coal is 5.o to 6.5 feet thick and heavily burned along the outcrop (section 25, T. 22 N., R. 13 W. and section 3o, T. 22 N., R. 12 W.). Coal-reserve calculations give the mesa 1.0 to 1.9 million tons of strippable coal.

Section 31 and the surrounding terrain are hilly badlands incised in the strata at the base of the Cliff House Sandstone. Burned coal clinker covers large areas and is believed to represent beds equivalent to the coal beds measured in pits in the northwestern part of the section. The coal is 9.7 feet thick and occurs as two beds separated by a shale parting.

No good exposures of the lower coal were found between Tsaya Canyon and section 31 to the west. This may be due either to a very sinuous depositional trend that is not intersected by present topography or, more likely, to the presence of several separate lower coal lenses. No additional coal reserves have been calculated for the lower coal owing to its very lenticular nature and sparsity of outcrops.

The upper coal appears to be a broad northwest-southeast-trending lens in the central part of the township along the north side of Chaco River. It is found in a shale-and-coal zone 120 to 150 feet above the lower coal zone and 4o to 5o feet below the top of the Cliff House Sandstone. The axis of the lens appears to trend northwest through sections

0, I I, 12, 13, and 14 where it is five to six feet thick and of good quality (fig. 21). Canyon exposures show a sharp thinning along the northeastern side of the lens in section where the coal is one to two feet thick and apparently is replaced by brown shales. Drilling (fig. 22) to the northwest (N.M.S.B.M.&M.R. test hole No. 7A in section 34, T. 23 N., R. 13 W.) revealed a similar replacement of the coal by brown shales. Thinning along the southwest and northwest sides is shown in sections 4 and 5 and to the north (section 32, T. 23 N., R. 13 W.) where the upper coal thins to 2.5 to 3.5 feet.

Coal-reserve calculations based on data shown on Figure 21 give the area approximately 3o million tons of strippable coal. Substantially all of the upper coal is less than 150 feet below ground surface. The strata overlying the upper coal are the upper part of the Cliff House Sandstone (as much as 5o feet), Lewis Shale (as much as 85 feet), and to the north, the Pictured Cliffs Sandstone (3o to 5o feet) and should not present any serious strip-mining problems.

CHACRA MESA MENEFEE AREA

by William R. *Speer*

The Chacra Mesa area (fig. 23) includes coal deposits of the Allison Member of the Menefee Formation and those of the overlying Cliff House Sandstone. In the southeastern San Juan Basin, these two formations together with the underlying Cleary Coal Member of the Menefee Formation and the Point Lookout Sandstone comprise the Mesaverde group as defined by Beaumont, Dane, and Sears (1956). This redefinition and revision of previous nomenclature, which resulted from the completion of Mesaverde surface mapping and the study of abundant subsurface well logs, has the following applications in the general area of Chacra Mesa as previously mapped by Dane (1936):

I) The upper part of the former "Hosta sandstone" (Dane, 1936, p. 94) is the basal unit of the Mesaverde Group. It is the stratigraphic equivalent of the Point Lookout Sandstone of the northwestern San Juan Basin. Where the Hosta sandstone is undivided or where its lower part is absent, as in the Chacra Mesa area, the name Point Lookout Sandstone is applied.

2) The Menefee Formation, resting on the Point Lookout Sandstone, includes the coal-bearing zone formerly called by Dane "the upper part of the Gibson coal member," as well

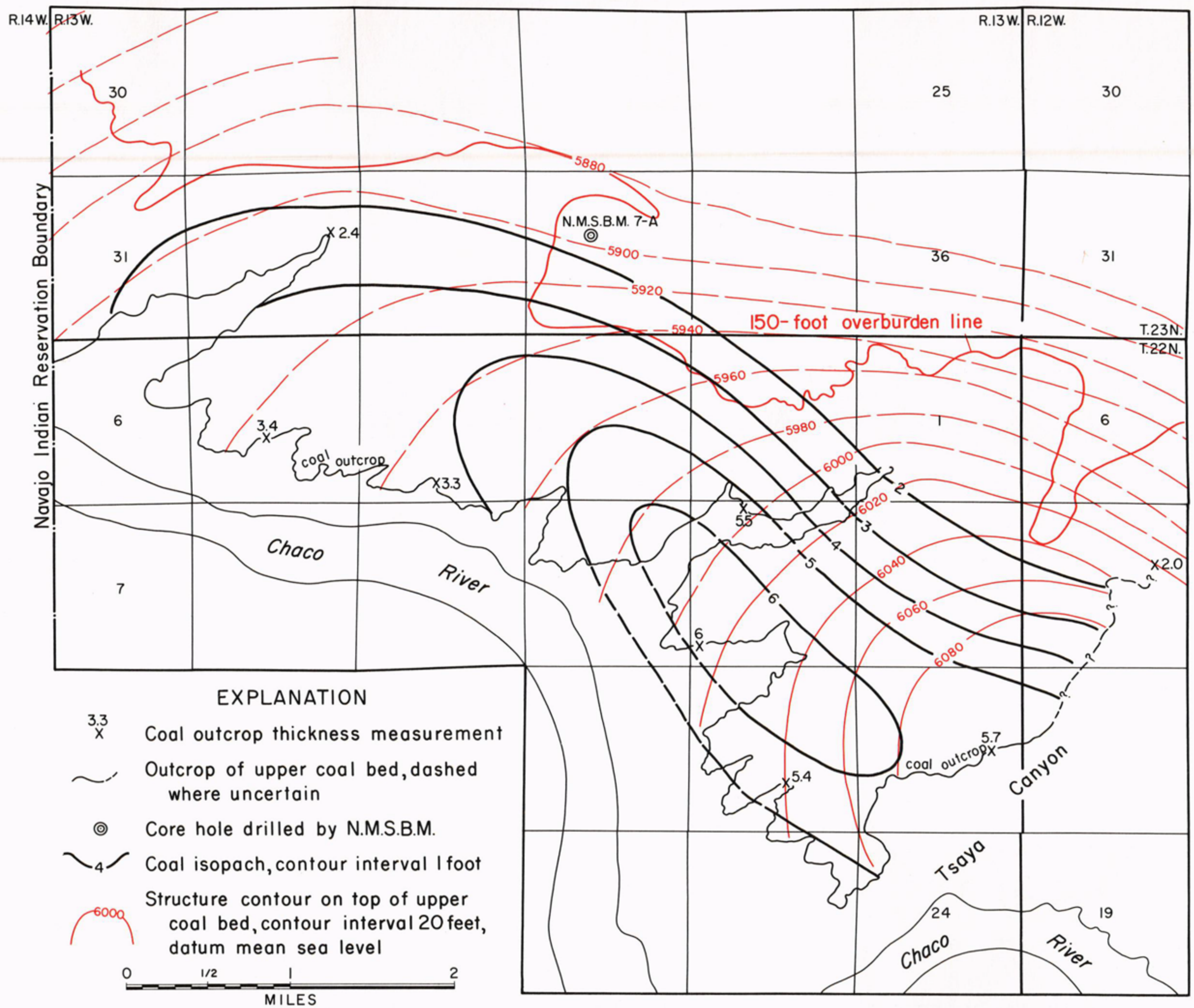

Figure 21
Map showing La Vida Mission subarea of Chaco Canyon Upper Menefee area

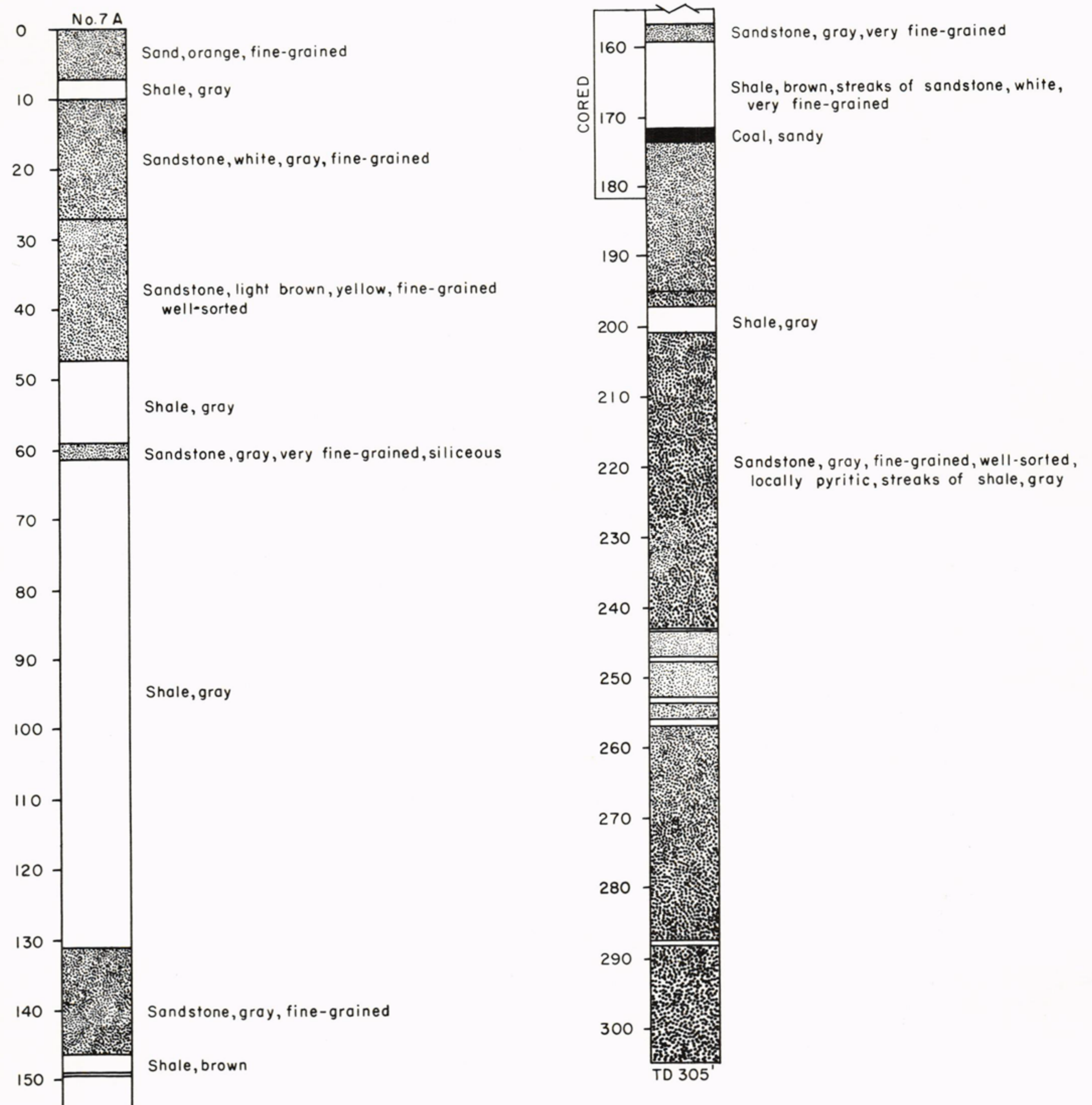

Figure 22

Graphic log of test hole No. 7A, SE¼SE¼NW¼ section 34, T. 23 N., R. 13 W., San Juan Co., N.M.
Logged by R. C. Lease

as the overlying beds formerly called "the Allison barren member." Since the Gibson Member is restricted to the Crevasse Canyon Formation in the revision, a new name, the Cleary Coal Member of the Menefee Formation, is applied to the beds described by Dane as the "Gibson coal member." The overlying Allison Member, which contains coal beds in the Chacra Mesa area, is made a member of the Menefee Formation.

3) The prominent sandstone overlying the Allison Member and upholding the Chacra Mesa escarpment as the dominant topographic feature was named by Dane "the Chacra sandstone." Its proven surface continuity with the previously named Cliff House Sandstone of the northern San Juan Basin requires priority be given the latter name. An older sandstone of considerable thickness (up to 1,250 feet), but of limited areal extent, was mapped and named

TABLE 4. ANALYSES OF COAL SAMPLES FROM CHACO CANYON UPPER MENEFEE AREA

LOCATION	KIND OF SAMPLE	PROXIMATE, PERCENT							ULTIMATE, PERCENT						HEATING VALUE	FORMS OF SULFUR			FUSIBILITY OF ASH, °F		
		CONDITION[1]	SAMPLE NO.	LABORATORY NUMBER[2]	MOISTURE	VOLATILE MATTER	FIXED CARBON	ASH	HYDROGEN	CARBON	NITROGEN	OXYGEN	SULFUR	ASH	BRITISH THERMAL UNITS PER POUND	SULFATE	PYRITIC	ORGANIC	INITIAL DEFORMATION TEMP.	SOFTENING TEMP.	FLUID TEMP.
Sec. 14, T. 20 N., R. 11 W.	mine sample	1		3823	17.5	32.9	41.2	8.4	—	—	—	—	2.2	—	—	—	—	—	—	—	—
Sec. 14, T. 20 N., R. 11 W.	outcrop sample	1		23004	14.4	34.8	42.3	7.5	—	—	—	—	1.5	—	10,220	—	—	—	—	2650	—
		2		—	—	40.7	50.5	8.8	—	—	—	—	1.8	—	11,940	—	—	—	—	—	—
SW¼ SW¼ Sec. 11, T. 22 N., R. 13 W.	pit sample	1	873	J-57562	14.4	32.6	42.8	10.2	5.7	57.1	1.3	24.8	0.9	10.2	9,870	0.21	0.03	0.64	2910+	—	—
		2		—	—	38.1	50.0	11.9	4.8	66.7	1.5	14.1	1.0	11.9	11,530	0.24	0.29	0.75	—	—	—
		3		—	—	43.3	56.7	—	5.4	75.7	1.7	16.0	1.2	—	13,090	0.28	0.33	0.85	—	—	—
																(Remarks)—Free-swelling index—noncaking					
SE¼ SE¼ NW¼ Sec. 34, T. 23 N., R. 13 W.	core, test hole No. 7A	1	7A-A	J-61760	7.2	16.8	14.7	61.3	2.8	22.6	0.5	11.5	1.3	61.3	3,980	—	—	—	2870	2910+	—
		2		—	—	18.1	15.8	66.1	2.1	24.3	0.5	5.6	1.4	66.1	4,290	—	1.03	—	—	—	—
																(Remarks)—Equilibrium moisture = 10.42%; Hardgrove grindability index = 71; free-swelling index—noncaking. Sample represents material just beyond pinchout of coal bed.					

[1]Condition: 1, as received; 2, moisture-free; 3, moisture- and ash-free
[2]Analysis by U.S. Bureau of Mines

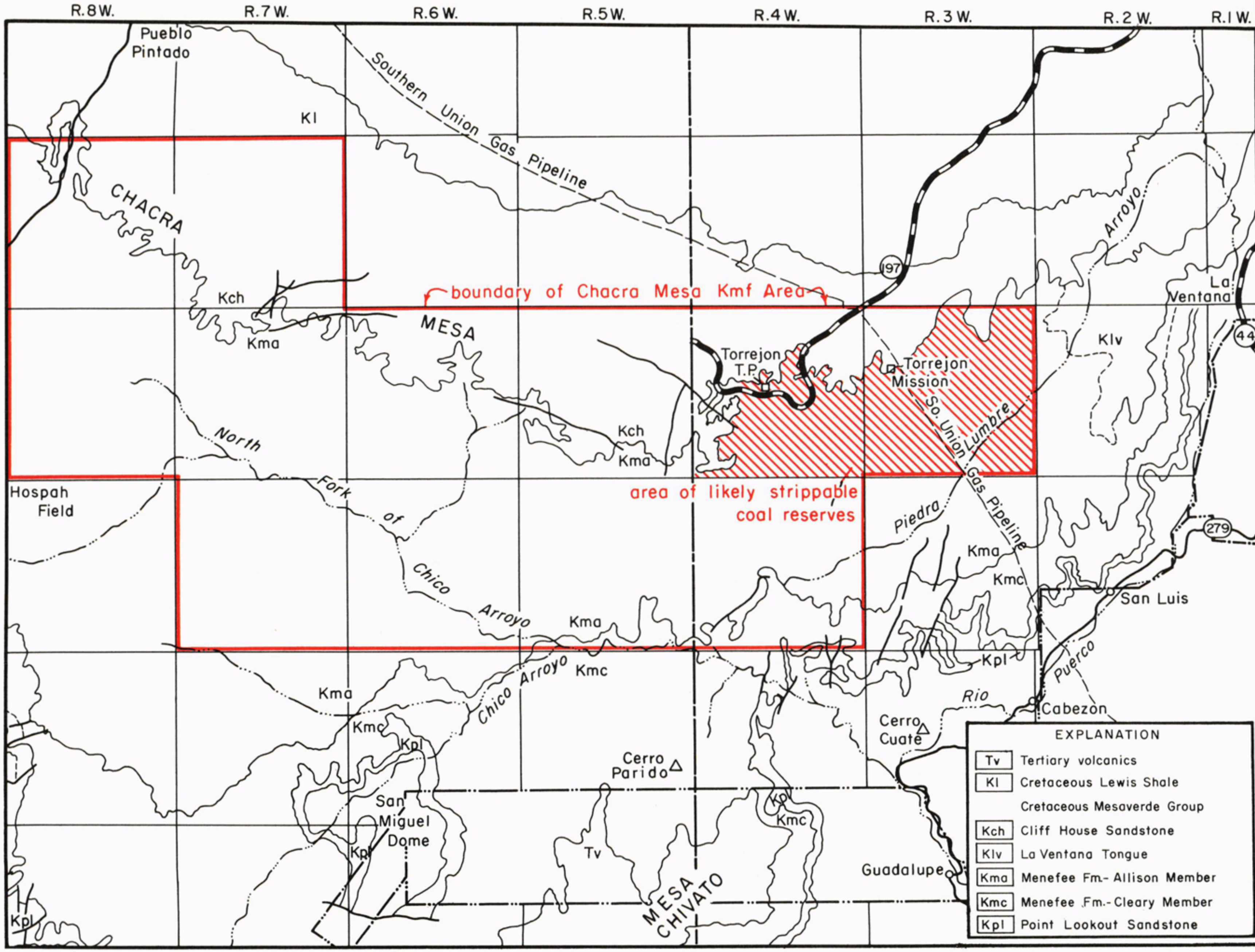

Figure 23

Map of Chacra Mesa Menefee area showing geology and strippable areas "the La Ventana sandstone member" by Dane from outcrops in T. 19 N., R. 1 and 2 W., and T. 18 N., R. 2 W. This unit was noted as being lower in the stratigraphic section than "the Chacra sandstone" (Dane, 1936, p. o8), but unconnected with it on the surface. Since it is believed to be genetically related to the Cliff House as a part of the transgressive upper part of the Mesaverde group (Beaumont, Dane, and Sears, 1956, p. 216o), it is now classified as the La Ventana Tongue of the Cliff House Sandstone.

It was surmised that the part of the Cliff House Sandstone constituting "the Chacra sandstone" of Dane, while of substantial thickness in its Chacra Mesa outcrop, might thin rapidly in the subsurface in a seaward or northeastward direction to merge into the silty shales of the overlying Lewis Shale. Sufficient well-log control is now available to verify this rapid thinning and loss of identity within a distance of five to seven miles basinward from the outcrop. This disintegration of a massive sandstone section into finer grained, thinner bedded units can be witnessed partially in the diverging surface outcrops in the southern portion of T. 18 N., R. 5 W., although relationships are somewhat obscured by the depositional changes also taking place in beds of the Allison Member. In this area the surface outcrops, responding both to the structural conditions and to erosional effects, reveal an "end-on" look at the upper Menefee-Cliff House section as it exists principally in the subsurface to the west.

Well-log control also indicates that directly northeast of Chacra Mesa the transgressive movement of the shoreline immediately following deposition of the La Ventana Tongue was apparently too rapid to allow continuous deposition of marginal marine sands connecting the La Ventana Tongue with the "Chacra sandstone" portion of the Cliff House Sandstone. This condition exists over a relatively large area in the subsurface, but the genetic relationship of these sandstone units as parts of a single transgressive phase is borne out by the continuous outcrops of equivalent beds in the Cliff House Sandstone along the western margin of the San Juan Basin.

The thick buildup of sandstones composing the La Ventana Tongue indicates a relatively long stillstand of the shoreline during its deposition. It was during this period that the time-equivalent coal beds and carbonaceous shales of the upper part of the Menefee were accumulated in a shoreward direction. These Allison Member beds are also of limited areal extent and crop out principally in T. 18 N., R. 2, 3, and 4 W. The coal beds are lenticular, relatively thin from a mining standpoint, and to some extent underlie Chacra Mesa at excessive stripping depths. These coastal-swamp deposits merge in a short distance southwestward into irregular, discontinuous fluvial sandstones derived from continental sources adjacent to the swamp environment. These light-colored, argillaceous, fluvial sandstones dominate the Allison Member outcrop in the Chacra Mesa area. They are very fine-grained, friable, and irregularly interbedded with structureless clay shales. Collectively this sandstone and shale sequence weathers to a rough but relatively featureless terrain. In the basal portion of the Allison Member immediately overlying the Cleary Coal Member, there is a more or less continuous group of ledge-forming sandstone beds, from 300 to 500 feet in thickness, that topographically form a series of cuestas along the southern edge of the Chacra Mesa area.

In the western two-thirds of the area, thin carbonaceous shales and subbituminous coals also occur in the basal part of the Cliff House Sandstone and the uppermost part of the Allison Member of the Menefee Formation. As many as six separate coal lenses, rarely exceeding two feet in thickness, occur in a discontinuous zone ranging from 5 to 55 feet in thickness. This zone includes the depositional contact of the Cliff House Sandstone with the underlying Allison Member.

In outcrops the maximum coal thickness is in the southwesternmost exposures of the Cliff House Sandstone in the extreme southwest corner of T. 19 N., R. 7 W., and the northwest corner of T. 18 N., R. 7 W., as well as in a fault-bounded segment in section 3o of T. 18 N., R. 5 W. These exposures are the remnants of marginal deposits of the marine Cliff House sands that were laid down in a transitional environment which graded laterally southwestward into the coastal-plain sedimentation of the Allison. These remnants probably represent more extensive coal and carbonaceous deposits which have been subsequently removed by erosion. Seaward, to the northeast, coal beds pinch out or are represented only by thin carbonaceous partings in the Cliff House sequence.

The maximum thickness of coal observed in these outcrops was 3.8 feet. This thick bed exhibits a characteristic common of coals near the Cliff House-Allison contact by thinning laterally in a distance of several hundred yards to a split section of two thin coals and an intervening carbonaceous shale. Being of very limited areal extent and being overlain by Cliff House sandstones more than 30o feet thick, these coal deposits offer little commercial possibility.

No coal has been commercially mined in the Chacra Mesa area, although small Navajo Indian prospect pits are found in many areas, principally around settlements in the Torrejon and Medio Arroyo drainage region of T. 18 N., R. 3 and 4 W.

DESCRIPTIONS OF TOWNSHIPS

The following evaluation of strippable coal reserves on a township basis in the Chacra Mesa area utilizes the geologic map and measured sections of Dane (1936), photogeologic mapping, subsurface well-log studies, and field examination of outcrops. Data were compiled on recent U.S. Geological Survey 7 1/2-minute quadrangle topographic maps.

T. 19 N., R. 8 W.

The Cliff House Sandstone crops out in the face of the 450-foot-high escarpment of Chacra Mesa which trends southeastward across the township from section 6 to section 25. Only very thin coal lenses occur in discontinuous carbonaceous shale intervals separating the major sandstone units. None exceeds a foot in thickness.

Several fairly continuous coal beds occur in the upper 5o feet of the Allison Member of the Menefee Formation in the face of the Chacra cliff. None exists in the lowland area of the township southwest of the escarpment. The band of thin coals extends along most of the face of the cliff and exhibits abundant burn and associated clinker. Where unburned, individual beds rarely exceed one foot in thickness, although one bed measuring 2.5 feet exists for a short distance in section 8 about 35 feet below the Cliff House-Allison contact. The beds dip gently (2-3°) north-northeast as evidenced in Pueblo Pintado Canyon which cuts through sections 4 and 8. This canyon is the only pass through the Chacra escarpment along its entire front until the escarpment breaks down near Torrejon Arroyo. The thickest coal was traced into the canyon where it was seen to change laterally into coaly, carbonaceous shale in the southwest quarter of section 4.

All coal beds of both formations lie beneath an overburden of Cliff House Sandstone from 75 to 35o feet thick; no strippable reserves are calculated.

T. 19 N., R. 7 W.

The Cliff House Sandstone underlies most of the southern half of this township veneered on its dip slope by a thin section of Lewis Shale. Cliff House coal beds, however, are exposed again only in the cliff face of the escarpment running through sections 3o and 31. At the head of a box canyon in the extreme southeastern corner of section 30, a shale and carbonaceous shale interval 25 feet in thickness contains several coal beds, but it grades out to the northwest. This zone appears to be about 75 feet below the top of the Cliff House at a horizon containing comparable beds in Pueblo Pintado Canyon.

Allison Member coal beds exist in insignificant thicknesses along the top of the formation in the escarpment in sections 3o and 31. No strippable-coal-reserve estimates are made due to insufficient thicknesses and areal extent and an excess of overburden.

T. 18 N., R. 8 W.

The entire township is underlain by continental, fluvial sedmientary beds of the Allison Member of the Menefee Formation. In the southwestern corner, well-consolidated basal sandstones of the member outline the northeastern flank of the Hospah anticline. No coal beds were found or measured in this township.

T. 18 N., R. 7 W.

The Cliff House Sandstone escarpment extends irregularly through the northernmost tier of sections in this township and contains no measurable thicknesses of coal.

The Allison Member of the Menefee Formation in the northernmost portion of section 6 contains the thickest measured coal bed in the Chacra Mesa area at 4.1 feet. It is also an excellent example of the type of depositional conditions existing in this transitional, coastal-margin environment, as it may be traced northward along the outcrop into basal sandstones of the Cliff House. Burned coal and clinker shale obscure the relationships along the escarpment face to the southeast. In the balance of the Allison Member forming a gentle slope southward from the cliff face down to the North Fork of Chico Arroyo, no coal crops out.

Coal beds of both the Cliff House and Allison are of insufficient extent and under too much overburden to warrant reserve estimation.

T. 17 N., R. 7 W.

No coal beds were measured in this township in the Allison Member of the Menefee Formation. The topography has more relief than previously described in townships to the north and west, as the fluvial sandstones of the Allison become more resistant and form low, northward-dipping cuestas and mesas.

T. 18 N., R. 6 W.

No coals were measured in the Cliff House Sandstone which crops out along the escarpment through sections 6, 7, 8, 15, i6, 17 and 24. The cliff, still prominent in height, dips northward at a very low angle and consists of massive sandstone units separated by occasional thin carbonaceous shale intervals.

Thin coal beds occur at the top of the Allison Member in the eastern portion of the township where the box canyon, Rincon Marquez, is cut into the face of the Chacra Mesa escarpment. None of the coals exceed 1.5 feet in thickness and several are partly cut out by local erosional unconformities on which Cliff House sandstone beds have been deposited.

Discontinuity and lack of appreciable thicknesses preclude estimation of minable reserves.

T. 17 N., R. 6 W.

The entire township is underlain by Allison Member sandstones, siltstones, and shales of continental origin. No coals are evident in this stratigraphic section. In the southern portion, a major drainage, the North Fork of Chico Arroyo, has created substantial topography in the basal sandstone sequence of the Allison Member. The generally north-dipping cuestas exhibit some minor folding and faulting, particularly in sections 22, 23, and 25. A test well drilled in the southeast quarter of section 34 shows the Cleary Coal Member of the Menefee, underlying the Allison Member, to occur at a depth of 120 feet.

T. 18 N., R. 5 W.

Near the center of this township, the solid facade of the Chacra escarpment begins to deteriorate as a result of both sedimentary changes and minor structural effects. The change is marked as the massive sandstone units in the Cliff House become a series of less cohesive, thinner bedded units separated by silty shale intervals. Outcrops of the Cliff House fan out as the basal sandstone unit trends more southerly and the upper units retreat northward. This results primarily from differential erosion rather than structural changes, as the regional dip remains northward. Structurally, faulting becomes a factor which has aided the erosional processes. A north-south fault, upthrown on the west, intersects the mesa along the eastern edge of the township in sections 13, 24, 25, and 36. Another fault of minor displacement, paralleling the mesa face, isolates a peninsular outcrop of Cliff House as an upthrown block in sections 27, 28, 29, and 30. Nowhere is a coal bed developed in the Cliff House outcrop which occupies three-quarters of the township.

All Allison Member coals occur in the southwestern corner of the township, immediately below the Cliff House contact. They are extremely lenticular and give evidence of having been deposited in a marginal environment. A discontinuous coal bed 13 feet below the Cliff House contact crops out in the southwest quarter of section 3o within the isolated fault block. It attains a thickness of 3.6 feet at that point, but it has thinned to less than **2** feet on the opposite side of the block and is terminated at the fault line.

Strippable-coal reserves are not present in this township.

T. 17 N., R. 5 W.

A more incised drainage pattern created a substantial relief on the fluvial sandstones of the Allison Member in this township. The formation crops out over the entire area in a series of south-facing escarpments and mesas isolated by broad sand washes. It is barren of coal or carbonaceous deposits.

T. 18 N., R. 4 W.

Continuing the rapid loss of formational identity commenced in T. 18 N., R. 5 W., the remaining Cliff House Sandstone outcrop caps an escarpment of more moderate height trending east-west along the north-central portion of the township. It contains no coals and has the lithologic characteristics of a deeper marine deposit.

It is in this township that the coal zones of the Allison Member are best developed. Four separate zones have some continuity over the area, although individual coal beds continue to be irregular and thin. All four zones are in the upper 30o feet of the Allison and each rarely contains coal beds exceeding two feet in thickness on the outcrop. In the east-central portion of the area, extensive burning of the coal beds has occurred.

These Allison coal beds are within reasonable strip-mining depths, but they lack sufficient thickness and continuity to be considered minable. It is possible that the beds are thicker in the subsurface; however, well logs in the area tend to confirm the relative thinness of the coals. Oxidation by surface burning would also be of consideraton. No strippable reserves were estimated.

T. 17 N., R. 4 W.

No coals exist in that part of the Allison Member that crops out in this township. Approximately the basal two-thirds of the member is exposed and consists of thick-bedded, light-colored sandstones and siltstones forming north-dipping cuestas and mesas. The massive basal sand sequence creates a more rugged terrain in the southern part of the township.

The only exposure of the Cleary Member in the Chacra Mesa area occurs in the southeastern quarter of this township. It underlies the basal Allison Member sandstone and consists predominantly of a coal-bearing shale, carbonaceous shale, and a thin-bedded sandstone sequence. The member is about 43o feet thick in this township, as determined by a well log in section 29. The Cleary contains measurable thicknesses of coal in the lower 240 feet, principally near the top of the Point Lookout Sandstone. Lenticular coal beds up to a maximum of three feet in thickness crop out in sections 25, 26, 27, 34, 35, and 36. Some limited underground mining has been conducted in section 34, but strippable reserves are insufficient for estimation.

T. 18 N., R. 3 W.

The Cliff House Sandstone ceases to be a mappable entity eastward from section 5. It thus occupies only the extreme northwestern corner of this township as a relatively thin sandstone unit capping mesas underlain by silty shales of the Allison Member of the Menefee. It contains no coal.

In the absence of the Cliff House Sandstone, the Allison Member of the Menefee Formation is in direct contact with silty shales of the Lewis Shale in the northern two-thirds of the township. It contains abundant coals which are exposed in a number of outcrops. The tracing of these coal beds is difficult because of their lenticularity, discontinuity, and variability in the stratigraphic section. They are generally associated depositionally with relatively thick, crossbedded sandstone units of the Allison, and usually immediately underlie them. The coal beds rarely exceed two feet in thickness and have abundant interbedded carbonaceous shales. As in T. 18 N., R. 4 W., they are in the upper 30o feet of the Allison. The relationship of individual beds is obscured by large dry washes and by the number of outcrops which have been burned. Two outcrops of coal found in sections 19 and 21 exceed three feet in thickness, but in each case the outcrop was exposed sufficiently to observe lateral thinning in less than a quarter of a mile. While in places they are amenable to strip mining from a topographic standpoint, none of the coal beds have sufficient areal extent to warrant reserve calculation. A study of several well logs in this area does not indicate thicknesses exceeding those observed on the surface outcrops.

COAL QUALITY

No published coal analyses for the Chacra Mesea area are known, and no samples were collected during the investigation. It can probably be assumed, however, that the quality of the coal is similar to that in the adjoining Chaco Canyon and La Ventana areas. Thus, as-received heating value can be expected to be 9,500 to 11,000 Btu per pound, ash content 5 to 10 percent, and sulfur content 1.5 percent or less. No coals from the adjoining areas are known to have any coking properties.

SUMMARY

Coal beds in the Chacra Mesa area occur in the Cliff House Sandstone and the Allison Member of the Menefee Formation. Coals in the Cliff House are very thin, lenticular, and merge rapidly northward from their outcrops in the face of the Chacra Mesa escarpment into carbonaceous shales and sandstone units of the same formation. They are everywhere overlain by a prohibitively thick overburden of Cliff House Sandstone. The Allison Member in its upper part contains more numerous beds of coal, but these coals have the same deficiencies as the Cliff House coals in being thin and lenticular and underlying a thick overburden. Only in T. 18 N., Rs. 3 and **4** W. are these beds sufficiently shallow for stripping; however, they do not have sufficient thickness and continuity in this area to warrant consideration for mining. The minor amount of Cleary Coal Member of the Menefee Formation exposed in the Chacra Mesa area also contains no minable coal.

SAN MATEO MENEFEE AREA

by Walter H. Pierce and John W. Shomaker

Coal has been reported in this area by Gardner (191o) and Hunt (1936). Since their work, aerial photographs and 7 1/2-minute topographic quadrangle maps have been made available. Coal distribution, with particular emphasis on strippable coal, is described using data by Hunt and Gardner and data based on field work with the aid of photographs and topographic maps.

The best routes into the San Mateo Menefee area are by way of San Mateo from the southwest and Cabezon from the east. Access from the north is difficult if not impossible. An old crossing on Chico Arroyo is no longer passable but recently drillers have opened a new crossing and road.

Three areas in the San Mateo Menefee area have distinctive topography. To the west of San Miguel Creek dome, the nonresistant, flat-lying Cleary Member of the Menefee Formation forms low rolling grasslands. To the southwest and east, flatirons of the Point Lookout Sandstone rise above the grasslands. To the north, the resistant sandstones of the Allison Member of the Menefee Formation form monuments and mesas capping the coal-bearing units.

East of the San Miguel Creek dome, the Cleary Member of the Menefee is in most places overlain by sandstones so that the area is characterized by monument topography which is less suitable for strip mining.

In that part of the area east of the McKinley-Sandoval County line, strata begin to dip at steeper angles into the San Juan Basin. The Cleary Member of the Menefee Formation forms a narrow strike valley bounded by the continuous mesa of the overlying Allison Member of the Menefee Formation.

The generalized geologic map (fig. 24) shows the outcrop of the Cleary Member of the Menefee Formation. The Cleary Member-Allison Member contact had not been mapped previously and helps to delineate areas of strippable coal in the San Mateo Menefee area. The contact as mapped on aerial photographs is transitional. Sandstone units pinch out and others appear along the contact. The contact therefore jumps stratigraphic horizons in some places.

The regional stratigraphic relationships are shown in Figure 25. The only coal-bearing strata of any importance in the San Mateo Menefee area are in the Cleary Member of the Menefee Formation. One exposure of the Gibson Member of the Crevasse Canyon Formation is reported by Hunt (1936) in the exposed part of the San Miguel Creek dome. In general, the sedimentary sequence of the Satan Tongue of the Mancos Shale overlain by the Point Lookout Sandstone overlain by the Menefee Formation with its lower coal-bearing Cleary Member and upper Allison Member with numerous discontinuous sandstones suggests a regressive sequence. The Point Lookout Sandstone represents the littoral and possible beach-dune environments. The close relationship between the presumably littoral sand and the succeeding coal-bearing Cleary Member suggest the coal may have been deposited in lagoons behind a barrier-island complex.

No coal beds have been reported of more than six feet in thickness and very few coals have a thickness greater than three feet. Those that are over three feet thick are described in the individual discussion of each township. The Cleary Member typically includes many thin beds of coal. As many as six beds of under six inches in thickness have been measured associated with thicker coals. In the area east of the San Miguel Creek dome, the thicker coals are generally at the base of the sequence. Dark-gray to black nodular chert and flat chert nodules locally in irregular beds, are above coal beds in some places. The chert forms a distinctive resistant-weathering product which may serve as a guide to coal-bearing units in the area west of the San Miguel Creek dome where the Cleary Member is poorly exposed.

In the eastern area, the coal sequence is generally overlain by sandstone. The sandstone in most places is medium grained, subangular, poorly sorted, and kaolinitic. Cross-stratification is the dominant sedimentary structure. Cross-stratification sets are three to four feet high with the foresets becoming tangential at the base of the set. Sets are very continuous with changes in dip angle seldom occurring in a single outcrop. These sandstones sometimes cut into and truncate coal beds. Mainly for ease of photogeologic mapping, the contact between the Cleary Member and the Allison Member was chosen at the base of these sandstones.

Figure 25 is a schematic diagram modified after diagrams by Dane (1936) and Hunt (1936). The significance of the diagram to coal distribution in the San Mateo Menefee area warrants discussion. Coal beds in this area are mainly associated with "continental" strata. An early period of continental sedimentation, represented by the Crevasse Canyon Formation, lacks economic coal beds to the northwest because in the vicinity of Cabezon the continental strata grade northeastward into marine strata. The Gallup Sandstone and the Hosta Tongue of the Point Lookout Sandstone pinch out, and the Crevasse Canyon Formation wedges out above and below the Mulatto Shale Tongue of the Mancos Shale. This facies relationship as shown on the state geologic map of New Mexico (Dane and Bachman, 1965) delimits prospective coal-bearing strata to the southwest.

A later period of continental sedimentation represented by the Menefee Formation has greater economic significance in the San Mateo Menefee area because during this period of sedimentation the continental coal-producing sedimentation moved farther to the northeast (fig. 25), allowing coal-bearing strata to be deposited in this area.

STRIPPABLE COAL RESERVES

Reserves have been estimated for coal beds more than three feet in thickness with less than 100 feet of overburden. Because of the lenticularity of coal beds in the Cleary Member, the limit of extrapolation of the lateral extent of a coal bed from a known thickness was 2,000 feet. It was this arbitrary cutoff that limits coal-reserve calculations. In most areas, structure and overburden would allow substantially higher reserves calculations, such as in T. 15 N., R. 7 W. where drilling extended the 2,000-foot cutoff. The following

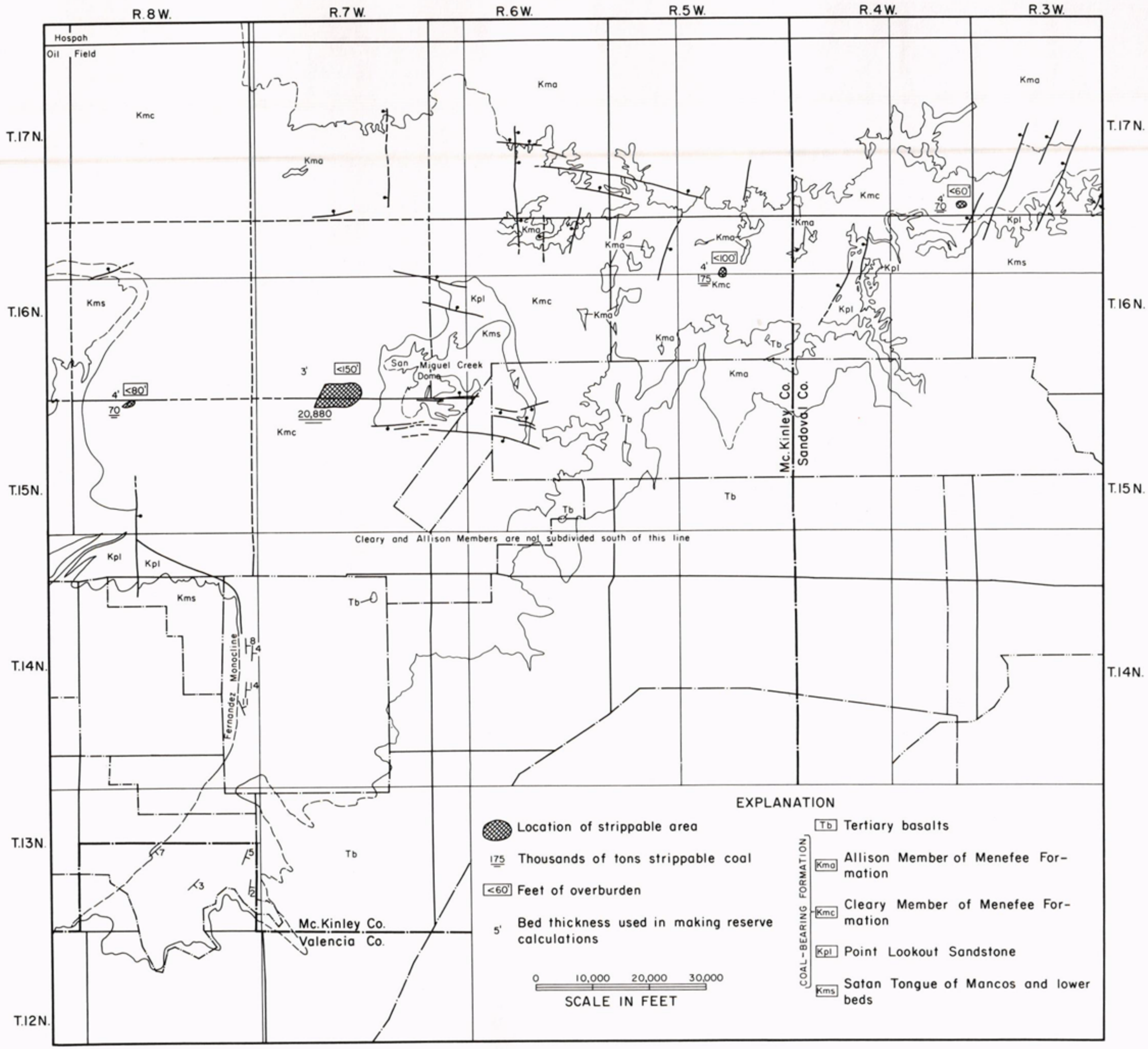

Figure 24

Geologic map of San Mateo Menefee area showing strippable areas

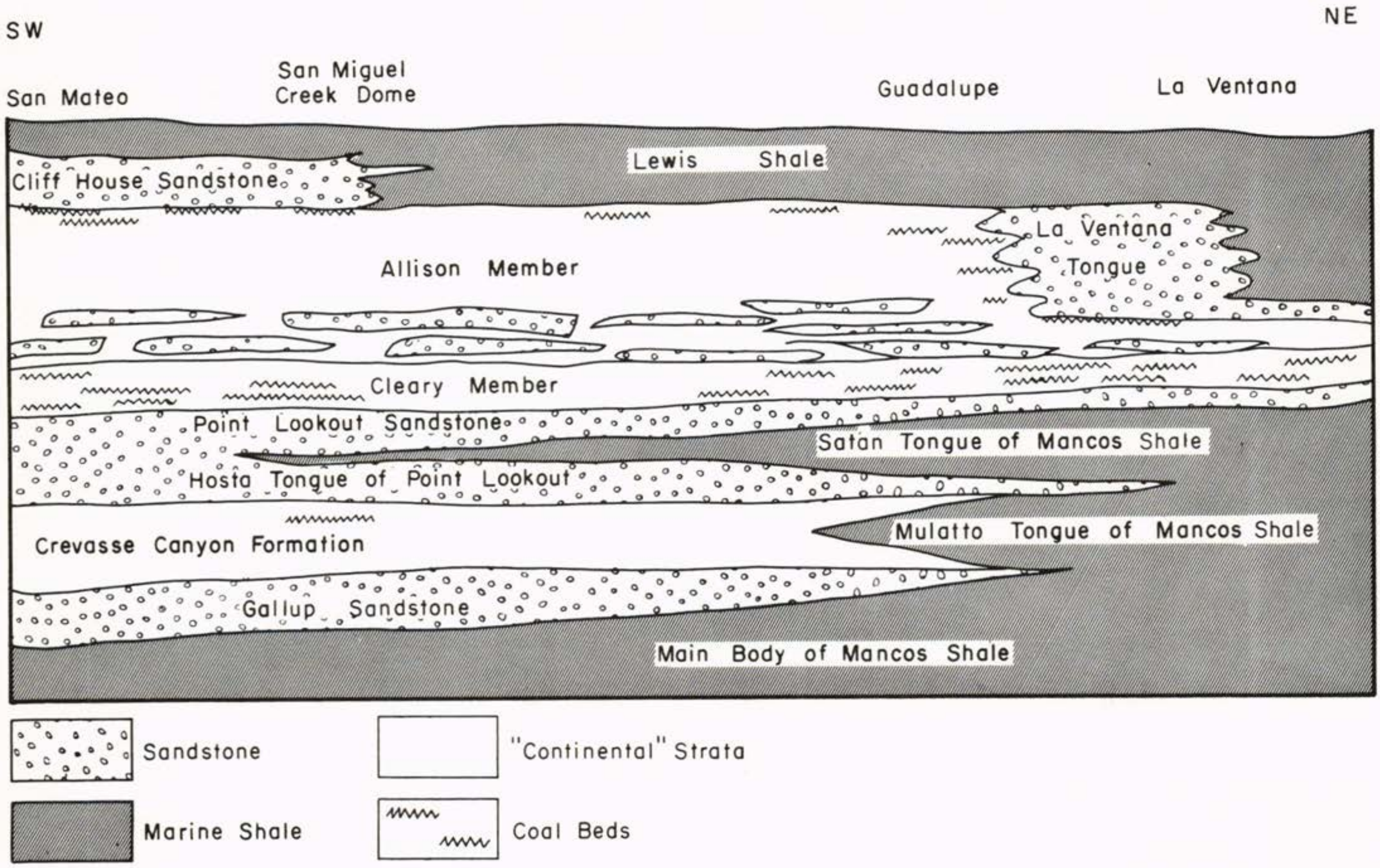

Figure 25

SCHEMATIC DIAGRAM OF STRATIGRAPHIC RELATIONSHIPS IN SAN MATEO MENEFEE AREA

list includes the reserves for four areas of strippable coal in the San Mateo Menefee area and the overburden.

Location	Strippable reserves in thousands of tons	Overburden
T. 17 N., R. 4 W.	70	less than 60 feet
T. 16 N., R. 5 W.	175	less than 100 feet
T. 15 N., R. 8 W.	70	less than 60 feet
T. 15 N., R. 7 W.	20,885	less than 150 feet
Total	21,200	

In the individual descriptions, emphasis is placed on coals which are greater than three feet in thickness. The presence or absence of the Cleary Member of the Menefee Formation and relationship of structure and topography to strippability are also included.

T. 17 N., R. 8 W.

This township includes large expanses of the Cleary Member of the Menefee Formation. No coal thicknesses have been reported. Access from the south is difficult and the township has not been adequately field searched. A stratigraphic cross section published by King and Wengerd (1957) showed coals to be present in the vicinity of the Hospah oil field. Because of the presence of coal in the Hospah area and the abundant outcrop of the Cleary Member in this township, further field work should find more coal exposures.

T. 17 N., R. 7 W.

The northern half of this township is covered by the coal-barren Allison Member of the Menefee Formation. The Gibson Member of the Menefee is exposed in the southern half of the township and although Hunt (1936) did not report coal thicknesses, coal beds apparently exist in the south half of section 19 and the north half of section 20 as evidenced by interpretation of photographs. The beds generally have a low dip to the north. A moderate mesa-and-valley topography exists in the north while in the south the more rounded hills of the Cleary Member rise 200 feet above Arroyo Lucero.

T. 17 N., R. 6 W.

The Cleary Member of the Menefee Formation crops out in the southwest corner of this township along the drainage of the north fork of Arroyo Chico. The Cleary Member dips under the high mesa-forming Allison Member north of the north fork. To the south, isolated remnants of the Allison Member remain as monuments overlying the Cleary Member. No bed thicknesses were reported by Hunt or Gardner but it seems likely that detailed field work could find coal beds in the area of the Cleary Member outcrop. Canyon-and-monument topography would make stripping difficult.

T. 17 N., R. 5 W.

Limited exposures of the Cleary Member of the Menefee Formation exist in the extreme southern margins of the township along Arroyo Chico. These outcrops are covered to the north by the high mesa cap of the Allison Member of the Menefee. Hunt reported no coals in the township. Coal appears to be present on the photographs in section 35. Gardner (1910) noted a coal bed 2.5 feet thick, at his locality No. 8. It is reasonable to assume that more exposures could be found in this area; however, the mesa-and-canyon topography would severely restrict strippable coal.

T. 17 N., R. 4 W.

The Cleary Member of the Menefee Formation is exposed in the southeast corner of this township. Most of the area is characterized by canyons and mesas which would make stripping difficult. Along Torreon Wash in sections 26, 27, 34, and 35, several coal beds crop out at the base of the canyon. The lowest coal is three feet in thickness. Two small mines existed in the north part of section 34.

In section 36, an outcrop of coal was found that is more than four feet thick. The base of the coal is not exposed. In this region, an estimated 7o thousand tons of coal are possible with less than 6o feet of overburden. A fault of small stratigraphic separation could limit reserves to the east. This area is accessible either by an unmapped road originating from the mouth of Arroyo Empedrado or from the east from the road along the upper reaches of Canada Santiago. Coal beds measured by Hunt and Gardner in this region are all less than three feet in thickness.

T. 17 N., R. 3 W.

The Cleary Member crops out as an east-northeast-trending narrow strip in this township. The narrow outcrop band testifies to the steeper dip in this region, up to four degrees. To the northwest, the Cleary Member is covered by the Allison Member which forms a prominent mesa as much as 30o feet high. The Allison mesa prohibits strip mining. Only a few isolated remnants of the coal beds crop out in the strike valley between the Allison and Point Lookout mesas.

T. 16 N., R. 8 W.

This township is almost completely underlain by the Cleary Member of the Menefee Formation. No coals reported by Hunt (1936) in this area are over three feet thick. One poorly exposed coal measured just to the south of this township is four feet thick; this coal bed probably extends northward beneath T. 16 N., R. 8 W. The low, rolling topography of the township would be favorable for stripping if coal were found in the Cleary Member.

The township lies between a known area of strippable coal in the southern part of T. 17 N., R. 9 W. and the northern part of T. i6 N., R. 9 W. and an oil test in section 23, T. 15 N., R. 8 W. in which a 12-foot-thick coal bed was penetrated. In section 17, T. 16 N., R. 8 W., another oil test (Crown Central No. 1 Fernandez), appears to have penetrated one thin coal between 5o and 52 feet, but it is so close to the Menefee outcrop that a possible thicker coal bed somewhat higher in the stratigraphic section may have been missed. Further exploration of the area is warranted.

T. 16 N., R. 7 W.

The Cleary Member crops out over most of this township except where it is eroded on the San Miguel Creek dome in the southwest corner of the township. No data are available for measured thicknesses of coal in this township; however, one of Hunt's thickest coals, 5.8 feet, crops out just to the south in T. 15 N., R. 7 W. This coal could extend northward under this township. The topography of the area is of low mesas with as much as 100 feet of relief. Shallow-lying coals could have broad extent with less than 100 feet of overburden.

T. 16 N., R. 6 W.

The Cleary Member of the Menefee Formation is exposed over a large part of this township. To the north, the Allison Member overlies the Cleary Member on isolated mesas. To the south, the Cleary Member is eroded from the San Miguel Creek dome. No thicknesses are reported but there certainly are coal outcrops; "photogeologic" coal occurs in sections 7 and 8.

T. 16 N., R. 5 W.

Extensive outcrops of the Cleary Coal Member are present in this township. To the north and south, the Cleary Member is overlain by the Allison Member of the Menefee Formation. A few isolated remnants of Allison Member overlie the Cleary in the central region. Many outcrops of coal exist but most beds are less than three feet in thickness. In the NE1/4 of section 11, a 5-foot bed with a 6-inch impure zone was measured. At Coal Spring in section 15, a 4-foot-thick coal bed is intersected by an igneous dike. There is a definite possibility of strippable coal and further exploration is warranted. Hunt also showed a 3.8 coal bed in NE1/4NE1/4 of section 22. In this section, the Cleary is in many places covered by 800 to 90o feet of the Allison Member of the Menefee Formation. Strippable coal in this township is estimated at 175 thousand tons.

T. 16 N., R. 4 W.

The Cleary Member of the Menefee Formation is exposed in the east part of this township. To the south and north, the Cleary Member is overlain by the Allison Member. To the east, the Cleary Member has been eroded from an uplifted fault block. A thin outcrop band exists to the southeast along the Mesa Chivato escarpment. No coals have been reported from the escarpment where the topography would not allow stripping of coal beds if they were present. The topography in the western part of the township is gently rolling with a few monument-like mesas. If coals were found in the west, strip mining would be possible.

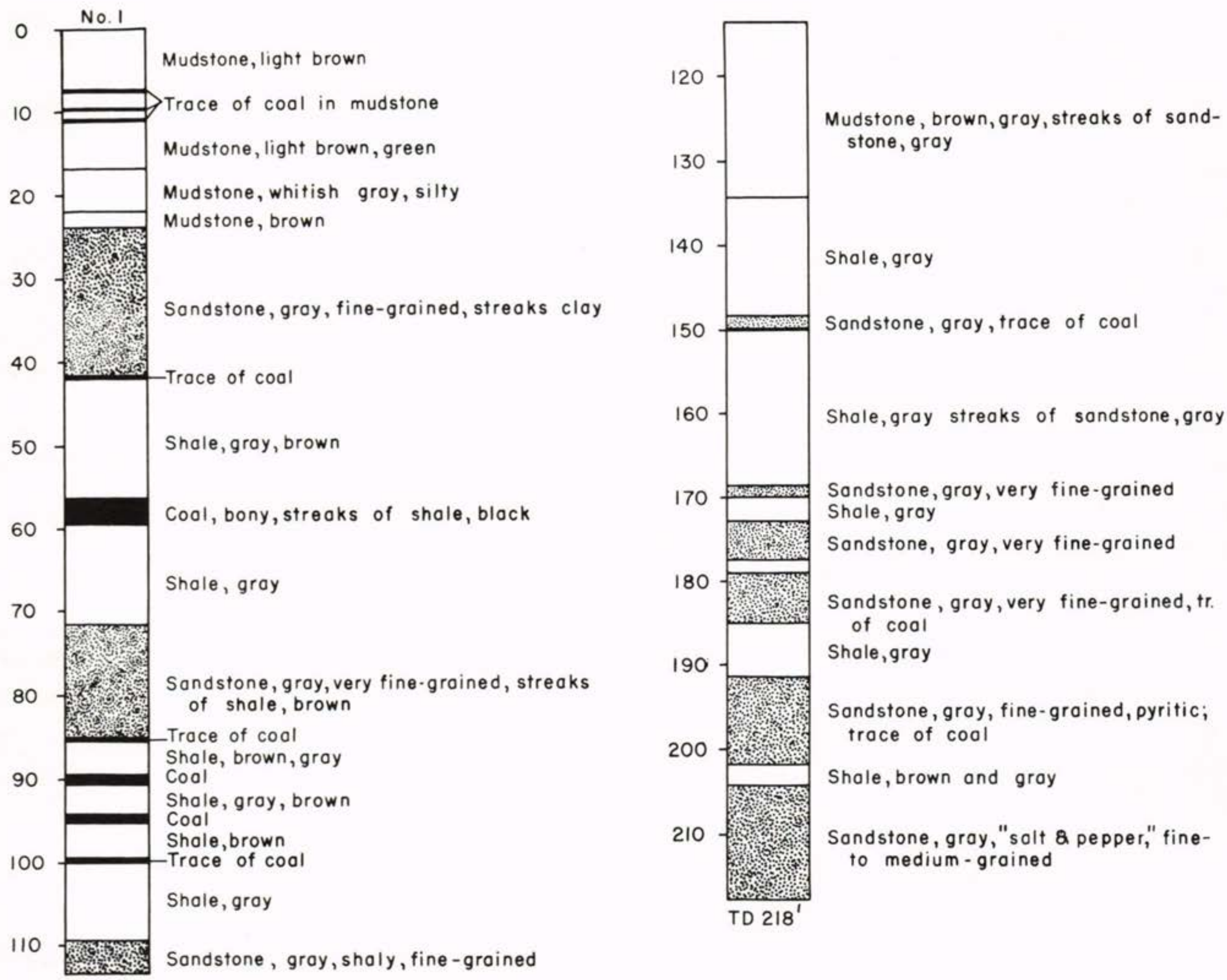

Figure 26

Graphic log of test hole No. 1, NW¼SW¼SW¼ section 9, T. 15 N., R. 7 W., McKinley Co., N.M. Logged by W. H. Pierce

T. 15 N., R. 8 W.

The Cleary Member of the Menefee Formation is exposed in a broad area in this township, which lies in a flat-bottomed structural reentrant between the southwest edge of the San Juan Basin and the San Miguel Creek dome. The low-relief topography would be especially advantageous for stripping if coals were present; however, only one coal was found to be more than three feet in thickness. This coal bed is poorly exposed (about four feet thick) and contains impure coaly laminate. About 70 thousand tons of strippable coal are possible in this area beneath less than 60 feet of overburden.

A formation-density log of the Crown Central No. 2 Fernandez oil test in section 23, T. 15 N., R. 8 W. shows several coal beds, including a 3-foot-thick bed (with a shale parting) between 191 and 194 feet, and a 12-foot bed between 203 and 215 feet of depth. This indicates that a significant amount of coal might be strippable in this township.

T. 15 N., R. 7 W.

The Cleary Member of the Menefee Formation is widely exposed in this township. In the northeast quarter of the township, the Cleary Member is eroded from the San Miguel Creek dome. Coal beds dip gently off the flanks of the dome and then flatten out to lie almost horizontally. The topography is rolling with relief of the broad hills ranging up to 200 feet from valley to crest. Hunt (1936) reported one thick coal in section 2 as being 5.8 feet thick. A test hole (fig. 26) in the NW1/4SW1/4SW1/4 of section 9, T. 15 N., R. 7 W. found one 3-foot and one 1 1/2-foot coal separated by a 1 1/2-foot parting at what is probably the same horizon. Assuming a three-foot average coal thickness and interpolating between Hunt's section and the test hole gives reserves of 20.88 million tons at depths of less than 150 feet.

T. 15 N., R. 6 W.

The Felipe Tafoya and Ignacio Chavez Grants are discussed separately from this township. Hunt (1936) published a fairly optimistic coal sequence which he measured near the Michael ranch along the south side of the road in the NW1/4 NW1/4 of section 20. A lower 1-foot-thick coal bed and an upper 17-foot carbonaceous shale zone with two 6-inch coals was measured there during the present study. The carbonaceous shale is poorly exposed and it is possible that Hunt's thicker coal beds exist beneath cover. Section zo lies on the down-faulted southern flank of the San Miguel Creek dome. Faulting could complicate the area for coal mining.

Coal is also apparent on photographs in section 28 and 29 in the NE1/4 and NW1/4, north of the Jaramillo ranch.

Felipe Tafoya Grant

The Cleary Member is widespread in this grant. The northeast end of the grant contains the older strata exposed in the San Miguel Creek dome. Hunt reported a single 1.7foot-thick coal bed in the Gibson Member of the Crevasse Canyon Formation. This is the only reported outcrop of coal below the Menefee Formation within the San Mateo Menefee Area.

Ignacio Chavez Grant

This grant covers areas of several unsurveyed townships. General location is referred to by using projected township and section lines. In the west side of the grant, in approximately N1/2 section r o, T. 15 N., R. 6 W., a bed of coal three feet thick crops out along the road. At this point the bed dips to the east but farther east the bed flattens out. Faulting and thick overburden make for a pessimistic stripping potential.

In almost all of the central part of the Ignacio Chavez Grant, the Cleary Member is deeply covered by the Allison Member of the Menefee and by Tertiary basalt flows of Mesa Chivato.

Near the eastern side of Mesa Chivato, T. 15 N., R. 4 W., the Cleary Member of the Menefee Formation crops out in the Mesa Chivato escarpment. No coal beds have been reported from this area and overburden thickness would preclude stripping.

Bartolome Fernandez Grant

The Cleary Member crops out along San Lucas Canyon. One bed with unexposed base is more than three feet thick near what would be the NE1/4NE1/4 of section 25, T. 14 N., R. 8 W. The area has been mapped by Santos (1966a).

T. 13 N., R. 8 W.

Outcrops of the Menefee Formation are present but no coals have been reported. The township has been mapped by Santos (1966b).

San Mateo Springs Grant

Outcrops of the Menefee Formation exist along the north La Jara Mesa escarpment. No coals have been reported (Santos, 1966b). Topography would preclude stripping.

COAL QUALITY

No coal sampling was done of coals in the San Mateo Menefee area for the present study and no published analyses are known. A general indication of coal quality can be gained from the analysis of core taken from the Cleary Member in New Mexico State Bureau of Mines test hole No. i6 (in SE1/4 section 36, T. 17 N., R. 10 W.) in the adjoining Standing Rock area. In that sample, as-received heating value was 10,070 Btu per pound, ash content was 9.7 percent, and sulfur content was o.6 percent. The complete analysis is in Table 5.

STANDING ROCK CLEARY AREA

by John W. Shomaker

SUMMARY

The Standing Rock area is a belt of outcrop of the Upper Cretaceous Menefee Formation. A few discontinuous and lenticular coal beds crop out, but no major reserves are evident from surface exposures. Drilling, however, has revealed thick coal in two localities and indicated that commercial reserves (perhaps 6o to 75 million tons each) may be present. Coal quality is good; heating value ranges from 8,870 to 10,810 Btu per pound, ash content from 4.9 to 18.4 percent, and sulfur content from 0.5 to 1.0 percent in samples analyzed (table 5).

INTRODUCTION

The Standing Rock area encompasses the outcrop of the Cleary Coal Member of the Menefee Formation (and the overlying Allison Member in some areas) in a broad band from T. 18 N., R. i 7 W. eastward to T. 16 N., R. 9 W. (fig. 27). The area lies in the upper reaches of the northward-flowing tributaries of Chaco River east of U.S. Highway 666.

Evaluation of coal reserves is based on maps and measured sections of Sears, Hunt, and Dane (1936), O'Sullivan (1955), and on extensive field reconnaissance. Three test holes drilled by the New Mexico State Bureau of Mines and Mineral Resources gave much information as to the nature of the coal-bearing section in areas where coal was thought to be present but outcrops are obscured.

The occurrence of coal beds of significant thickness is restricted to the Cleary Coal Member, the basal member of the Upper Cretaceous Menefee Formation, though very thin beds have been found higher in the stratigraphic section, in the Allison Member, at a few localities. The coals of the Cleary are typically lenticular and thicken and thin erratically.

Southward and westward from the west end of the Standing Rock area, the Point Lookout Sandstone, which separates the Cleary above from the Gibson Coal Member of the Crevasse Canyon Fonnation below, is not present. Thus the Gibson and Cleary merge into a combined coal zone. The area in which the two coal-bearing members are present as a single unit is, for convenience, assigned to the Gallup field for the purposes of this study.

The quality of the Cleary coal in the Standing Rock area can be assumed to be similar to that of corresponding beds in the Gallup field. No outcrop samples were taken because the coal beds are so poorly exposed and deeply weathered. Samples of beds penetrated in the core holes were analyzed (table 5), however, and provide some direct information in the Standing Rock area.

In the Gallup field (which adjoins the Standing Rock area at its western end), coals approximately equivalent to the Cleary coals of the Standing Rock area are the uppermost

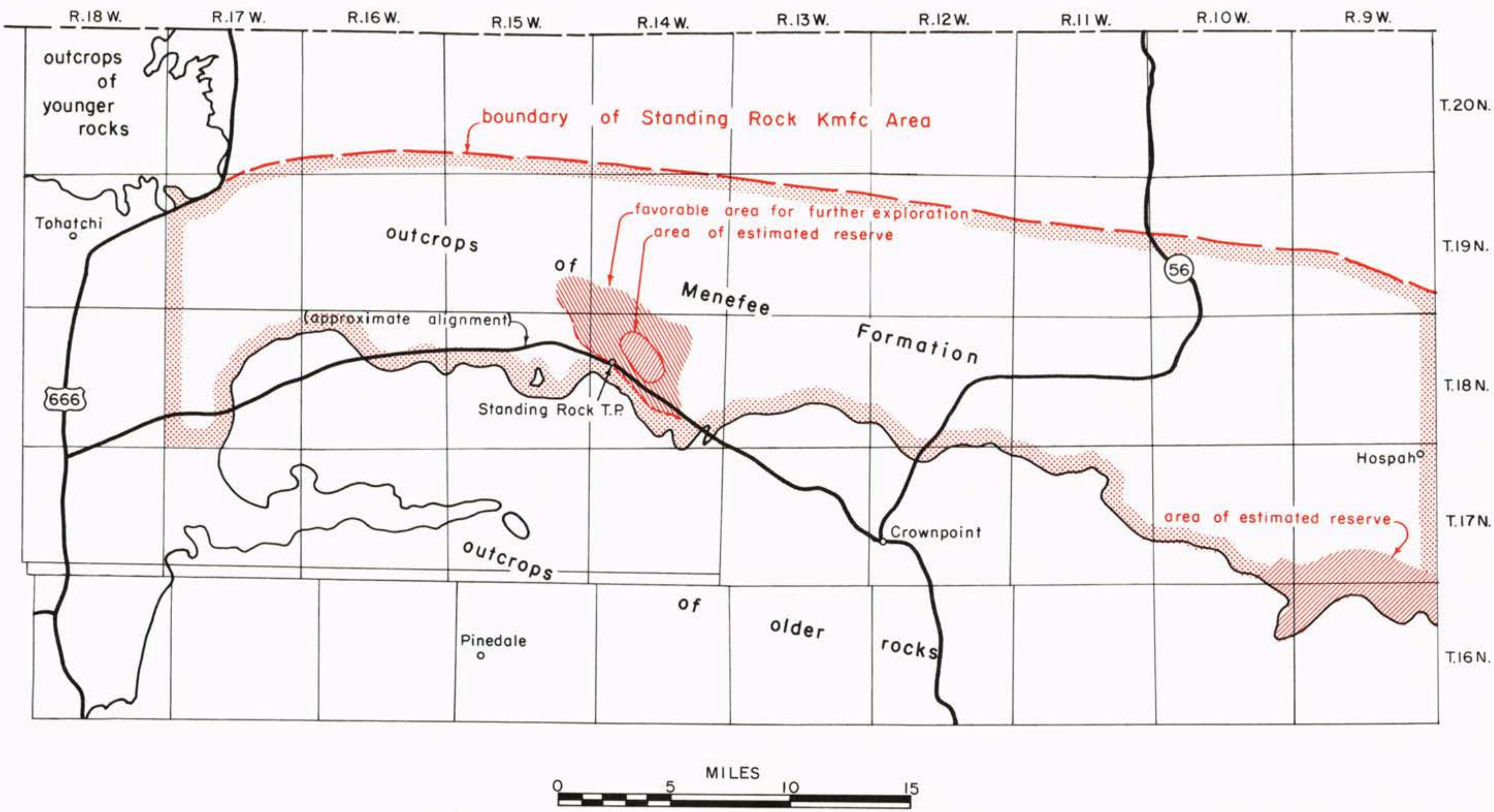

Figure 27

INDEX MAP OF STANDING ROCK CLEARY AREA AND AREAS OF ESTIMATED COAL RESERVES beds of the combined Gibson-Cleary zone. The coal zone was a major producer in the Gallup field during the period from 1885 to 1951, and many analyses are available for the various beds. The highest bed mined in the Heaton mine (the mine nearest the Standing Rock area in which the upper beds were sampled) in section 35 of T. 16 N., R. 18 W. yielded coal with as-received heating value of 11,030 Btu per pound and 11,070 Btu per pound in two analyses, with corresponding values of o.6 and 0.4 percent sulfur, 14.6 and 15.3 percent moisture, 38.8 and 38.2 percent volatile matter, 40.9 and 42.0 percent fixed carbon, and 5.7 and 4.5 percent ash. Analytical results for samples of coal cored in New Mexico State Bureau of Mines test holes Nos. 3A, 3B, and 16, in the Standing Rock area are shown in Table 5.

The gentle northward dip of the strata, and the predominance of relatively soft shale and shaly sandstone have led to the development of a topography of flats, gently undulating plains, and low sandstone-capped cuestas. The low relief and soft bedrock cause coal outcrops to be obscure in most areas, so that drilling will be the only satisfactory way of exploring the area thoroughly.

DESCRIPTIONS OF TOWNSHIPS

T. 16 N., R. 9 W.

One to three thin coal beds are exposed in the Cleary Member in this township. The only measured section is that mentioned by Sears, Hunt, and Dane (1936) in section 6, in which 1.4 feet of coal was exposed. No outcrop measurements in the township adjoining to the north exceed 2.5 feet, and few well-exposed outcrops exist in T. 16 N., R. 9 W.

Several oil tests drilled in T. 17 N., R. 8 W., and T. 17 N., R. 9 W., and New Mexico State Bureau of Mines test hole No. 16 in section 36 of T. 17 N., R. 10 W. penetrated coal (fig. 28) of minable thickness at depths not greatly beyond the reach of stripping (see fig. 29). Based on the very sparse data available, a speculative estimate of the strippable reserve (down to 25o feet) would be on the order of 75 million tons. The area involved is in T. 16 N., R. 9 W.; T. i6 N., R. 10 W.; T. 17 N., R. 8 W.; T. 17 N., R. 9 W.; and T. 17 N., R. 10 W. There is too little evidence to compute reserves on a township basis.

T. 16 N., R. 10 W.

The Cleary is exposed in sections 1, 2, 12, 13, and 14, over an area of about two square miles. A single coal bed was mapped in section 1 by Sears, Hunt, and Dane (1936) but no section was measured. A measured section in section 6 of T. 16 N., R. 9 W., about one-half mile from the nearest point along the bed in T. 16 N., R. 10 W., indicated a thickness of 1.4 feet.

The coal bed encountered at 186 feet in New Mexico State Bureau of Mines test hole No. i6 probably underlies parts of sections 1 and 12, in which case they may contain some minable reserves. See T. 16 N., R. 9 W.

T. 17 N., R. 9 W.

Allison and Cleary beds are exposed throughout the township, and two coal beds crop out sporadically across the southern two tiers of sections. Unfortunately both are thin; the thickest measured section of coal is a single bed 2.5 feet thick.

Five oil tests, in sections 27, 32, 35, and 36, indicate substantial thicknesses of coal at depths of 142 feet or more (see fig. 29). Near the south line of the township, some strippable reserves are undoubtedly present; the coal in this township was not estimated separately, but is included in the description of T. 16 N., R. 9 W.

T. 17 N., R. 10 W.

Allison and Cleary beds crop out over all but about six square miles of the southwestern part of the township. Three coal beds have been mapped, but only one is continuous across the township. The thickest coal section measured was 1.6 feet.

New Mexico State Bureau of Mines test hole No. 16, in the SE1/4NW1/4NE1/4 section 36, penetrated 3 feet of coal between 65 and 68 feet, 4 feet between 136 and 140 feet, 3.5 feet between 164.5 and 168 feet, and 24 feet (with 2 partings totalling 4.5 feet) between 18o and 204 feet. This hole extended the reserves indicated by the oil tests in T. 17 N., R. 9 W., described in Figure 29 and under the T. 16 N., R. 9 W. heading, and indicates that substantial reserves are present in T. 17 N., R. 1 0 W. There are not enough data to permit a separate estimate for this township.

T. 17 N., R. ix W.

Cleary Member beds crop out over about 11.5 square miles along the northern and eastern edges of the township. No coal beds were mapped by Sears, Hunt, and Dane (1936), and none were found during field investigation for this study.

T. 17 N., R. 12 W.

Only about one square mile of Cleary outcrop is present in this township. No coal was found.

T. 18 N., R. 12 W.

Virtually all but section 31 and part of section 3o of the township is outcrop of Cleary, and possibly Allison beds. Short, discontinuous beds of coal were mapped in section 21 and 3o; nowhere does the coal thickness exceed 1.5 feet in surface exposures. No reserves were estimated.

T. 18 N., R. 13 W.

Cleary and probably Allison beds crop out over most of the township. Coal beds are present in sections 16, 18, 19, 20, and 25,. but nowhere are they more than 1.3 feet thick according to available measurements. No reserves were estimated.

T. 18 N., R. 14 W. (projected)

The New Mexico State Bureau of Mines drilled test holes at two locations in the township (see fig. 3o). Test hole No. 3A was drilled in the NW1/4SW1/4NE1/4 of section 16 (projected); it penetrated (fig. 31) 216.5 feet of Cleary strata, including seven coal beds. Beds of commercial thickness

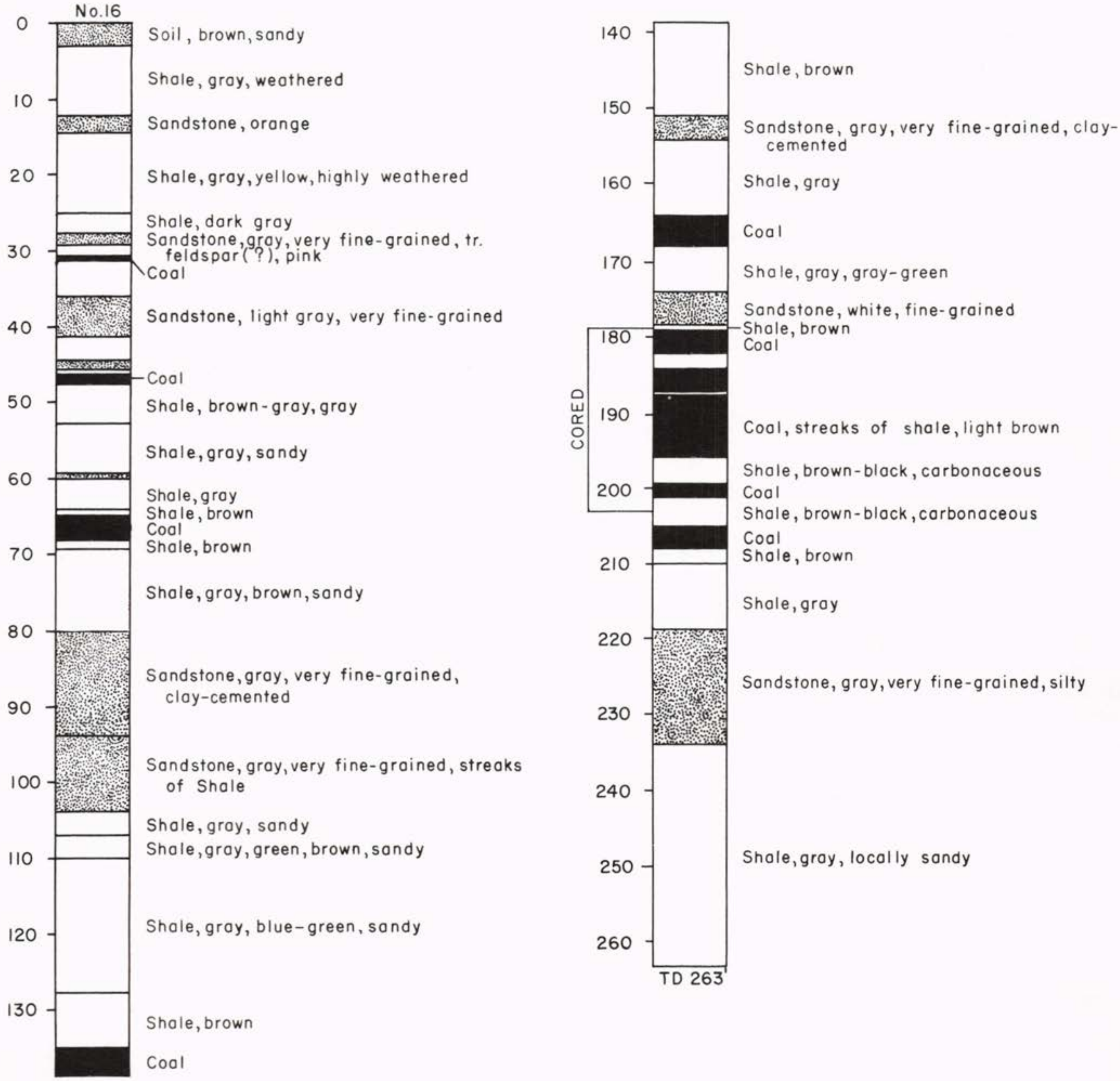

Figure 28

GRAPHIC LOG OF TEST HOLE No. 16, SW¼NW¼NE¼ SECTION 36, T. 17 N., R. 10 W., MCKINLEY CO., N.M. LOGGED BY R. C. LEASE

were penetrated between 128.1 feet and 131.6 feet (3.5 feet), 141.3 feet and 145.8 feet (4.5 feet), and 150.8 feet and 162.2 feet (11.4 feet, with a black shale parting 2.4 feet thick). Test hole No. 3B was drilled (fig. 32) in the NW1/4NE1/4 NE1/4 of section 8 (projected), to a depth of 112.6 feet. In hole No. 3B, a 3-foot coal was penetrated between 63.0 and 66.0 feet, and a coal bed 21.1 feet thick (including a 2.5-foot thick parting) and correlative with the 11.4 foot bed in hole No. 3A, was penetrated from 82.5 feet to 103.6 feet. Continuous 2 1/8-inch core was taken in all of the coals mentioned above, and analyses of the samples are shown in Table 5.

No satisfactory topographic or detailed geologic maps are available for the western part of the Standing Rock area, but several generalizations can be made as to stripping conditions by a cursory examination of the area. The topography is one of low south-facing cuestas and broad, alluviated flats. The dip of geologic formations is gentle—on the order of two to four degrees. Hole No. 3A was located at the stratigraphically highest point in the vicinity, and at almost the highest topographic level, and should represent the greatest thickness of overburden for an area of at least ten square miles. In hole No. 3A, the overburden above the main bed is 141.3 feet thick, and consists of about 40 feet of gray or light-brown, fine-grained sandstone in several beds and about 80 feet of brown and gray shale. The thickest sandstone bed is about 20 feet thick.

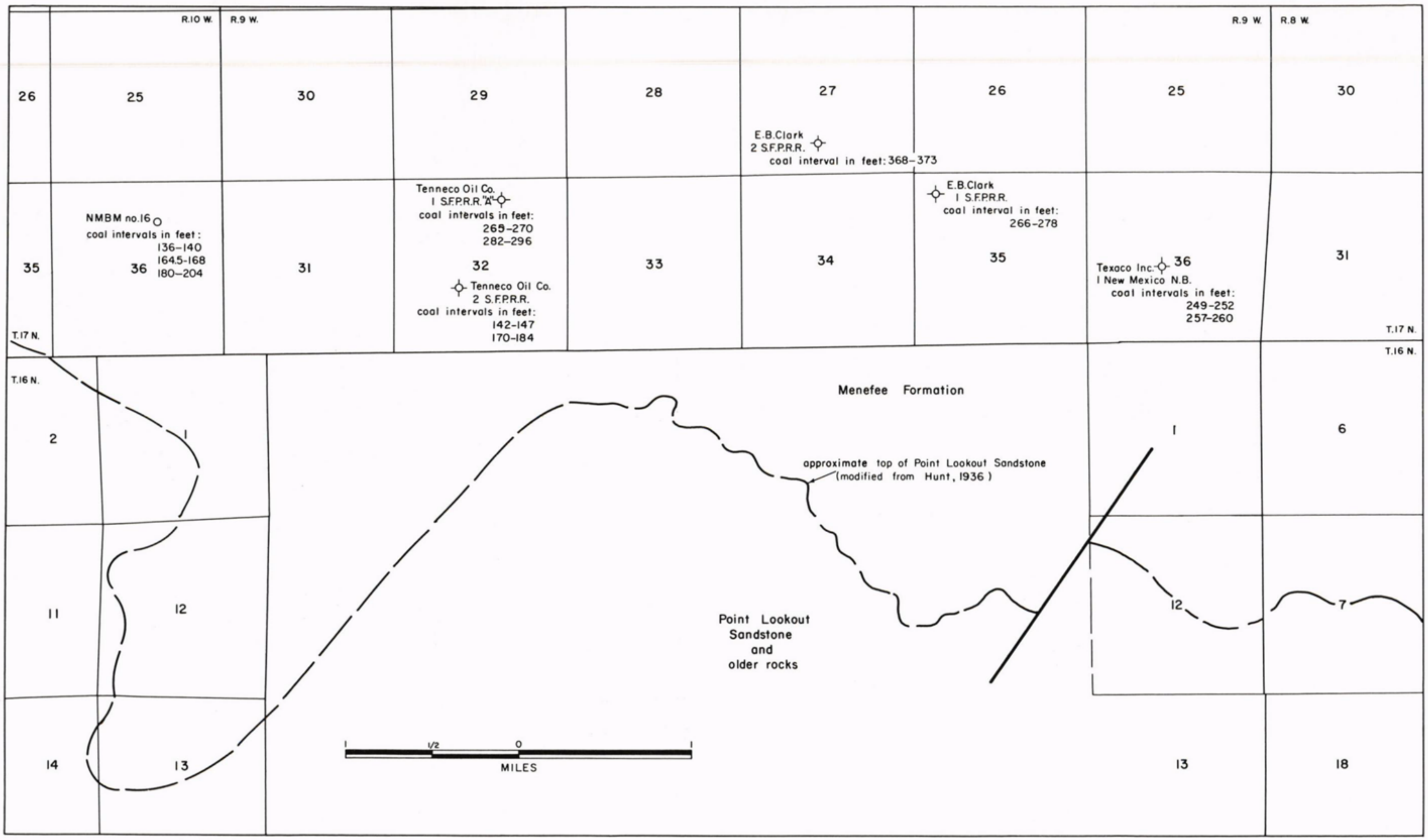

Figure 29

Map showing approximate top of Point Lookout Sandstone and locations of drill holes in coal area south of Hospah

TABLE 5. ANALYSES OF COAL SAMPLES FROM STANDING ROCK UPPER MENEFEE AREA

LOCATION	KIND OF SAMPLE	CONDITION[1]	SAMPLE NO.	PROXIMATE, PERCENT: LABORATORY NUMBER[2]	MOISTURE	VOLATILE MATTER	FIXED CARBON	ASH	ULTIMATE, PERCENT: HYDROGEN	CARBON	NITROGEN	OXYGEN	SULFUR	ASH	HEATING VALUE: BRITISH THERMAL UNITS PER POUND	FORMS OF SULFUR: SULFATE	PYRITIC	ORGANIC	FUSIBILITY OF ASH, °F: INITIAL DEFORMATION TEMP.	SOFTENING TEMP.	FLUID TEMP.	REMARKS
SW¼ NW¼ NE¼	core, test hole	1	16-A	J-63534	16.5	33.4	40.4	9.7	6.0	57.4	0.9	25.4	0.6	9.7	10,070	—	—	—	2830	2900	2910+	Equilibrium moisture = 16.4%;
Sec. 36,	No. 16	2	—	—	—	40.0	48.3	11.7	5.0	68.8	1.1	12.7	0.7	11.7	12,060	—	0.17	—	—	—	—	Hardgrove grindability index = 62;
T. 17 N., R. 10 W.		3	—	—	—	45.3	54.7	—	5.7	77.8	1.2	14.5	0.8	—	13,650	—	—	—	—	—	—	free-swelling index—noncaking.
NW¼ NE¼ NE¼	core, test hole	1	3B-A	J-61755	16.0	31.1	34.5	18.4	5.4	50.4	0.8	24.5	0.5	18.4	8,870	—	—	—	2790	2840	2890	Equilibrium moisture = 15.41%;
Sec. 8,	No. 3B	2	—	—	—	37.1	41.5	21.9	4.2	60.0	1.0	12.3	0.6	21.9	10,570	—	0.03	—	—	—	—	Hardgrove grindability index = 62;
T. 18 N., R. 14 W.		3	—	—	—	47.5	52.5	—	5.4	76.8	1.3	15.8	0.7	—	13,530	—	—	—	—	—	—	free-swelling index—noncaking.
NW¼ NE¼ NE¼	core, test hole	1	3B-C	J-61756	15.4	33.2	37.5	13.9	5.8	54.3	0.9	24.3	0.8	13.9	9,480	—	—	—	2410	2470	2520	Equilibrium moisture = 15.69%;
Sec. 8,	No. 3B	2	—	—	—	39.2	44.4	16.4	4.8	64.1	1.1	12.6	1.0	16.4	11,200	—	0.41	—	—	—	—	Hardgrove grindability index = 56;
T. 18 N., R. 14 W.		3	—	—	—	46.9	53.1	—	5.8	76.7	1.3	15.0	1.2	—	13,390	—	—	—	—	—	—	free-swelling index—noncaking.
NW¼ SW¼ NE¼	core, test hole	1	3A-A	J-61752	15.3	36.9	40.7	7.1	6.4	60.9	1.0	24.1	0.5	7.1	10,620	—	—	—	2570	2620	2670	Equilibrium moisture = 15.84%;
Sec. 16,	No. 3A	2	—	—	—	43.6	48.0	8.4	5.5	71.9	1.2	12.5	0.5	8.4	12,540	—	0.01	—	—	—	—	Hardgrove grindability index =56;
T. 18 N., R. 14 W.		3	—	—	—	47.6	52.4	—	6.0	78.5	1.3	13.6	0.6	—	13,690	—	—	—	—	—	—	free-swelling index—noncaking.
NW¼ SW¼ NE¼	core, test hole	1	3A-B	J-61753	17.3	34.5	43.3	4.9	5.9	61.5	1.0	26.2	0.5	4.9	10,810	—	—	—	—	—	—	Equilibrium moisture = 17.20%;
Sec. 16,	No. 3A	2	—	—	—	41.7	52.4	5.9	4.8	74.3	1.2	13.2	0.6	5.9	13,070	—	0.03	—	—	—	—	Hardgrove grindability index = 62;
T. 18 N., R. 14 W.		3	—	—	—	44.3	55.7	—	5.1	79.0	1.3	13.9	0.7	—	13,900	—	—	—	—	—	—	free-swelling index—noncaking.
NW¼ SW¼ NE¼	core, test hole	1	3A-C	J-61754	16.4	31.8	37.7	14.1	5.8	54.7	0.9	23.5	1.0	14.1	9,520	—	—	—	2260	2460	2710	Equilibrium moisture = 16.00%;
Sec. 16,	No. 3A	2	—	—	—	38.1	45.0	16.9	4.7	65.4	1.1	10.7	1.2	16.9	11,390	—	0.75	—	—	—	—	Hardgrove grindability index = 57;
T. 18 N., R. 14 W.		3	—	—	—	45.8	54.2	—	5.7	78.7	1.3	12.9	1.4	—	13,710	—	—	—	—	—	—	free-swelling index—noncaking.

[1] Condition: 1, as received; 2, moisture-free; 3, moisture- and ash-free.
[2] Analyses by U. S. Bureau of Mines.

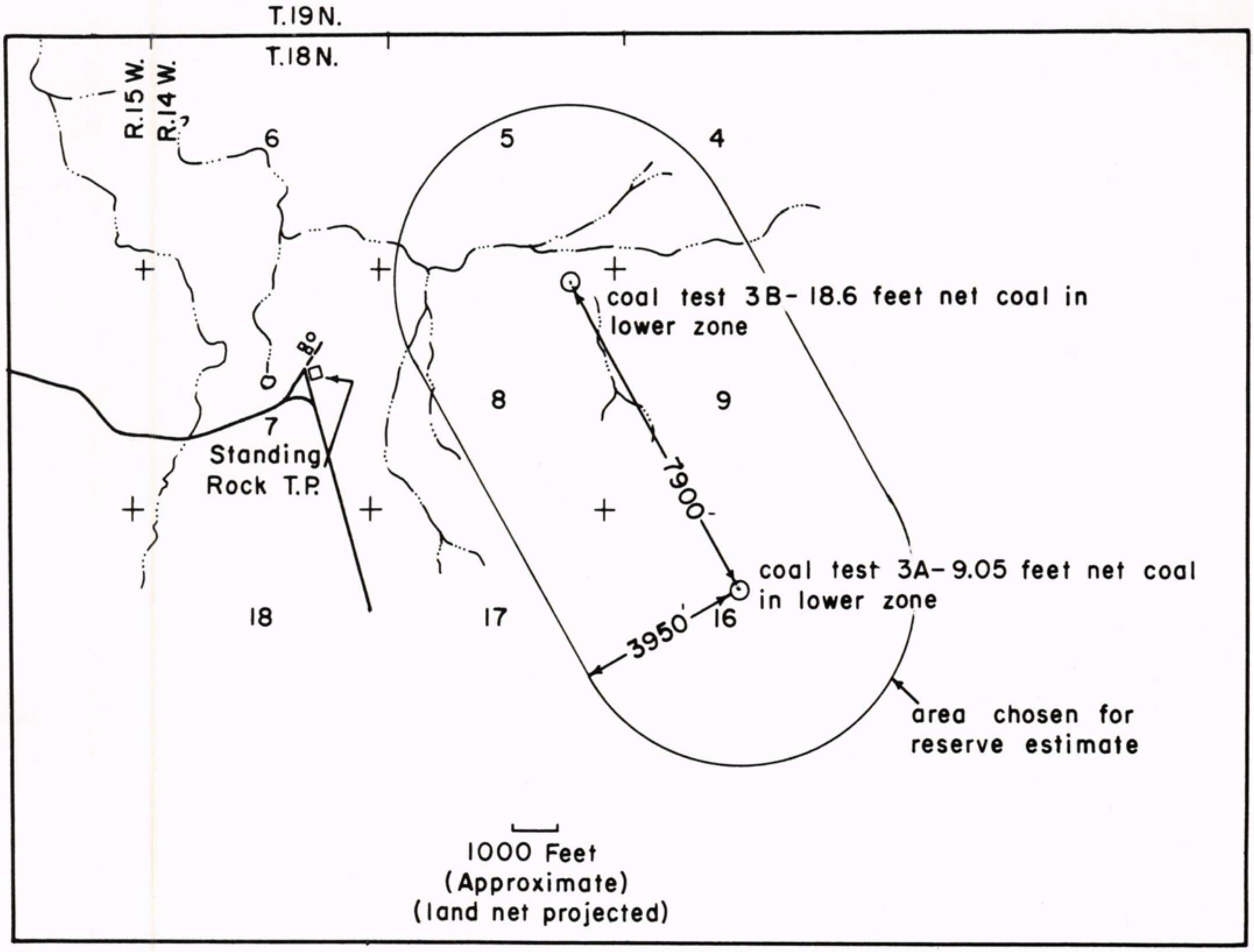

Figure 30

Map showing locations of test holes Nos. 3A and 3B in Standing Rock area, and arbitrary area chosen for reserve estimates

A very crude estimate of the coal reserve represented by the two test holes might be made by averaging the net coal thicknesses of the main bed and assuming that the average applied over an area between the holes as wide as the distance between them (about 7,900 feet) and within a circumference around each hole defined by a 7,900-foot diameter (fig. 30). The reserve arrived at in this manner is 63.5 million tons, a figure to be considered highly speculative because of the obviously inadequate data.

T. 18 N., R. 15 W. (projected)

The northern four tiers of sections of this township are exposures of Cleary beds. Coal beds crop out around the topographically higher areas, and at one point (in the southeast quarter of section 8) a coal bed reaches a thickness of six feet. The bed can be traced more than a mile to the north; a bed above it, 1.3 feet thick, maintains its thickness for about two miles to the south. Though the coal zone can be traced for some distance, there are almost never more than two beds in it at any point and thicknesses are so vari able that any significant strippable reserves are unlikely. The only real possibility appears to be in a few tens of acres in the southeast quarter of section 8 and the southwest corner of section 9.

T. 19 N., R. 14 W. and T. 19 N., R. 15 W.

The body of coal found by exploratory drilling in the northwestern part of T. 18 N., R. 14 W. may well extend into the southwestern part of T. 19 N., R. 14 W., and the southeastern part of T. 19 N., R. 15 W. There is no evidence available to indicate whether it does or not, but the areas seem to be likely prospects.

ZUNI MESAVERDE AREA

by Frank E. Kottlowski

The Zuni coal area lies in the southern part of the Gallup-Zuni Basin, which is a generally north-northwest-trending syncline plunging northward into the southwestern part of

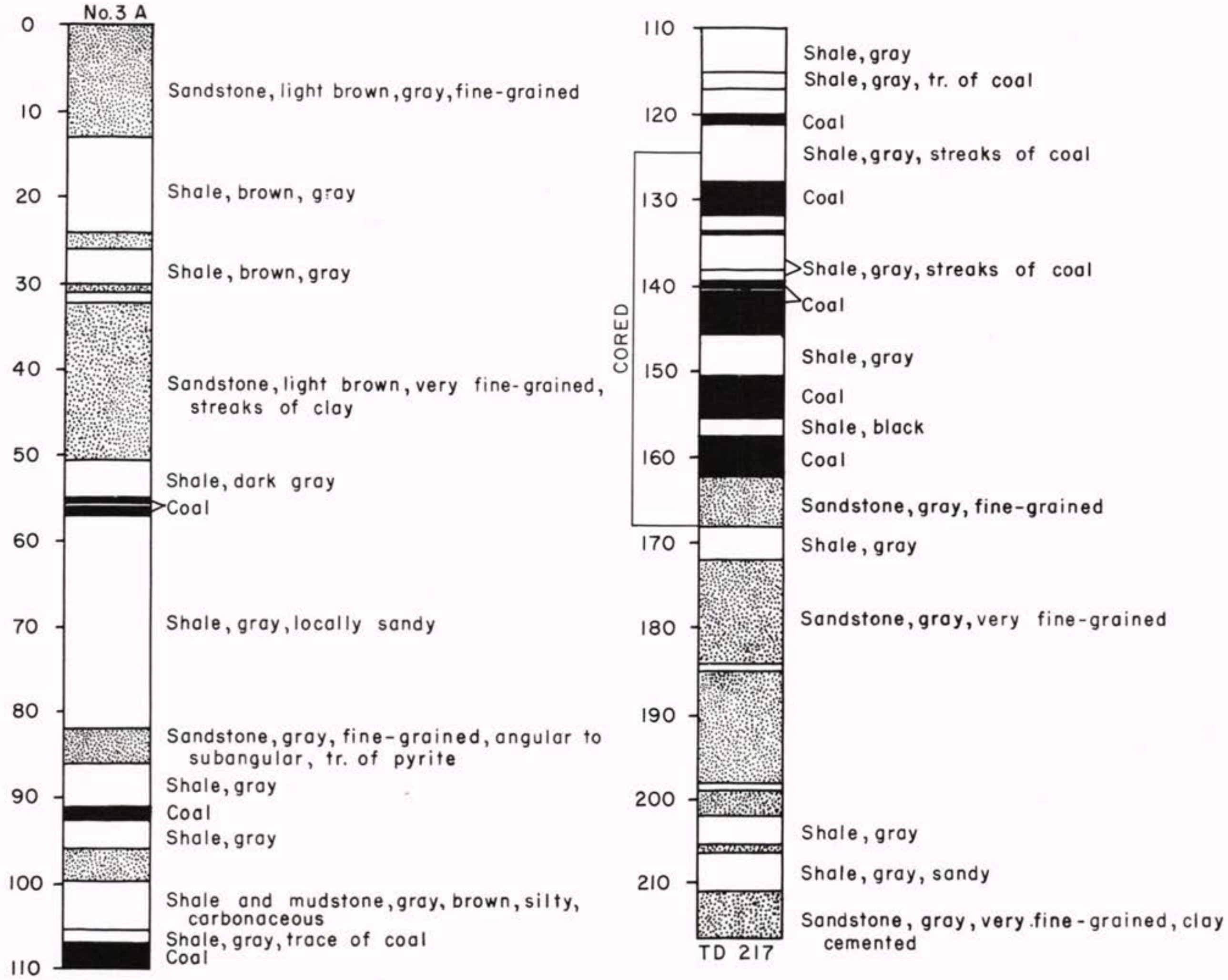

Figure 31

Graphic log of test hole No. 3A, NW¼SW¼NE¼ section 16, T. 18 N., R. 14 W., McKinley Co., N.M.
Logged by W. H. Pierce, R. C. Lease, and J. W. Shomaker

the main San Juan Basin. Coal-bearing beds in the Mesaverde Group crop out in Ts. 16 to 18 W. and Rs. 1 o to 12 N. (fig. 33), as well as in immediately adjacent areas. Most of this area is in the eastern part of the Zuni Indian Reservation.

The coal-bearing strata dip gently east-northeast from the Piñon Springs anticline that lies west of the coal area to the broad, vague axis of the Allison-Ramah syncline (fig. 33). This syncline trends north and north-northwestward along an axis that lies near the east edge of the coal area where the dips reverse to west-dip and the strata rise onto the Nutria monocline, which is the southwestern flank of the Zuni Mountains uplift. The dips of the sedimentary rocks are less than five degrees except along the Nutria monocline where the strata locally are vertical and form the Hogback.

Rio Nutria, Rio Pescado, and Horsehead Canyon dissect the area and join near the southwestern corner to form the Zuni River. The outcropping Cretaceous rocks have been eroded into irregular ridges and mesas by these streams and their tributaries; coals and the coal horizons crop out as jagged, sinuous lines on the hillsides.

Mesas bordering the valleys, especially Rio Pescado valley, are capped by thick, massive sandstone of the upper Gallup Sandstone, which could make strip mining costly. Outcrops of coal, as well as of all rocks except the more resistant sandstones, are sparse and deeply weathered. Hillsides and mesa tops are covered by much soil, by windblown sand eroded from the sandstone beds, and by thick growth of piñon, juniper, scattered Ponderosa pine, scrub oak, agave, and cactus. On hillsides there are many slump blocks of the sandstones that cap the ridges and that form cliffs along the edges of the ridge tops. Many of the mesa tops are flat or gently rolling, with large areas of bare sandstone and of eolian sand weathered from the sandstone.

Winchester (Sears, 1925) mapped the coal field of the Zuni Reservation in detail during 1912, compiling a geologic and coal-outcrop map, and measured numerous sections of the coal beds. Shaler (1907) had previously described some of the more prominent coal outcrops and the two small mines that supplied coal to the Zuni school.

Thin coals, less than a foot thick, occur as lenses in the Dakota Sandstone in the Gallup-Zuni region, and are not

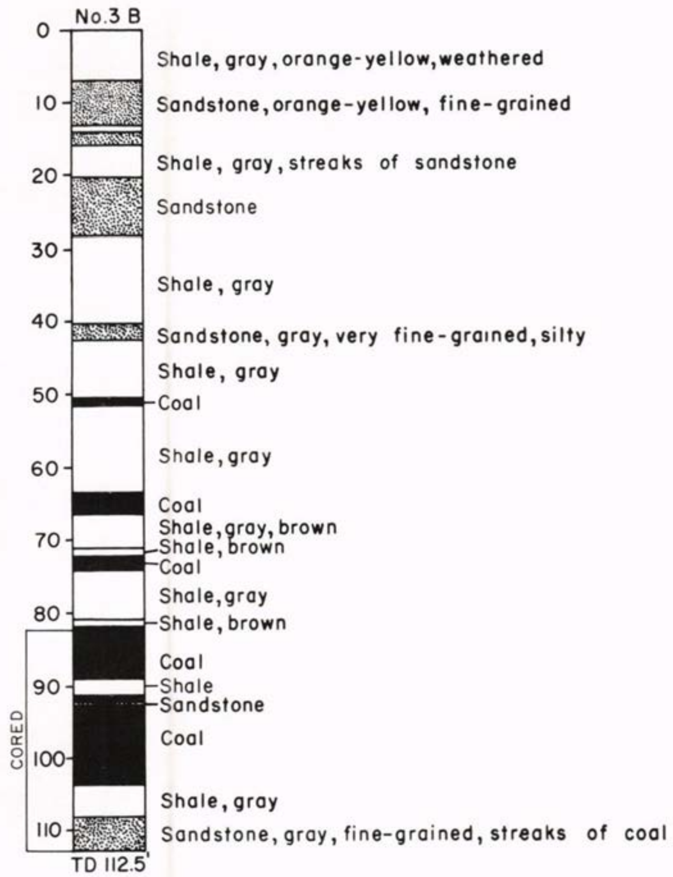

Figure 32

GRAPHIC LOG OF TEST HOLE No. 3B, NW¼NE¼NE¼ SECTION 8, T. 18 N., R. 14 W., McKINLEY Co., N.M. LOGGED BY R. C. LEASE

considered minable. These Dakota coals occur within carbonaceous shale units in the lower 20 feet of the Dakota Sandstone, above a basal sandstone. They crop out in the western part of the area in section 17, T. I I N., R. 18 W. and along Horsehead Canyon in section 25, T. 10 N., R. 18 W.

According to Shaler (1907, p. 418), the coal at the Harper mine (fig. 33, No. 2) had many shale partings and was of inferior quality, although an 11-inch bench was an excellent blacksmith's coal. This coal, in the lower part of the Gallup Sandstone, is the lowest of three beds cropping out in the N1/4 section 7, T. II N., R. 17 W.; it had been opened by a 300-foot slope on the dip of the bed, which is 3°.

Shaler's measured section is typical of the dirtier Gallup coals:

shale roof	—
bony coal	0.3 feet
coal	0.4
bony coal	0.4
coal	1.2
bony coal	0.4
coal	0.9
bony coal	0.4
coal	0.8
underclay	—
	4.8 feet

The School mine (fig. 33, No. I), in SE1/4NW1/4 section 6, T. I I N., R. 17 W., was in the upper Gallup Sandstone, about 70 feet above the Harper seam, and was worked from several openings after the Harper mine had been closed. Although high in ash, it is a good subbituminous coal, about 3.3 feet thick, with a shale roof and fireclay floor. Two inch-thick bone-coal layers occur near the top of the bed. About seven feet higher, another subbituminous coal crops out; it is 2.5 feet thick with a medial 0.3-foot bone-coal parting. Both the roof and floor are massive sandstone typical of the Gallup Sandstone.

Two analyses of the School mine coal, sampled six years apart, give pertinent information on sulfur content. The first sample, collected by Shaler in 1906, is from the entire thickness of the coal, including bone-coal laminae. The analysis showed (Sears, 1925, p. 50) 15.98 percent ash and 1.48 percent sulfur (volatile matter 37.6 percent and fixed carbon 38.7 percent). The second sample was collected by Winchester in 1912 and did not include bone-coal laminae. This analysis yielded 8.82 percent ash and 0.79 percent sulfur (volatile matter 34.9 percent and fixed carbon 41.6 percent). About half of the ash and sulfur was from the bone coal which makes up 0.2 to 0.4 foot of the coal bed's overall thickness of three to four feet. Sulfur in these beds is much more concentrated in the bone coal and shale laminae than in the clean coal.

The minable coal beds of the Zuni area occur in three distinct units: (I) in the lower part of the Gallup Sandstone, in an unnamed coal-bearing and carbonaceous shale tongue lying above the Horsehead Tongue of the Mancos Shale and below the Pescado Tongue of the Mancos Shale (fig. 34); (2) in the upper part of the Gallup Sandstone; and (3) in the Dilco Coal Member of the Crevasse Canyon Formation. The lower Gallup Sandstone of the Zuni area is older than the type Gallup Sandstone, according to Dane (1957).

Winchester's detailed geologic mapping (Sears, 1925, pl. 16) showed the outcrops of the coal beds, and he measured numerous sections within the eastern part of the Zuni Reservation. The upper part of the Crevasse Canyon Formation has been removed by erosion south of sections I to 4, T. 12 N., R. 17 W. so that no upper post-Dilco Mesaverde coals remain.

DESCRIPTIONS OF TOWNSHIPS

T. 12 N., R. 16 and 17 W.

Three coal horizons occur in the Dilco Coal Member on the northern edge of the Zuni area. The lowest coal lens crops out in sections 28 and 29, T. 12 N., R. 17 W. on a south-trending ridge northwest of the Rio Nutria valley. Two coal beds make up this horizon, each two to three feet thick, and separated by a sandstone-and-shale lens that is as much as six feet thick. This coal underlies about 160 acres, mainly in the SE1/4 section 29, where the overburden is no greater than 70 feet thick, and the two splits of the coal total more than four feet thick.

A coal bed at about this "lowermost" Dilco horizon crops out in SE1/4 section 32, T. 12 N., R. 16 W., just west of the steep dips of the Nutria monocline. Dips range from 16° to

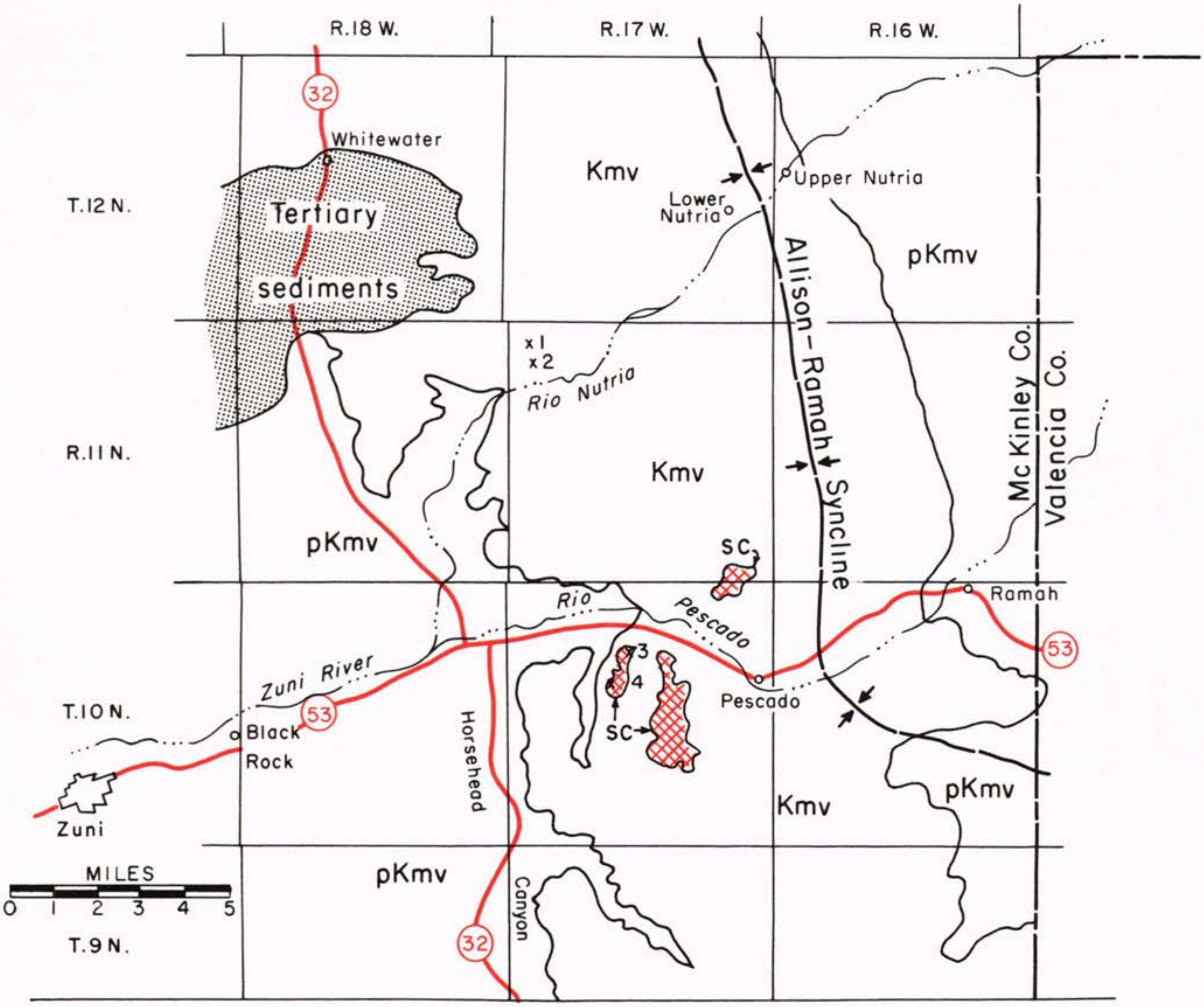

Figure 33

MAP OF ZUNI COAL AREA. Kmv = MESAVERDE GROUP; pKmv = PRE-MESAVERDE ROCKS; SC = AREAS OF POSSIBLE STRIPPABLE COAL; 1—SCHOOL MINE, 2—HARPER MINE, 3—ZUNI MINE, 4—ZUNI NO. 2 MINE

7°, to the west, and the coal crops out on the edge of a steep ridge, thus the overburden is too thick for strip mining.

About 80 feet higher stratigraphically, a "middle" coal crops out in the Dilco Coal Member, in sections 20 and 29, T. 12 N., R. 17 W. Most of the former outcrop is marked by burned clinker; where the coal is exposed, it averages only about two feet in thickness.

The highest Dilco coal in the area crops out in section 2 and sections 7 through 18 in T. 12 N., R. 17 W., lying along the ridges northwest of Rio Nutria valley. Only in parts of sections 7, 17, and 18 is this coal more than three feet thick, and in most of that area the overburden exceeds 50 feet. Thus there are no strippable reserves.

T. 11 N., R. 16 and 17 W.

Coal beds in the lower part of the Gallup Sandstone were called the Pescado "coal group" by Winchester (Sears, 1925). This is a zone of very lenticular coals that are banded by many shaly partings. Coal beds at horizons in the lower part of the unit are less than a foot thick, but from 110 to 160 feet above the underlying Horsehead Shale Tongue (fig. 34) of the Mancos Shale, thicker coal beds occur. This was the coal mined in the Harper mine; it crops out on both sides of Rio Nutria valley from the Harper mine southward for four miles and for a few miles eastward along Rio Pescado valley. The coal ranges from two to four feet in thickness, but is split by two to four bone-coal laminae. In all areas, this coal is overlain by 50 to 100 feet of sandstone and shale, with the upper 35 feet being a massive tan sandstone that forms a prominent cliff and caps wide benches along Rio Nutria and Rio Pescado. No strippable reserves are present.

The best coal in the Zuni area, mined at the School mine and in the two Blackrock or Zuni mines south of Rio Pescado, is in a zone of lenticular coals below the pink sandstone that caps the Gallup Sandstone in this area. This is at the stratigraphic position of the Myers coal in the Gallup coal

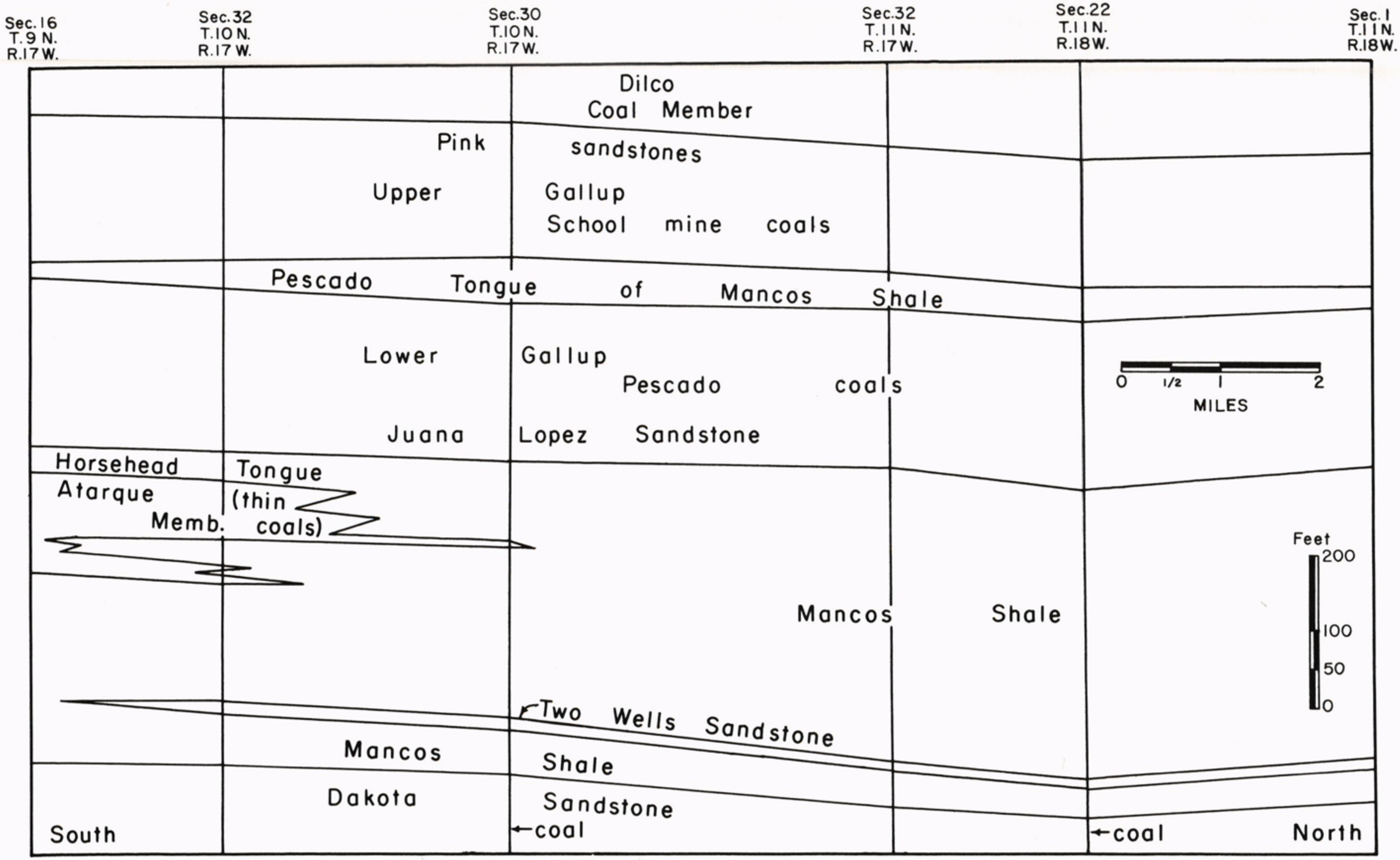

Figure 34
Stratigraphic relationships of coal beds in Zuni Mesaverde area

field, and was called the School mine coal group by Winchester.

Along the Nutria monocline in sections 28 and 33, T. 11 N., R. 16 W., one of the School mine coals is three to four feet thick, but dips to the west are 16° to 24° and steeper, thus none of the coal could be strip mined. In the main part of the Zuni coal area, the School mine coals crop out on the edges of mesas along a southeast trend from the School mine to Pescado and southward. North of Rio Nutria valley, on both sides of the mouth of Coal Mine Canyon near the School mine, two coal beds crop out, separated by seven to ten feet of sandstone and shale. The lower coal is 1.3 to 3.8 feet thick and the upper coal about 2.6 feet thick with a 0.2-foot bone-coal parting. The two flat-topped ridges in this area in section 1, T. 11 N., R. 18 W., and section 6, T. 11 N., R. 17 W. are underlain by these two coal beds but the overburden ranges from 50 to 150 feet in thickness and is mainly of the massive sandstones typical of the uppermost Gallup Sandstone. These would be expensive to remove in any stripping operation.

To the south, along the east side of Rio Nutria valley and north of Rio Pescado, the School mine group contains two similar lenticular coal horizons, separated by 5 to 15 feet of sandstone and some shale. The lower coal ranges from one to three feet in thickness, averaging about two feet; the upper coal is about two feet thick in section 8, T. 11 N., R. 17 W., thins to less than a foot southward, but then thickens on the north side of Rio Pescado valley to as much as four feet. About 150 acres of the ridge top extending southward from sections 36 and 35, T. 11 N., R. 17 W. into sections 1 and 2, T. 10 N., R. 17 W. may contain strippable coal; overburden, mostly of hard sandstone and sandy shale, is 60 to 120 feet thick, and the two School mine coal beds total five to six feet in thickness. Possible inferred reserves are about 1.3 million tons if the massive sandstone overburden can be economically removed.

In part of this area between Rio Nutria and Rio Pescado, a third, higher coal bed crops out about 15 to 20 feet above the other two School mine coals, but it is only 1 to 1.5 feet in thickness.

T. 10 N., R. 17 W.

South of Rio Pescado, the School mine coals have been mined in the two Zuni drifts in section 9, T. 10 N., R. 17 W., and NW1/4 section 16. Two coal beds, at similar stratigraphic positions as those to the north, occur locally, but the lower bed is apparently persistent only along a half-mile-wide belt trending south from section 10 to section 27, T. 10 N., R. 17 W. This bed ranges from 0.8 to 3.3 feet in thickness with a local 2-foot shale split.

The upper bed, the one mined in the Zuni mine and Zuni No. 2 mine (also called the Blackrock and Blackrock No. 2 mines) varies greatly in thickness, ranging from 1.2 feet to more than 5 feet. In both the Zuni and Zuni No. 2 mines, the thicker lenses of coal were about 5.5 feet thick with three partings of bone coal that ranged from 0.1 to 0.3-foot thick. Thinner parts of the bed had a total thickness of four feet with as much as 0.5 foot of bone coal.

This upper coal crops out (sparsely) around the ridge on which the two mines were worked, in sections 9 and 16, T. 10 N., R. 17 W., and outlines an area about a mile long north-south and 0.4 mile wide east-west. The coal is overlain by sandy gray shale, massive yellow-gray sandstone, or locally by the pink crossbedded upper Gallup sandstone. Overburden thickness ranges from 20 feet on the south to 110 feet at the north, with the coal having a probable average thickness of 4.5 feet. The massive sandstone and some sandy shale of the uppermost Gallup Sandstone overlie the coal, and these may be expensive to remove for strip mining. Indicated strippable reserves, which would need to be checked by closely spaced core drilling, underlie about 240 acres, and could yield 1.9 million tons of coal.

The lower School mine coal crops out in a few gullies below the Zuni mines coal beds, but is thin and rarely exposed amid the piñon forest. A small hill to the south of the Zuni mines, just south of the center of section 16, contains about 20 acres of the upper coal within 10 to 30 feet of the surface; the coal bed is about three feet thick.

David R. Stewart (letter, 6 May 1970), U.S. Geological Survey, reported that the Zuni mine operated from 1928 to 1943 and produced about 32,000 tons of coal; the Zuni No. 2 mine produced about 14,000 tons of coal from 1939 to 1951. Analyses made by the U.S. Bureau of Mines in 1941 yielded the following ranges: moisture 6.0 to 9.8 percent; volatile matter 31.8 to 33.0 percent; fixed carbon 41.7 to 42.4 percent; ash 16.4 to 18.6 percent; sulfur 0.6 percent; and 10,470 to 10,570 Btu. Similar analyses were reported in 1953 by the U.S. Bureau of Mines from three samples mined at the Zuni No. 2 mine; however, these samples gave several percent higher volatile matter and about four percent more fixed carbon.

The flat-topped ridge extending southward from section 10 to section 22, T. 10 N., R. 17 W., and eastward into section 23 contains about two square miles underlain by two School mine coals with thicknesses ranging from 1.2 to 3.6 feet and with aggregate thicknesses locally of 7 feet; overburden ranges from 30 to 110 feet. Average thickness of total coal is about 3.1 feet suggesting reserves of more than 6 million tons of coal. However, the coals occur in irregular lenses, with numerous bone-coal partings, and are overlain by massive pink sandstones of the upper Gallup Sandstone. These coals would be much more costly to strip mine than those in the area to the west near the Zuni underground mines. Probably only half of the coal could be recovered even by careful strip mining; thus an indicated reserve of three million tons is suggested.

SUMMARY

As shown on Figure 33, three areas of possible strippable coal are outlined in the Zuni coal area, with total reserves of as much as 6.2 million tons. The strippable coals are in the School mine coal group of the upper Gallup Sandstone. At best, strip mining of these coals would be marginal because of their thinness, lenticularity, many bone-coal partings, local overburden of massive sandstone, and perhaps most pertinent, the distance of the Zuni region from the nearest railroad at Gallup, which is 35 miles north of Rio Pescado valley. Closely spaced test drilling is necessary to prove any of the strippable coal.

CROWNPOINT CREVASSE CANYON AREA

by John W. Shomaker

SUMMARY

The Gallup Sandstone, the Gibson Coal Member, and Dilco Coal Member of the Crevasse Canyon Formation include coal beds in the Crownpoint area. The coals are of sub-bituminous rank with low sulfur content, but are highly lenticular, and correlation of beds is difficult or impossible in most areas. The Gibson is almost everywhere overlain by a hard sandstone cap, as much as 300 feet thick, made up of Point Lookout Sandstone (and the Hosta Tongue of the Point Lookout). The Dilco does not commonly contain beds of minable thickness, and it is overlain in most areas by prohibitively thick overburden. The Gallup Sandstone contains almost no minable coal; the only coal more than three feet thick is under 30o to 400 feet of overburden. Several minor areas in which strippable coal can be found in the Gibson contain a total of perhaps 15 million tons, and at least one additional small area appears to have some promise and should be tested by drilling.

INTRODUCTION

Evaluation of strippable coal reserves in this area is based on the geologic maps and measured sections of Sears, Hunt, and Dane (1936) and on field examination and geologic mapping to correlate the published geologic data with the topographic maps recently prepared by the U.S. Geological Survey.

Coal occurs in three stratigraphic units in the Crownpoint Kcc area. They are, in descending order, the Gibson Coal Member of the Crevasse Canyon Formation, the Dilco Coal Member of the Crevasse Canyon Formation, and the Gallup Sandstone (figs. 35, 36). All are assigned to the Mesaverde Group of Late Cretaceous age. The rather complex relationships between the coal-bearing units and intervening barren strata are shown in the accompanying diagram (fig. 35) modified from Sears, Hunt, and Dane (1936, pl. 1).

As indicated by the diagram, a fourth coal-bearing unit (the Cleary Coal Member of the Menefee Formation) exists above the Crevasse Canyon Formation within the Crownpoint Kcc area. To simplify the organization of the study, the Cleary beds are treated as parts of the Gallup Kmv area and the Standing Rock Kmfc area; the Cleary and Gibson are separated by barren units east of the middle of T. 17 N., R. 17 W. and the Gibson can be conveniently discussed with the Dilco Coal Member and Gallup Sandstone, while west of the pinchout of the intervening barren rocks, the Gibson and Cleary coalesce and it is more logical to discuss them as a single unit within the Mesaverde Group.

The coal beds of all three units are generally highly lenticular, although a few fairly persistent thin beds exist in the Dilco. The coal beds of the Gallup Sandstone are apparently never of commercial thickness in the Crownpoint Kcc area, and therefore are not discussed, except for T. 16 N., R. 14 W. and T. 16 N., R. 17 W., in the individual township descriptions. Analyses of coal from the Crownpoint mine of the Eastern Navajo Indian Agency (section 3o, T. 17 N., R. 12 W.) and the Tohatchi Indian School mine (section 22, T. 17 N., R. 17 W.) show the Gibson coal to be subbituminous and of fairly good grade (U.S. Bur. Mines, 1936, table 9). The single analysis of coal from the Tohatchi Indian School mine indicates an as-received heating value of 10,830 Btu per pound, sulfur content of 0.7 percent, and ash content of 10.5 percent. Three analyses of coal from the Crownpoint mine indicate an average as-received heating value of 10,517 Btu per pound, and ash content of 9.5 percent. A single ultimate analysis shows an as-received sulfur content of 1.3 percent.

The dominant topographic features of the Crownpoint Kcc area are the high cliffs formed by the southern edge of the gently northward-dipping Point Lookout Sandstone. The cliffs, while much modified by erosion, extend from the southwestern part of T. 17 N., R. 16 W. eastward the entire length of the Crownpoint area, and are broken only by four passes in which erosion has cut down to older beds.

High cliffs also mark a northern eroded edge of the Point Lookout Sandstone from the center of T. 17 N., R. 14 W. eastward, leaving a chain of irregular mesas capped by the massive sandstone.

In general, the Gibson forms steep slopes below the Point Lookout cliffs, and is also exposed in broad flats, from which the Point Lookout has been eroded, in a belt trending eastward from the center of T. 17N., R. 14 W.

The Dalton Sandstone Member forms a lower step south of the high Point Lookout cliffs. The Dalton is underlain by the Mulatto Tongue of the Mancos Shale, which forms a long strike valley, and is in turn underlain by the Dilco Coal Member and the Gallup Sandstone which forms a still lower, rather inconspicuous step or bench.

DESCRIPTIONS OF TOWNSHIPS

T. 13 N., R. 8 W.

The Gibson Coal Member of Crevasse Canyon Formation crops out in the mesa in sections z, 3, 9, and 1 o, beneath a capping of Point Lookout Sandstone. The thickest bed measured is 2.4 feet thick. The Gibson is also exposed in a band about half-a-mile wide in sections 20, z8, 29, and 32; it dips steeply (12 degrees or more) and no coal was measured.

The Dilco Coal Member of Crevasse Canyon Formation crops out in sections 29 and 31; dips are on the order of 12 degrees, and no coal was measured.

T. 14 N., R. 8 W.

San Mateo Mesa is underlain by coal beds of the Gibson Coal Member of Crevasse Canyon Formation, but none measure much more than three feet thick. Nearly all of the coal is covered by at least 7o feet of Gibson sandstones and shales and 150 feet or more of Hosta Tongue and Point Lookout Sandstone. A bed five feet thick was measured in an isolated location in section 23, but its extent is unknown and the dip is too steep for stripping.

The Dilco Coal Member crops out in an area of less than 1/2 square mile in section 31, and only one coal bed, 1.1 feet thick, was measured. No coal was estimated.

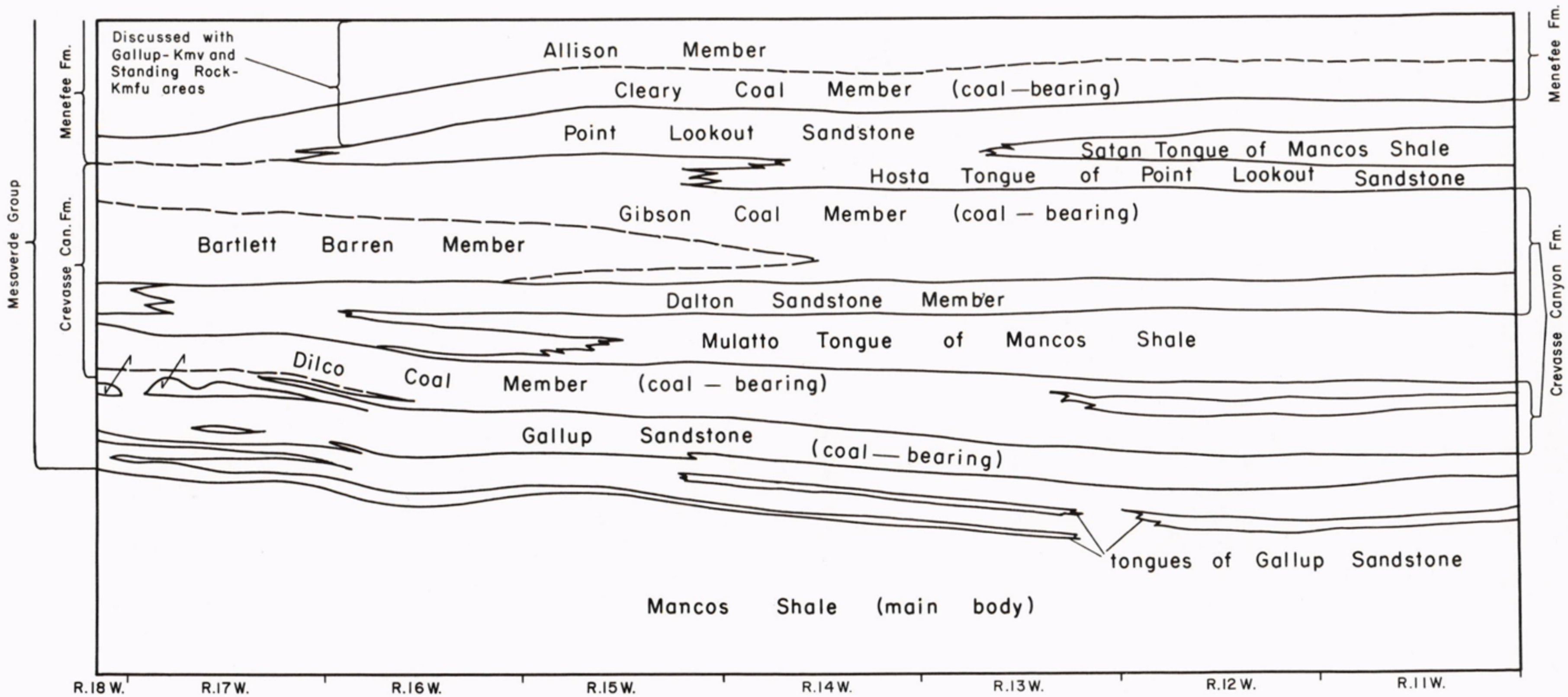

Figure 35

Diagrammatic east-west cross-section showing relationships of coal-bearing and barren units in Crownpoint Crevasse Canyon area. Section drawn along north line of T. 16 N., Rs. 11 to 18 W.; modified from Sears, Hunt, and Dane (1936, pl. 1)

T. 14 N., R. 9 W.

The Gibson Coal Member of Crevasse Canyon Formation is exposed along about six miles of the escarpment that crosses the township from the northwest to southeast. Of eight measured sections, none contain a coal bed as thick as three feet.

The Dilco Coal Member of Crevasse Canyon Formation crops out in a northwest-southeast-trending band about 1/2-mile wide across the township. It apparently contains no coal beds as thick as three feet.

T. 15 N., R. 9 W.

The cap of Mesa de los Toros (Hosta Tongue) is underlain by coal-bearing beds of the Gibson Coal Member of Crevasse Canyon Formation. One bed reaches a thickness of 5.1 feet, but it pinches out in less than one mile; the thicknesses of the other beds are also extremely irregular. No reserves were estimated because of the lenticular nature of the coal beds, and because the entire area underlain by coal is less than one square mile.

In an area of about two square miles in sections 15, 16, 21, and 22, a continuous bed averages 4.8 feet in thickness. The overburden, mostly sandstone of the Hosta Tongue and Point Lookout Sandstone, is less than 250 feet thick over all of the area, and less than 150 feet thick over much of it. It is likely that 9.5 million tons or more underlie this area, but probably very little, if any, could be recovered at a stripping ratio of 10:1. Additional field work and one or two drill holes would refine, and probably increase, this tonnage estimate.

The thick coal bed mentioned above is also present in the north face of Mesa de las Vacas (in sections 27, 28, and 29), but it becomes abruptly thinner somewhere beneath the mesa cap; few beds as thick as three feet are present in the south face of the mesa. No reserves were estimated.

Only a small area (about 1/2 square mile) of Dilco Coal Member outcrop is present in the township. There are no coal measurements.

T. 16 N., R. 9 W.

The Gibson Coal Member of Crevasse Canyon Formation crops out over about three square miles in the southwest corner of the township. Several beds, including one measuring four feet thick are present beneath an area of about 0.2 square miles. No reserves were estimated.

The Dilco Coal Member of Crevasse Canyon Formation does not crop out in this township.

T. 14 N., R. 10 W.

The Gibson Coal Member of Crevasse Canyon Formation does not crop out in this township. The Dilco Coal Member of Crevasse Canyon Formation is exposed only in a narrow sinuous outcrop. No measurements of coal beds were made.

T. 15 N., R. 10 W.

The Gibson Coal Member of Crevasse Canyon Formation is either exposed, or underlies a sandstone cap (the Hosta Tongue of Point Lookout Sandstone) over about 16 square miles of the township. In one area of less than one-fourth square mile, in section 9, a bed has been measured at more than five feet, but otherwise few beds measure more than three feet. There are often six or more beds in a particular measured section, but the thickest may thin drastically or disappear in a short distance, so that the thicker beds in adjacent measured sections are not correlative. A bed measured at 4.9 feet in section 2 may extend far enough to allow some strippable tonnage (perhaps one or two million tons) but probably not more than one mile along the outcrop. The area underlain by this bed is bounded on the east by a fault which separates it from another likely coal-stripping area in section 36, T. 16 N., R. 10 W.

The outcrop of the Dilco Coal Member of Crevasse Canyon Formation encompasses less than two square miles in an irregular strip along the south edge of the township. No coal was measured.

T. 16 N., R. 10 W.

Two small areas in which the Gibson Coal Member of Crevasse Canyon Formation is capped by the Hosta Tongue show some promise. A coal bed six feet thick was measured beneath the cap of Mesa del Corral in section 36, and the same bed appears to continue northward along the mesa rim for a mile or more. There may be about two to four million tons of strippable coal in the mesa, all beneath less than 150 feet of overburden.

A small area in section 30 is underlain by a bed that measures 3.3 to 4.8 feet in thickness. Though the areal extent of the bed cannot be determined without drilling, it probably contains one million tons or more.

The Dilco Coal Member does not crop out in this township.

T. 15 N., R. 11 W.

Coal-bearing strata of the Gibson Coal Member of Crevasse Canyon Formation underlie about 5 1/2 square miles of the northeastern part of the township. At least one bed thicker than three feet is present in all but one of the eight sections measured in the area by Sears, Hunt, and Dane (1936), but the thickest bed is only 4.5 feet thick. The coals are lenticular and occur most erratically in the stratigraphic section. The Gibson is covered by the massive Point Lookout Sandstone; near its southern edge, the covering of Point Lookout is as much as 250 feet thick, but in the northeastward-trending canyons that dissect the Point Lookout it probably is no more than 50 feet thick. Unfortunately the canyons are rather steep walled, and only in very narrow strips along their axes can the top of the Gibson be reached at less than 150 feet.

Because of the extreme irregularity of the coal beds, the small average thickness of coal, and the overburden of massive sandstone, no reserves were estimated.

The Dilco Coal Member of the Crevasse Canyon Formation is exposed over several square miles of the township in an irregular band from the northwest corner to the southeast corner. It contains one, two, or three coal beds throughout that area, but none reaches a thickness of three feet. No reserves were estimated.

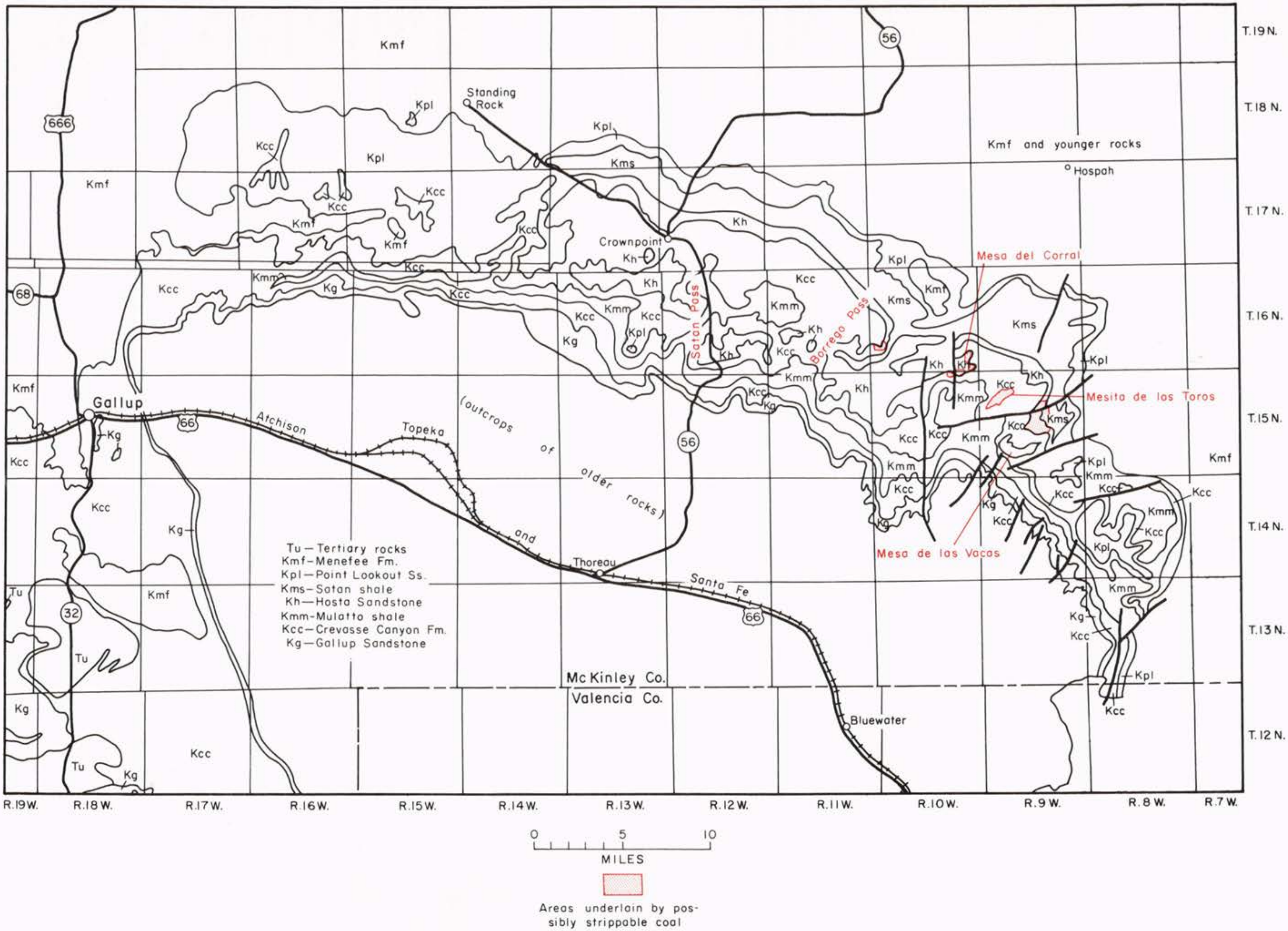

Figure 36
Map showing outcrops of members of Mesaverde Group in Crownpoint area

T. 16 N., R. I I W.

West of Borrego Pass, in section 27, the Gibson Coal Member of the Crevasse Canyon Formation is present only beneath a narrow, sinuous capping of Point Lookout Sandstone. Probably less than three square miles is underlain by Gibson, and though it contains numerous coal beds distributed in random fashion through as much as 285 feet of rock, few beds are more than three feet thick and even those thin abruptly.

East of Borrego Pass, the Gibson is present beneath about five square miles of Point Lookout Sandstone cover, and is exposed over about 13 square miles. According to the mapping of Sears, Hunt, and Dane (1936), it nowhere contains more than two coal beds thicker than 14 inches; the thickest bed measured during the present study was 1.3 feet thick. It is possible that additional coal beds exist beneath the broad outcrop of the Gibson, for the base of the member is partly covered. This possibility may warrant further investigation by drilling, since the Gibson dips gently and would be strippable, but the general thinness and irregularity of the Gibson coals in the region allows little more than speculative consideration. No reserves were estimated.

The Dilco Coal Member of the Crevasse Canyon Formation is not exposed in the township.

T. 17 N., R. 11 W.

The Gibson Coal Member of the Crevasse Canyon Formation crops out in a two-mile-wide band across the southwest corner of the township, and there contains a single coal bed less than 14 inches thick. Additional beds may be present beneath the surface but there is no reason to expect beds of minable thickness.

The Dilco Coal Member of the Crevasse Canyon Formation is deeply buried throughout the township.

T. 15 N., R. 12 W.

The Gibson Coal Member of the Crevasse Canyon Formation is not exposed in the township.

The Dilco Coal Member of the Crevasse Canyon Formation crops out in a 1/2- to 1 1/2-mile-wide band along the northern edge of the township. It contains one, or in places two, thin coal beds. Most of the coal-bed measurements were less than 14 inches, and in only one section was a thickness greater than three feet (3.3 feet) measured (Sears, Hunt, and Dane, 1936, pl. 12). No reserves were estimated.

T. 16 N., R. 12 W.

The Gibson Coal Member of the Crevasse Canyon Formation is present beneath a capping of Point Lookout Sandstone over about one-half of the township. In only a few places are thicknesses more than three feet measured, and these thicker beds are not correlative. The capping, which consists of massive sandstone, or of two massive sandstone units (the Hosta Tongue of the Point Lookout and the main body of Point Lookout) separated by the Satan Tongue of the Mancos Shale, is probably more than roo feet thick over nearly all of the area and more than zoo feet thick over much of it. No reserves were estimated.

T. 17 N., R. 12 W.

In this township, the Gibson Coal Member of the Crevasse Canyon Formation is exposed in the north-facing cliffs in the southwest corner of the township and crops out in a band about two miles wide across the southern half of the township. The only coal beds of minable thickness occur high in the Gibson, and therefore are restricted to the mesa areas where they are capped by as much as 24o feet of Point Lookout Sandstone. The thickest bed measured by Sears, Hunt, and Dane (1936, pl. 15) is 3.5 feet thick; it is overlain at the site of the measurement by about 93 feet of shale, sandstone, and coal assigned to the Gibson, and another 25 feet of Point Lookout Sandstone. No reserves were estimated.

The Dilco Coal Member is deeply buried throughout the township.

T. 15 N., R. 13 W.

The Gibson Coal Member of the Crevasse Canyon Formation is not present in the township. As many as three thin coal beds of the Dilco Coal Member crop out in the northeast corner of the township; at only one site does a bed as thick as three feet occur. No reserves were estimated.

T. 16 N., R. 13 W.

The Gibson Coal Member of the Crevasse Canyon Formation is present beneath a capping of Point Lookout Sandstone in the mesa along the northern edge of the township. As many as nineteen coal beds were measured at a single site by Sears, Hunt, and Dane (1936), but none were as thick as three feet and all were separated by partings at least as thick as the coals. No minable beds were described anywhere in the township. No reserves were estimated.

The Dilco Coal Member of the Crevasse Canyon Formation is exposed over a broad area of the western and southern part of the township. Except for one location in section 20 and another in sections 35 and 36, no coal beds as thick as 14 inches were mapped. At the location in section 20, a single bed 3.4 feet thick was measured, and in sections 35 and 36 up to four beds are present but only the lowermost approaches three feet in thickness. No reserves were estimated.

T. 17 N., R. 13 W.

The Gibson Coal Member of the Crevasse Canyon Formation crops out or underlies a capping of Point Lookout Sandstone over most of the township; however, the coal beds appear to be concentrated in the upper part, beneath the capping, in the extreme southern and southwestern area of the township. The only area in which a coal bed over three feet thick is likely to exist is along the western edge of the township beneath 100 to 300 feet of cover, most of which is sandstone. No reserves were estimated.

The Dilco Coal Member of the Crevasse Canyon Formation is deeply buried beneath the Gibson and the Dalton Sandstone Member in the township.

T. 16 N., R. 14 W.

The Gibson Coal Member of the Crevasse Canyon Formation is present in only about 1 1/2 square miles of the township. There it contains several beds which attain minable thickness in a few places, but which underlie at least 250 feet of overburden. No reserves were estimated.

The Dilco Coal Member of the Crevasse Canyon Formation crops out in a band about one mile wide across the northern part of the township. It contains two comparatively persistent coal beds, neither of which has been measured at more than 1.3 feet. No reserves were estimated.

Within this township the Gallup Sandstone contains one fairly continuous thin coal bed. The maximum thickness measured was about 2.2 feet (Sears, Hunt, and Dane, 1936, pl. 12). No reserves were estimated.

T. 17 N., R. 14 W.

Twenty-six stratigraphic sections of the Gibson Coal Member of the Crevasse Canyon Formation were measured in this township by Sears, Hunt, and Dane (1936), and 20 of them contained one or more coal beds three or more feet in thickness. However, the minable beds in the various sections are not correlative for more than about a mile, and in only two cases do they exceed five feet in thickness. The coal measures are overlain almost everywhere in the township by the Point Lookout Sandstone; only in about 2 1/2 square miles is the Gibson exposed in any situation other than as the lower part of a steep slope or cliff beneath the Point Lookout. None of the measured sections indicate strippable coal beneath overburden corresponding to a 0:1 stripping ratio, even if the thickness of the Point Lookout (which ranges from about 50 feet to more than 200 feet) is ignored.

It is possible that strippable coal exists in sections 1, 11, and 12 beneath the 2 1/2-square mile area of Gibson outcrop from which the Point Lookout has been eroded. The general lack of sufficiently thick coal beds in the lower part of the Gibson makes the area a discouraging prospect if (as appears to be the case) part of the Gibson has been eroded away as well. No reserves were estimated.

The Dilco Coal Member of the Crevasse Canyon Formation is deeply buried throughout the township.

T. 16 N., R. 15 W.

The Gibson Coal Member of the Crevasse Canyon Formation is not present within the township. The Dilco Coal Member of the Crevasse Canyon Formation crops out in a belt up to about one mile wide across the northern part of the township, and contains from one to three beds of coal; none reach a thickness of three feet. No reserves were estimated.

T. 17 N., R. 15 W.

The Gibson Coal Member of the Crevasse Canyon Formation contains several beds of minable thickness in the township, though they are lenticular and thin to less than three feet, or disappear, in a mile or less. The thicker beds, however, do lie at about the same stratigraphic level, some 40 to 80 feet below the base of the Point Lookout Sandstone. In the southern part of the township, the Point Lookout is generally less than 200 feet thick so that it is conceivable that some significant amounts of coal are present beneath less than 250 feet of overburden. It is most unlikely that any significant amount is available at a stripping ratio as favorable as 20:1. No reserves were estimated.

The Dilco Coal Member of the Crevasse Canyon Formation is deeply buried within the township.

T. 16 N., R. 16 W.

The Gibson Coal Member of the Crevasse Canyon Formation (as distinguished from the underlying, similar-appearing but noncoal-bearing Bartlett Barren Member) is present in only about 1/4-square mile in the township. No reserves were estimated.

The Dilco Coal Member of the Crevasse Canyon Formation crops out in an irregular band across the northern part of the township, and contains up to three coal beds. In a few locations, one or another of these reaches a thickness of slightly more than three feet. No reserves were estimated.

T. 17 N., R. 16 W.

In this township, the Gibson Coal Member of the Crevasse Canyon Formation is present beneath the Point Lookout Sandstone under 29 square miles. In seven or eight square miles of this area, the Cleary Coal and Allison Barren Members of the Menefee Formation overlie the Point Lookout Sandstone. Several coal beds five to eight feet thick have been measured, and 17 of 23 sections contain beds more than three feet thick. Because of the thickness of the overlying Point Lookout Sandstone (seldom less than 100 feet, and often 200 feet or more), and the fact that the minable coals are 40 feet or more below the base of the Point Lookout, no reserves are likely to be present under less than 150 feet of overburden in the northern and eastern areas of the township.

Potential for strippable Gibson coals appears better in the southwestern part where the Point Lookout Sandstone thins rapidly westward and pinches out in the next township to the west. Unfortunately the few measurements in the southwestern part of T. 16 N., R. 16 W., indicate no beds of minable thickness except for a single four-foot-bed 120 feet below the base of the Point Lookout at one location.

The Dilco Coal Member of the Crevasse Canyon Formation is deeply buried within this township.

T. 16 N., R. 17 W.

The Gibson Coal Member of the Crevasse Canyon Formation crops out over about one square mile in the northwest corner of the township; in only one measured section, some 280 feet or more below the top of the unit, was a coal bed as thick as three feet measured. No reserves were estimated.

The Dilco Coal Member of the Crevasse Canyon Formation crops out in an irregular patch across the northern half of the township. It contains two persistent coal beds (Beds "C" and "D" of Sears, Hunt, and Dane, 1936, pls. x and 11) and, near the eastern edge of the township, a third bed appears between them. In two measured sections in sections

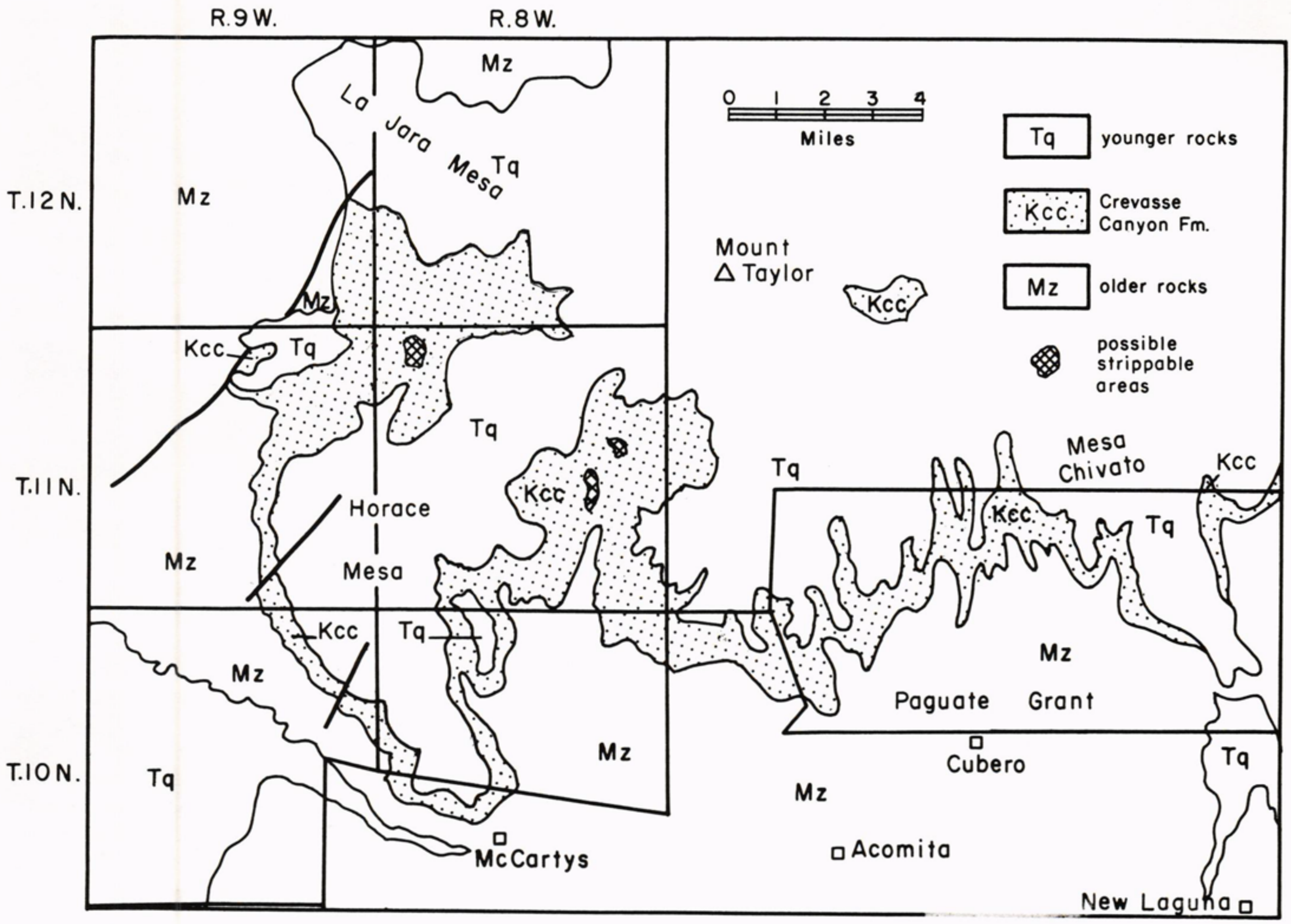

Figure 37
MAP OF SOUTH MOUNT TAYLOR CREVASSE CANYON AREA

and 12 of the township, the Bed "C" coal zone exceeds three feet in thickness; in both locations the coal lies 115 feet or more below the base of the Dalton Sandstone Member which is itself more than 100 feet thick. No reserves were estimated.

The Gallup Sandstone contains a single persistent coal (Bed "A") which is two to four feet thick in the northwestern quarter of the township, and an erratically appearing Bed "B," which has not been measured at more than 2.2 feet. The outcrops of Bed "A," unfortunately, are near the bases of cliffs and steep slopes 30o to 400 feet high composed of the Dilco Coal Member and Dalton Sandstone Member. No reserves were estimated.

SOUTH MOUNT TAYLOR CREVASSE CANYON AREA

by Frank E. Kottlowski and Thomas A. Parkhill

SUMMARY

Coal beds in the South Mount Taylor area occur in the Gibson Coal Member and Dilco Coal Member of the Crevase Canyon Formation. Coal beds are highly lenticular and correlation is difficult. The coal is high-volatile bituminous with an average sulfur content of about 0.6 percent. The Gibson Coal Member in most of the area is overlain by flow sheets of basalt and andesite as much as 100 feet thick. Coals in the Dilco Coal Member are mostly less than three feet thick and in most places are overlain by at least several hundred feet of overburden. No coal beds occur in the Gallup Sandstone in this area. The several small areas of strippable coal in the Gibson contain a total of nearly 1.4 million tons (fig. 37).

INTRODUCTION

Evaluation of strippable coal reserves in this area is based on the geologic maps and measured sections of Hunt (1936) and on field examination and geological mapping using topographic maps recently published by the U.S. Geological Survey.

Coal occurs in two stratigraphic units in the South Mount Taylor Kcc area. They are, in descending order, the Gibson Coal Member and the Dilco Coal Member of the Crevasse Canyon Formation. They are separated by the Dalton Sandstone Member, also part of the Mesaverde Group, and by the Mulatto Shale Tongue of the Mancos Shale. The rather complex relationship between the coal-bearing units and intervening barren strata are shown in the accompanying diagram (fig. 38, modified from Hunt, 1936, fig. 1). There are no coal beds above the Crevasse Canyon Formation within the South Mount Taylor Kcc area. The Hosta Sandstone Member of the Point Lookout Sandstone, the lower part of that unit, tends to pinch out toward the southwest. Most of the other units are continuous over the entire area.

The coal beds of the Crevasse Canyon Formation are highly lenticular, although a few fairly persistent beds occur in the Gibson Member. The Gallup Sandstone is apparently barren of coal in this region. Analysis of coal from the Boone mine (SE1/4 section 6, T. II N., R. 8 W.) shows the Gibson coal to be high-volatile C bituminous (U.S. Bur. Mines, 1936, table 9), with an as-received heating value of 11,400 Btu per pound, sulfur content of o.6 percent, and ash content of 5.7 percent.

The dominant topographic features of the South Mount Taylor Kcc area are the high lava-capped mesas extending from the ancient volcano of Mount Taylor. La Jara Mesa, northwest of Mount Taylor, is the northern boundary of the area. Horace Mesa, southwest of Mount Taylor, separates the northern Lobo Canyon coal outcrops from those in Rinconada Canyon. Mesa Chivato, east of Mount Taylor, extends southeastward toward New Laguna, and borders the area on the east.

DESCRIPTIONS OF TOWNSHIPS

T. 12 N., R. 9 W.

The lower part of the Gibson Coal Member of the Crevasse Canyon Formation is present in the eastern parts of sections 24, 25, and 36. Outcrops are concealed beneath terrace gravel, alluvium, and talus; no coal was found.

The Dilco Coal Member of the Crevasse Canyon Formation crops out along a narrow northward-trending belt in the eastern parts of sections 14, 23, and 26. Coal beds are present but are less than three feet thick in measured sections.

T. 12 N., R. 8 W.

Extensive outcrops of the Gibson Coal Member of the Crevasse Canyon Formation occur in the southwest part of this township. A coal bed mined in NW% section 33 is uniformly 2.3 feet thick and is traceable for almost a mile. No coal reserves were calculated.

The coal beds that crop out in sections 28, 29, 31, 32, and 33 are extensively covered. None of these coal beds are as much as three feet in thickness, although two coals ranging from o.9 to 2.9 feet in thickness crop out in section 31.

The Dilco Coal Member of the Crevasse Canyon Formation is several hundred feet below the surface in this township.

T. 12 N., R. 7 W.

Most of this township is occupied by the crater and slopes of Mount Taylor, the outcrops being of volcanic rocks. In section 27, thin coals of the Gibson Coal Member crop out beneath the volcanic rocks in Water Canyon which breaches the east rim of the volcanic crater.

T. II N., R. 9 W.

The Gibson Coal Member of the Crevasse Canyon Formation underlies the lava cap on Horace Mesa and crops out along the thickly wooded northwest side of the mesa but its outcrops are obscured by landslides. No sections were measured.

The Dilco Coal Member of the Crevasse Canyon Formation crops out in section 10 and along the west side of Horace Mesa. Thin coal beds in the NE% section 15 and in N1/2 section 34 are less than three feet thick. No reserves were calculated.

T. II N., R. 8 W.

The Gibson Coal Member of the Crevasse Canyon Formation includes a coal-bearing zone about 35o feet above the Dalton Sandstone Member in this township. Several beds measured three, five, and seven feet in thickness. Coal reserves in this section in areas strippable under the 0:1 ratio limitation are estimated to be 1.4 million tons. These areas of possible strippable coal are in sections 6, I 1, 14, and 15.

Two small mines have been worked in the Lobo Creek canyon area in NE1/4 section 6, T. 1 I N., R. 8 W. about 0.4 mile east of the Tietjen ranch. The same 3.3-foot coal bed was mined at both locations. The Boone mine is about 0.2 mile east of the Tietjen ranch. This mine has been worked extensively in a uniform coal bed that measured about three feet in thickness. Coal was also mined farther up the small canyon southeast of the Boone mine. This area is favorable for strip mining as the overburden is about 6o feet thick. Coal reserves are estimated to be 28o thousand tons.

Another possible strippable area is along Rinconada Canyan in E1/2 section 15 and NW1/4 section 14. A coal bed, five feet thick, crops out in E1/2 section 15 and is strippable. About 15 feet below the five-foot coal bed there is a seam of good coal, 2.3 feet thick, which might be stripped after the five-foot seam has been mined. Four small mines have been opened into the five-foot bed, but little coal has been mined. Strippable reserves are estimated at 470 thousand tons.

Three coal sections measured by Hunt (1936) near the head of Rinconada Canyon indicate two favorable areas for stripping. In the NE1/2 section I 5, a 3.6-foot bed crops out at strippable depths and 65 feet below is a 7.0-foot seam. A reserve of possibly 45o thousand tons occurs in this area. The other coal beds, each five feet thick, were measured by Hunt in the SW1/4 section I1. Reserves are estimated to be 200 thousand tons but because of remoteness were not field checked. The jeep road is impassable from a point o.3 mile south of Guadalupe Canyon (NW1/4 section 26) to the measured coals in sections 15 and I I.

Thin coals occur in the Dilco Coal Member in sections 34 and 35 but crop out on cliffs beneath thick sandstone overburden.

T. II N., R. 7 W.

Only the southern part of this township contains outcrops of Cretaceous sedimentary rocks. The northern sections are

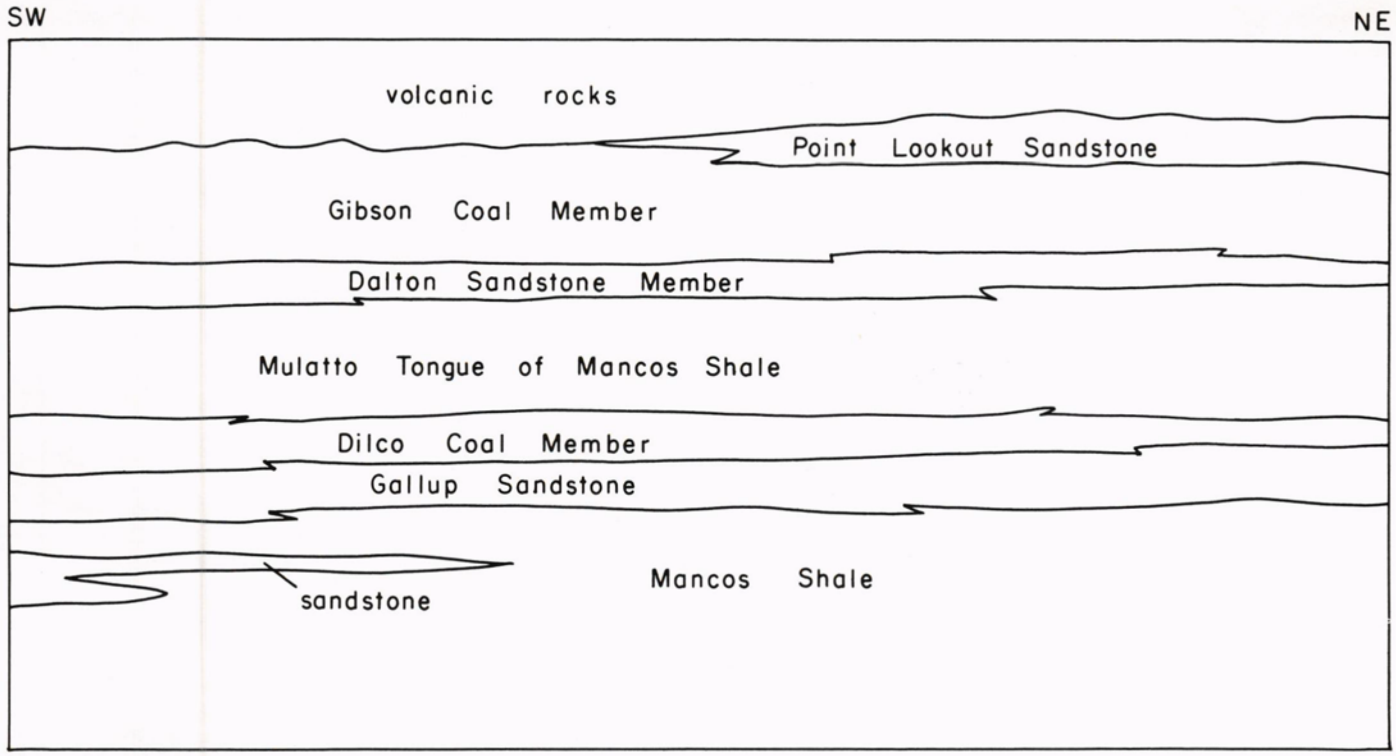

Figure 38

DIAGRAMMATIC NORTHEAST-SOUTHWEST SECTION OF UNITS IN THE SOUTH MOUNT TAYLOR CREVASSE CANYON AREA

of the rugged lava-covered country lying immediately south of Mount Taylor. The Gibson Coal Member of the Crevasse Canyon Formation is present, but exposures are poor; no coal outcrops are known.

Below a thick sequence of lava beds there are many exposures of the Dilco Coal Member of the Crevasse Canyon Formation. The single coal bed measured by Hunt in section 24 along Timber Canyon is less than three feet thick; it crops out about five miles north of Cubero.

T. 11 N., R. 6 W.

No outcrops of the Gibson Coal Member of the Crevasse Canyon Formation are known in the township. A lava-capped ridge extends southeastward from the main part of Mesa Chivato across the center of this township, terminating near New Laguna. Beneath the lava, the Dilco Coal Member of the Crevasse Canyon Formation is exposed, cropping out along both sides of the ridge. Exposures are sparse and the coal beds are less than three feet thick.

T. 10 N., R. 9 W.

The Gibson Coal Member of the Crevasse Canyon Formation does not crop out in this township and no exposures of coal are known in the Dilco Coal Member which occurs in sections 2 and 3.

T. 10 N., R. 8 W.

The Gibson Coal Member of the Crevasse Canyon Formation does not crop out in this township. The Dilco Coal Member of the Crevasse Canyon Formation is exposed in the north and northwestern parts of the township high on steep, talus-covered slopes of Horace Mesa. Thicknesses of the coal beds are less than three feet and depth to the Dilco Coal Member ranges from 250 to 400 feet.

T. 10 N., R. 7 W.

There are no exposures of the Gibson Coal Member of the Crevasse Canyon Formation in this township. The Dilco Coal Member crops out in sections 3, 4, 5, and 6 of this township but it contains no coal beds that are as much as three feet thick. Access is difficult because the Dilco Coal Member crops out on the steep slopes of the lava-capped mesa.

EAST MOUNT TAYLOR CREVASSE CANYON AREA

by Frank E. Kottlowski, Edward C. Beaumont, and Thomas A. Parkhill

SUMMARY

Coal beds in the East Mount Taylor area occur only in the Gibson Coal Member of the Crevasse Canyon Formation, as the Dilco Coal Member and the Gallup Sandstone are barren and intertongue northeastward with marine beds of the Mancos Shale. The coals are subbituminous to bituminous, highly lenticular, and difficult to correlate. Flow sheets of basalt and beds of tuff as much as 100 feet thick overlie the Gibson coal beds; no areas of strippable coal are outlined owing to the prohibitively thick overburden rising above the coal outcrops high on the steep slopes of the lava-capped mesas.

Evaluation of strippable coal reserves in this area (fig. 39) is based on geologic maps and measured sections by Hunt (1936), consulting reports and a brief field examination. Detailed geologic maps by Moench (1963) of the Seboyeta, quadrangle and by Schlee and Moench (1963) of the Moquino quadrangle showed areas of outcrop but barely mentioned the coals. As far as is known, coal of the Crevasse Canyon Formation occurs only in the Gibson Coal Member in the East Mount Taylor Kcc area. The complex intertonguing relationships between coal-bearing sediments and inter-

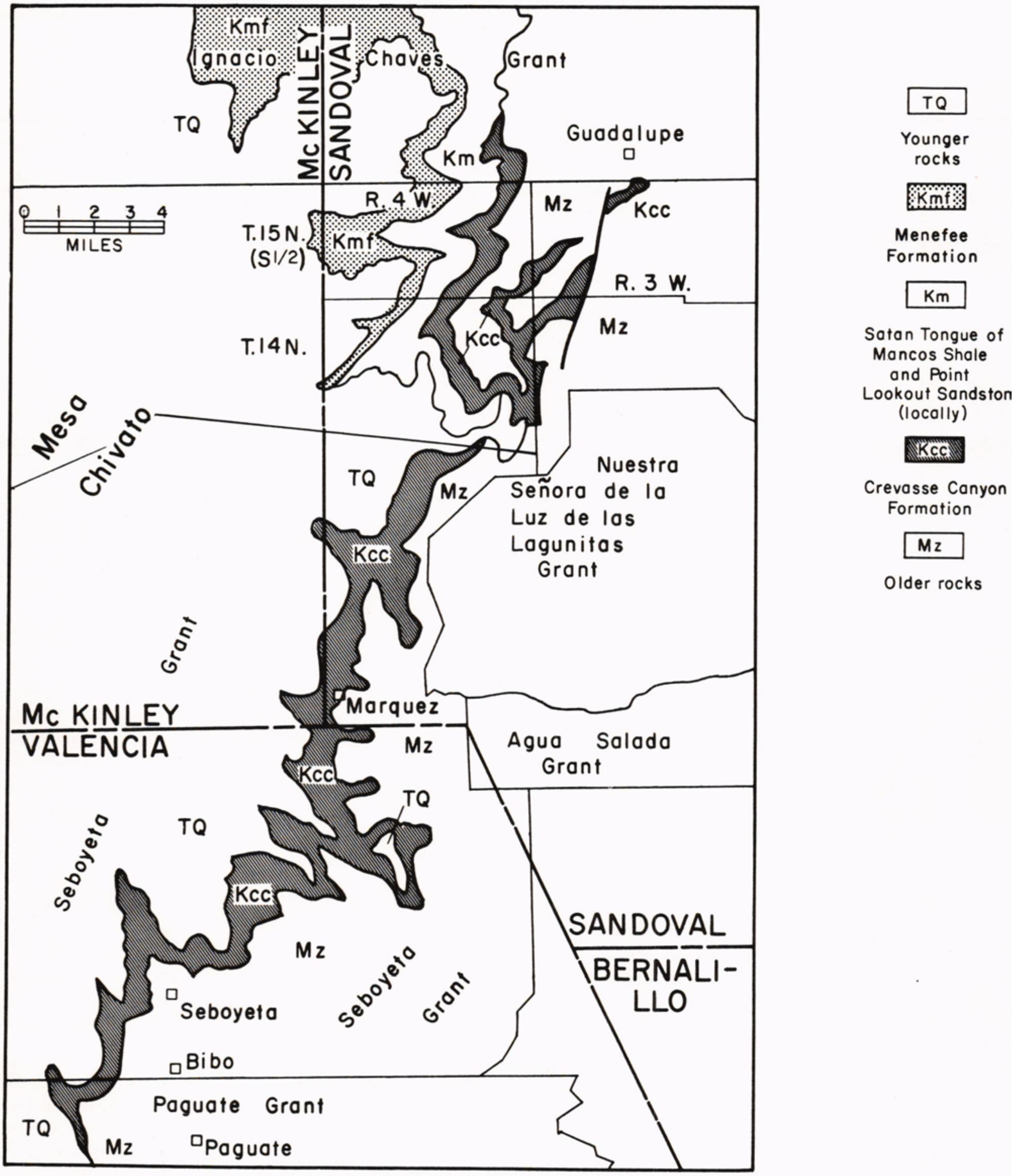

Figure 39
MAP OF EAST MOUNT TAYLOR CREVASSE CANYON AREA

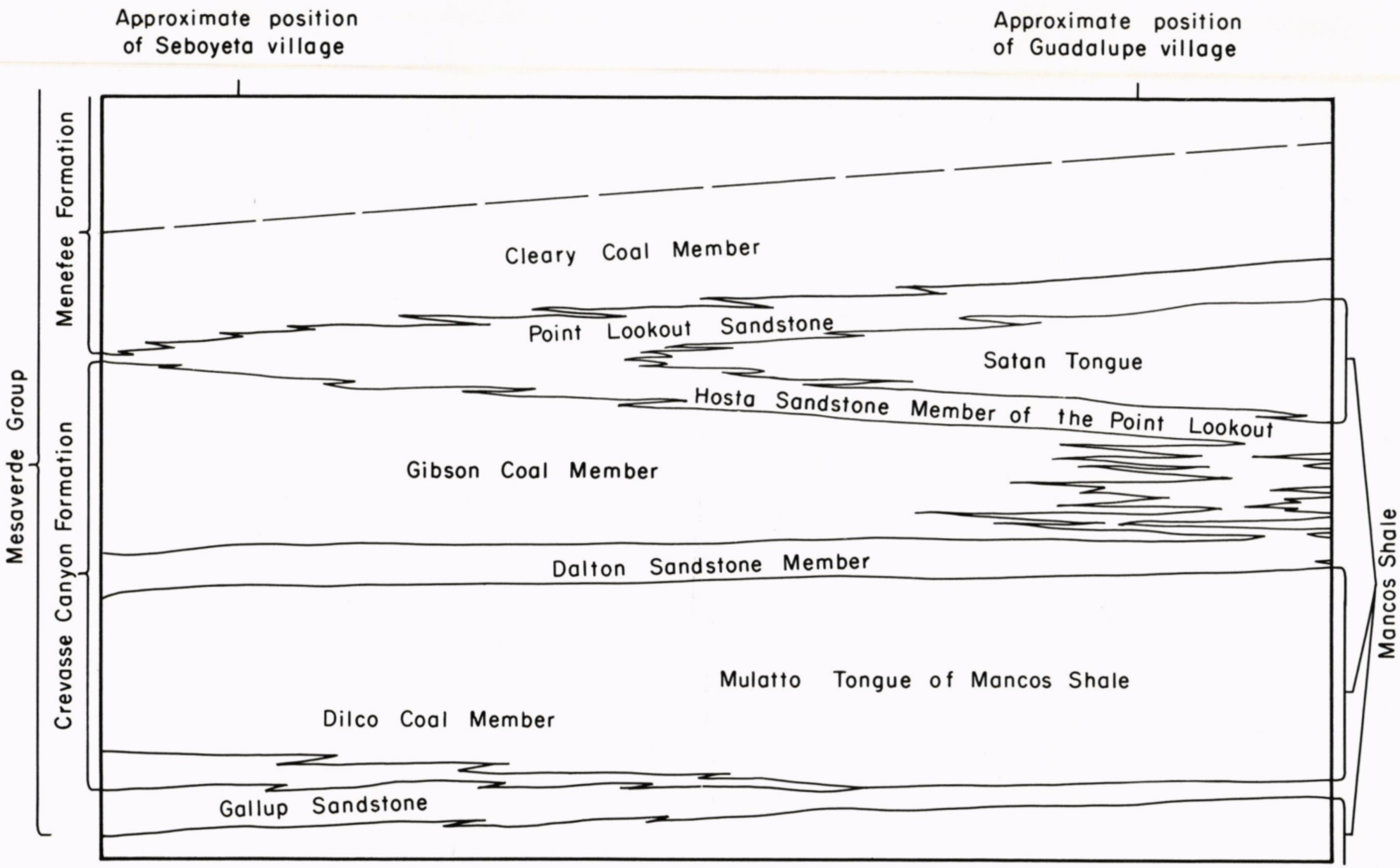

Figure 40
Diagrammatic northeast-southwest section of units in the East Mount Taylor Crevasse Canyon area

vening barren strata northeastward with marine units are shown in Figure 40 (modified from Beaumont, 1968a).

Only a few thin coal beds are reported from Mesaverde Group beds above the Gibson Coal Member. Strata equivalent to the Cleary Member of the Menefee Formation do occur above the Point Lookout Sandstone on the northeast flanks of Mesa Chivato and contain some coals that in most places are covered on the outcrop. The coal-bearing Gibson Member intertongues with marine shale belonging to the Mulatto Tongue of the Mancos Shale and marine sandstone of the Hosta Sandstone Member just south of the village of Guadalupe. The Dilco Coal Member of the Crevasse Canyon Formation is present in this area but it contains no reported coal. Analyses of the Gibson coals, made by the Guy Martin Laboratory in Albuquerque, indicated high-volatile C bituminous coal with about 11,000 Btu and 0.6 percent sulfur.

The dominant topographic feature of the East Mount Taylor area is Mesa Chivato which has an area of 400 square miles, an altitude of about 8,000 feet, and is topped by thick lavas. The Gibson Coal Member of the Crevasse Canyon Formation crops out on the east side of Mesa Chivato, being exposed chiefly in deep canyons or on steep slopes.

Seboyeta Grant

The towns of Seboyeta, Moquino, Marquez, and Bibo are in this grant. The lower part of the Mesaverde Group and upper part of the Mancos Shale are exposed on the east edge of Mesa Chivato. The areas of Mancos Shale are in the lower country in the eastern and southeastern parts of the grant.

The Gibson Coal Member of the Crevasse Canyon Formation contains many coal beds, but in most places exposures in the lower part of the Gibson are obscured by thick talus. Coal has been mined on a small scale on the northeast wall of Seboyeta (Cebolleta) Canyon two miles north of Seboyeta. The mine is reached by a road into the canyon from Seboyeta. The mined beds are 1.9 feet and 2.5 feet in thickness, and are separated by 15 to 20 feet of sandy shale. These two coal beds, although locally thin and split into several lenses, appear to be relatively persistent in the upper part of the Gibson Coal Member. The coal crops out along the east edge of Mesa Chivato from Bibo Canyon (northwest of Bibo) to several miles northwest of Marquez. The upper coal bed is 30 to 65 feet below the overlying Hosta Sandstone Member of the Point Lookout Sandstone, with the thickness of the interval to the base of the Hosta Sandstone increasing generally southwestward.

The two coals are 15 to 55 feet apart where they are both present, and in the outcrop they range from 1.1 to 3.0 feet in thickness. Drill-hole data, reported by Beaumont from a report for the Valencia Coal Corp., show thicknesses of three to five feet for these beds, and indicate the presence of a lower coal bed ranging from 4.0 to 6.5 feet in thickness.

Hunt's (1936) measurements showed as many as four coal beds in the middle and lower parts of the Gibson Member, but on the outcrop none of these beds is more than 1.6 feet thick. Outcrop data on coal are in many places less than satisfactory, especially on steep, rubble-covered slopes, thus drill-hole information is needed to reveal more of the true character and thickness of the coal beds.

As these outcropping coal beds on the Seboyeta Grant are for the most part less than three feet thick, and occur on steep slopes overlain by thick overburden, no strippable reserves were calculated. The Dilco Member of the Crevasse Canyon Formation contains no known coal beds of commercial potential in this area.

T. 14 and 15 N., R. 3 and 4 W.

These townships are on the northeast flank of Mesa Chivato. The stratigraphically higher beds are partly obscured by talus on the east side of the mesa and the coal-bearing units in R. 3 W. are involved in a series of fault blocks west of Rio Puerco and south of Guadalupe village.

According to Hunt (1936), this is the region wherein the sediments now assigned to the Crevasse Canyon Formation intertongue northeastward with marine shale and sandstone of the Mancos Shale and Point Lookout Sandstone. He did not find any coal beds in the Dilco Coal Member of the Crevasse Canyon Formation, and he reported that coal beds in the Gibson Coal Member are less than 1.2 feet thick in these townships. Hunt speculated that beds now assigned to the Cleary Member of the Menefee Formation are present beneath the lava cap on Mesa Chivato, but he found no outcrops of this unit. Sabins (1964), however, found coal and carbonaceous shale of the lower Menefee as far south as Marquez.

The Gibson Member intertongues northeastward with the Hosta Sandstone Member of the Point Lookout Sandstone (fig. 40) near the southern boundary of the Ignacio Chavez Grant, thus no coals are known in the thin remnant of the Crevasse Canyon Formation in that grant. The Cleary Coal Member of the Menefee Formation is thick north of the northeast tip of Mesa Chivato; coal beds in that part of the Ignacio Chavez Grant are described in the chapter on the San Mateo Kmf area.

RIO PUERCO MESAVERDE AREA

by John W. Shomaker

The Rio Puerco area is an irregular belt of outcrop of Upper Cretaceous Mesaverde Group rocks in the Rio Puerco valley, beginning about 25 miles west of Albuquerque and trending north-northeastward for a distance of about 40 miles (fig. 41). The Dilco and Gibson Members of the Crevasse Canyon Formation, both coal-bearing units of economic importance elsewhere in the southern San Juan Basin, are present in the area, and both contain coal. The following brief evaluation of the Rio Puerco area with respect to strippable coal reserves was made largely from the literature, particularly the work of Hunt (1936) and of Campbell (1967).

The outcrops of the coal-bearing units occur, for the most part, within the Rio Puerco fault zone, a north-northeast-trending swarm of high-angle faults. As a result, the outcrops appear in narrow, steeply dipping blocks. The eastern part of the area is covered by thick sand and gravel deposits of the Cenozoic Santa Fe Formation, which in some places obscure coal-bearing rocks.

According to Hunt (1936), the Dilco Member contains little or no coal of commercial value. The Dilco is found

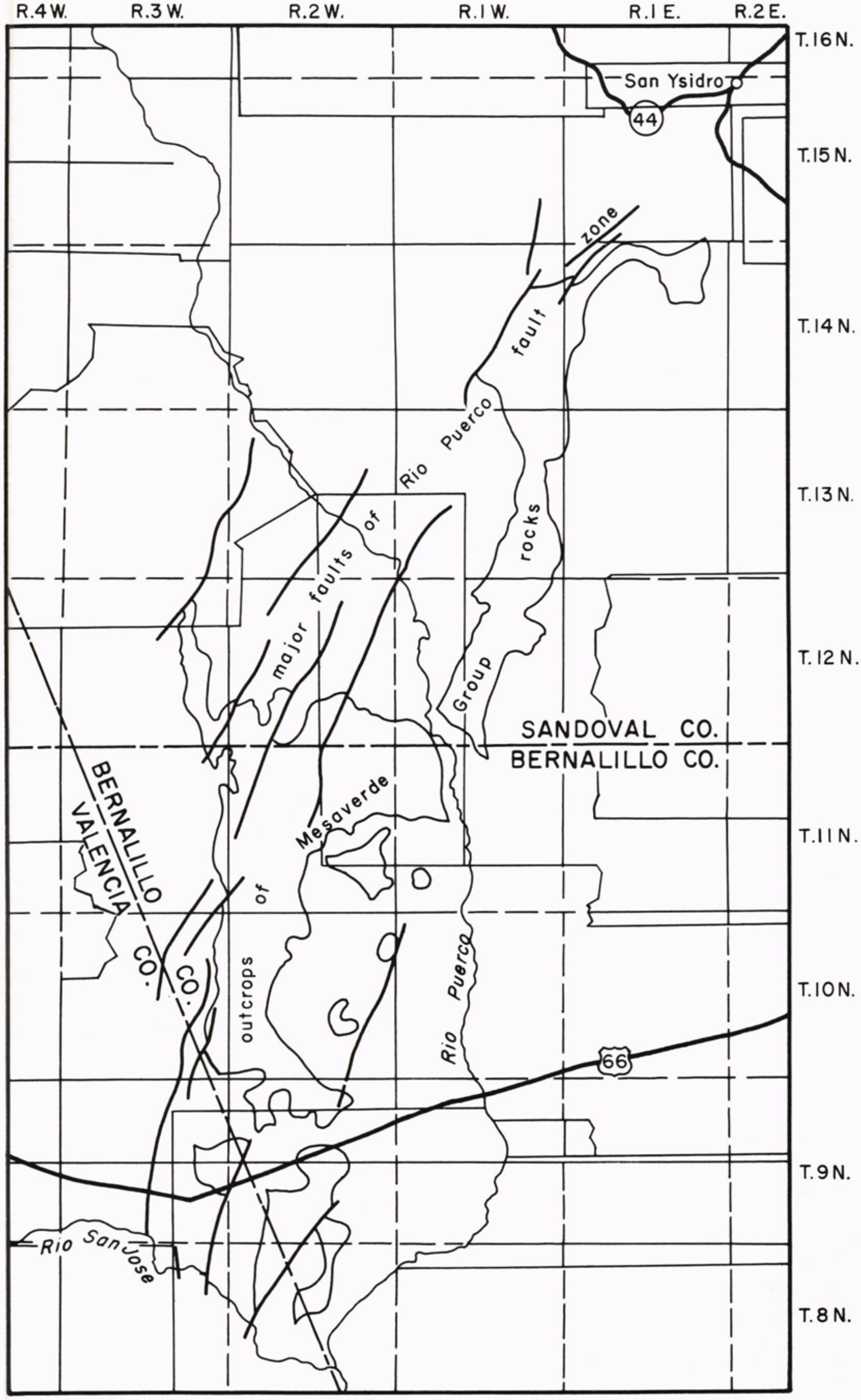

Figure 41

Index map of Rio Puerco Mesaverde area showing outcrop area of Mesaverde Group rocks and major faults of Rio Puerco fault zone only in small areas, generally bounded by faults and generally dipping too steeply for stripping.

The Gibson Member contains numerous coal beds, some of commercial thickness. In the northern extremity of the area, lenticular beds commonly reach thicknesses of five feet, and Hunt (1936) reported a bed 9.6 feet thick at one location in section 8 of T. 14 N., R. 1 E. Except for a few square miles of partly obscured outcrop in T. 9 N., R. i W., T. 9 N., R. 2 W. and T. 10 N., R. z W., in which dips are rarely less than five degrees, the Gibson Member is present only in areas of a square mile or less, commonly bounded by faults and characterized by steep dips. No place was found that appeared favorable for stripping, though drilling might reveal gently dipping Gibson coals beneath a cover of Santa Fe Formation in the northeastern part of T. 9 N., R. 2 W. and the south-central part of T. i o N., R. 2 W.

LA VENTANA MESAVERDE FIELD

by John W. Shomaker

SUMMARY

The La Ventana field was developed to a minor extent by underground methods in the 1920's and 1930's. Large tonnages of 10,500-Btu, low-sulfur coal still remain in beds of the Cleary and Allison Members of the Menefee Formation, but because of excessive dips and thick sandstone overburden, only a small amount, perhaps 15 million tons, can be considered strippable.

INTRODUCTION

The La Ventana field is defined to include the coal-bearing rocks of the Upper Cretaceous Mesaverde Group in the southeast corner of the San Juan Basin, from the west line of R. 2 W. northeastward to the vicinity of Cuba (fig. 42.). The occurrence of coal in the field has been well known since before the turn of the century; a number of small underground mines were operated during the 1920's and 1930's.

The geologic section in the La Ventana field is an alternation of fluvial and nearshore marine sandstones with lagoonal shales and coals. The oldest formation of the Mesaverde Group is the white or buff, marine Point Lookout Sandstone (the Hosta Sandstone of former usage). It is overlain by the Cleary Coal Member of the Menefee Formation, a sequence of carbonaceous shale, gray barren shale, lenses of soft tan or white sandstone, and coal. The Allison Member of the Menefee, which rests upon the Cleary Member and constitutes the remainder of the formation, is of similar lithologic makeup, though with more sandstone. The Allison Member was originally defined in the Gallup area as a barren member and thus the Cleary-Allison contact is drawn at the top of a locally prominent sandstone above the highest coal in the Cleary. In the La Ventana field, there is a persistent development of coal at the top of the Allison Member, but it has not been considered important enough to warrant separate member status. The aggregate thickness of the two members is 230 to 1,800 feet (Dane, 1936).

Where the Allison Member reaches its greatest thicknesses, it is overlain by the Lewis Shale, a thick accumulation of gray marine shale with minor, thin sandstones. Over most of the field, however, the upper part of the Allison Member is laterally equivalent to a thick buildup of buff or white marine sandstone assigned to the La Ventana Tongue of the Cliff House Sandstone. The La Ventana ranges from o to 1,25o feet in thickness.

The La Ventana sandstones and to a lesser degree the Point Lookout and the sandstones of the lower Allison, form very steep massive cliffs where dips are as much as 15 or 20 degrees, and hogback ridges where dips are steeper.

The coals of the Menefee Formation in the La Ventana field are primarily of subbituminous A rank, although some reach high-volatile bituminous C rank. As-received heating values are on the order of 10,500 Btu per pound, sulfur content is generally less than 1.0 percent, and ash content is generally less than io percent (U.S. Bur. Mines, 1936) (see table 6 for representative analyses). There is no apparent consistent difference between the coals of the Cleary Member and those in the upper part of the Allison Member.

DESCRIPTIONS OF TOWNSHIPS

T. 17 N., R. 2 W.

The Cleary Member forms a bench 1/2- to 1 1/2-miles wide and about five miles long across the northern part of the township from section 3 to section 19. The bench lies above an abrupt cliff formed by the Point Lookout Sandstone and below a line of irregular, broken cliffs formed by sandstones of the Allison Member. Two persistent coal beds occur in the Cleary Member; the upper is nowhere measured at as much as three feet, but the lower coal has thicknesses of 3.o, 3.8, and 5.o feet at three points (Dane, 1936). There is no assurance that it is everywhere thicker than three feet between these measurements, but it seems likely that a minable thickness of coal is present in most places. Using an average of 3.9 feet, the reserve beneath less than 150 feet of overburden would be about 11.3 million tons. The low relief and the character of the overburden, which is almost entirely shale, would make the area suitable for stripping.

T. 18 N., R. I W.

The Cleary Member underlies slightly more than one square mile in sections 2, 3, and 11. One bed near the base of the Cleary Member is of minable thickness, but the zone crops out at the base of La Ventana Mesa and is overlain by some 500 feet of overburden.

T. 18 N., R. 2 W.

The bench cut upon the Cleary Member extends across the township from north to south in sections 1, I I, 14, 23, 25, 26, 35, and 36. Two coal beds persist throughout this distance, but only in the southern part is a minable thickness developed in either. In sections 35 and 36 the lower coal bed (which lies but a few feet above the top of the Point Lookout Sandstone) has been measured at 3.o feet, 2.9 feet, and 3.5 feet; if a minimum thickness of 3.o feet were used to compute reserves, about three million tons could be estimated. North of section 35, dips steepen to six degrees or more and the beds seem to be of less regular thickness.

One or two beds form a persistent coal zone in the upper-

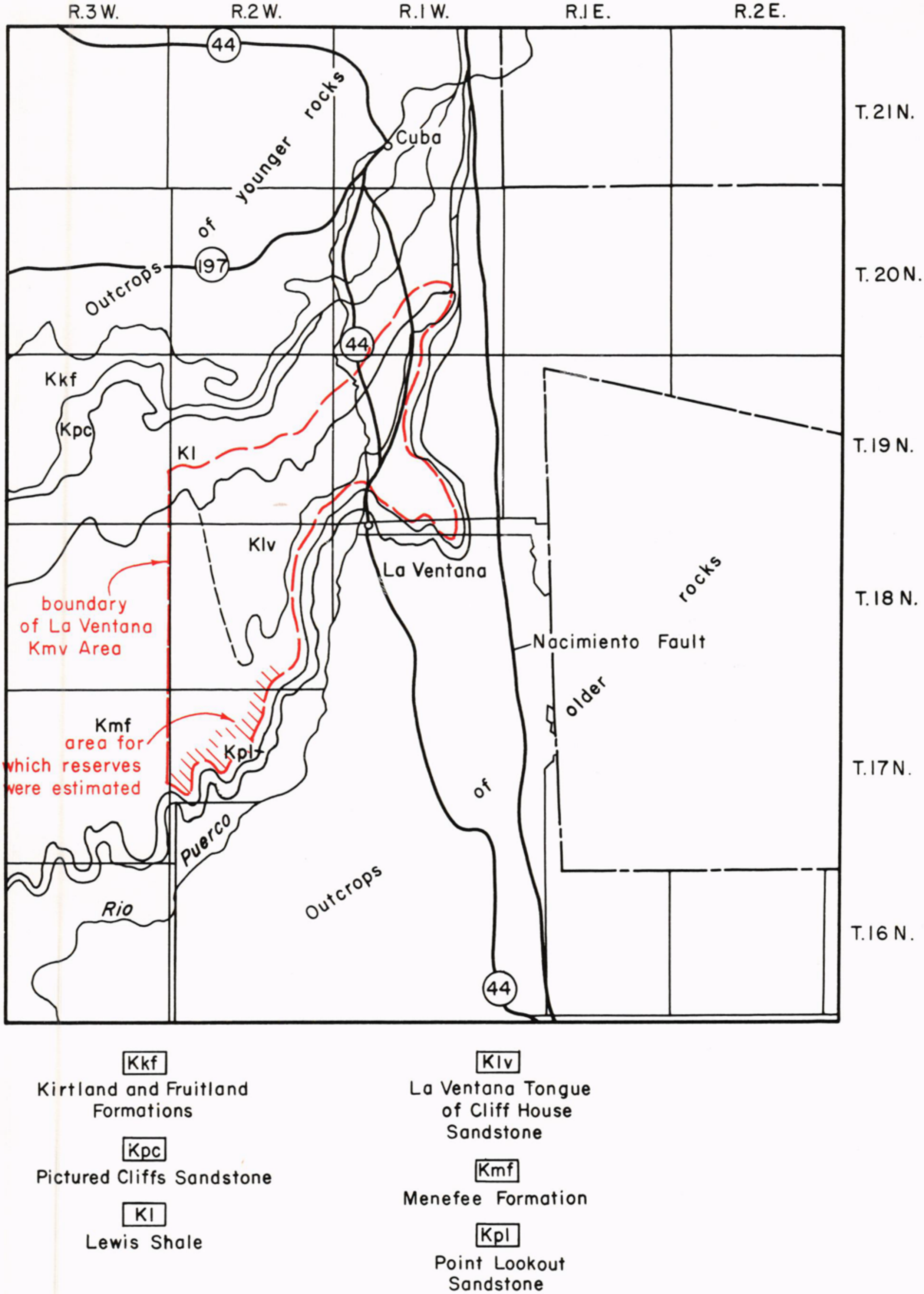

Figure 42

Map showing La Ventana coal field and area for which strippable reserves were estimated most Allison Member. The outcrop trends southward from section 2 into section 27, then westward in sections 28, 31, 32, and 33. The principal coal beds are rather irregular in thickness, but both reach thicknesses of six or more feet. Unfortunately, the coal zone crops out only at the base of the steep eastern escarpment of La Ventana Mesa and of the associated chain of hills to the southwest. Thus, the zone is overlain by 15o to 45o feet of massive sandstone of the La Ventana Tongue. The area might be suited to an auger-mining operation, but only minor tonnages in widely separated localities would be strippable.

T. 19 N., R. i W.

The Cleary Member underlies most of the western half of the township. The outcrop of the coal zone lies at the foot of the steep escarpment in sections 3o and 31, beneath no less than 200 feet of overburden; on the east side of the Rio Puerco in sections 29, 32, and 33 the same situation prevails. From section 35 generally northward through sections 26 and 27, 21 and 22, and 16 and 9, the zone is exposed in a prominent hogback ridge in which it dips too steeply for stripping. In section 35, the dip is as much as 8o degrees; farther north the dip is much less but still six degrees or steeper (Dane, 1936). Bedding attitudes measured on the surface above the zone indicate that the prohibitively steep dips continue for two miles or more in the up-section direction, away from the outcrop. At most, but not all, of the measured section localities a bed thicker than three feet is present.

The upper Allison coal zone crops out along an arc through sections 30, 20, 19, 16, 9, and 4, and contains in most measured sections a bed three to six feet thick. Thicknesses do appear to be rather erratic, and except for local areas of much less than one square mile, dips are excessive for stripping. Consolidation Coal Co. holds a lease on 8,663 acres of the area underlain by this coal in T. 19 N., R. r W., and T. 20 N., R. t W.; presumably the intent is to mine the coal by underground methods.

T. 19 N., R. 2 W.

The Cleary Member crops out in the southwest quarter of section 36, and underlies the entire remainder of the township. The coal beds exposed in section 36, and nearby, are extremely erratic. Dips are five to ten degrees, so that the likelihood of strippable reserves is remote.

The upper Allison coal zone crops out in the eastern part of section 35, the northwest corner of section 26, and along the line between sections 25 and 36. The coal zone contains one persistent coal bed that appears to be at least five feet thick, but it is overlain by upwards of 200 feet of La Ventana Tongue Sandstone and dips rather steeply, five to ten degrees (Dane, 1936).

In sections 3o and 31, a coal bed occurs at the top of the Allison Member west of the pinchout of the La Ventana Tongue, and thus near the base of the Lewis Shale. Its thickness is erratic, and it passes into "bone" in short distances, so that no reserves were estimated.

T. 20 N., R. z W.

The Cleary Member contains coal beds at several localities in this township, but no beds persist for significant distances.

The upper Allison zone crops out in a prominent hogback, supported by the La Ventana Sandstone Tongue, for a distance of about 3 1/2 miles in the south-central part of the township. The thickness is of economic significance but the dip of eight degrees and more (beds are even overturned in one area) precludes stripping. A persistent coal in the same stratigraphic position occurs in sections 2 and 11, but very steep, and overturned, dips again render the deposit unsuitable for stripping.

TIERRA AMARILLA MESAVERDE FIELD

by Edward C. Beaumont

The Tierra Amarilla coal field lies three to five miles south and southeast of Tierra Amarilla in north-central Rio Arriba County. It comprises a small outlier of coal-bearing beds in the Mesaverde Group lying on the east flank of the Chama subbasin about 12 miles east of the nearest Mesaverde rocks that crop out on the northeast flank of the main San Juan Basin. Coal beds occur in at least nine separate stratigraphic positions, cropping out along the rim of two mesas separated by the valley of Rito Tierra Amarilla, and structurally part of a small, faulted syncline. Most of the coal beds are thin and lenticular, and are overlain by excessive cover including massive cliff-forming sandstones.

The coal is of subbituminous A rank, has been mined for local domestic use, and contains 1.0 to 1.1 percent sulfur with about 8 percent ash. Two beds in the lower part of the Menefee Formation are as much as 4.1 feet thick. Landis and Dane (1969) estimated inferred resources, in two areas, of as much as a million tons of coal in beds more than 28 inches thick, and about 3.4 million tons of coal in beds 14 to 28 inches thick.

The two thicker coals crop out on the sides of the two mesas west and northeast, respectively, of Rito Tierra Amarilla. In most of the area they are overlain by 4o to 6o feet of sandstone and silty sandstone of the middle part of the Menefee Formation. Total overburden, except along the mesa slopes, ranges from 40 to more than 25o feet, thus there is essentially no strippable coal in the Tierra Amarilla coal field.

MONERO MESAVERDE FIELD

by John W. Shomaker

The Monero field is a north-south-trending belt of coal-bearing rocks assigned to the Menefee Formation of the Mesaverde Group that extends from section 34 of T. 26 N., R. r E. to the Colorado state line north of Monero, New Mexico (fig. 43). In the northern part of the area, near Monero and Lumberton, coal was mined on a small scale by underground methods for many years, principally for the Denver and Rio Grande Western Railroad which served both towns.

Except for a series of narrow blocks cut by a swarm of

TABLE 6. REPRESENTATIVE ANALYSES OF COAL SAMPLES FROM LA VENTANA MESAVERDE FIELD

LOCATION	KIND OF SAMPLE	CONDITION[1]	PROXIMATE, PERCENT: LABORATORY NUMBER[2]	MOISTURE	VOLATILE MATTER	FIXED CARBON	ASH	ULTIMATE, PERCENT: HYDROGEN	CARBON	NITROGEN	OXYGEN	SULFUR	ASH	HEATING VALUE: BRITISH THERMAL UNITS PER POUND	FUSIBILITY OF ASH, °F: SOFTENING TEMP.	REMARKS
NE¼ NW¼ SW¼ Sec. 31, T. 19 N., R. 1 W.	mine sample	1	A47085	15.8	34.5	43.8	5.9	—	—	—	—	0.6	5.9	10,900	2,340	Cleary Member, San Juan mine.
		2	—	—	41.0	52.0	7.0	—	—	—	—	0.7	7.0	12,950	—	
NE¼ NW¼ SW¼ Sec. 31, T. 19 N., R. 1 W.	mine sample	1	A46366	15.7	32.0	45.1	7.2	6.2	61.5	1.2	23.3	0.6	7.2	10,790	2,340	Cleary Member, San Juan mine.
		2	—	—	38.0	53.5	8.5	5.3	72.9	1.4	11.2	0.7	8.5	12,800	—	
		3	—	—	41.5	58.5	—	5.8	79.7	1.5	12.2	0.8	—	13,990	—	
SW¼ SW¼ SW¼ Sec. 26, T. 19 N., R. 1 W.	prospect pit	1	A47084	18.2	34.4	40.8	6.6	—	—	—	—	0.9	6.6	10,280	2,110	Cleary Member, Wilkins No. 2 prospect.
		2	—	—	42.0	49.9	8.1	—	—	—	—	1.0	8.1	12,570	—	
SE¼ Sec. 19, T. 19 N., R. 1 W.	mine sample	1	A60026	12.1	35.8	44.5	7.6	6.2	61.1	1.1	21.2	2.8	7.6	10,940	2,110	Allison Member, Rio Puerco mine.
		2	—	—	40.7	50.6	8.7	5.6	69.5	1.3	11.7	3.2	8.7	12,460	—	
		3	—	—	44.6	55.4	—	6.1	76.1	1.4	12.9	3.5	—	13,640	—	
NE¼ NW¼ SE¼ Sec. 35, T. 19 N., R. 2 W.	mine sample	1	A64268	20.0	32.5	42.6	4.9	6.4	58.6	1.1	28.3	0.7	4.9	10,240	2,340	Allison Member, Anderson mine.
		2	—	—	40.7	53.2	6.1	5.3	73.2	1.4	13.2	0.8	6.1	12,790	—	
		3	—	—	43.3	56.7	—	5.6	78.0	1.5	14.0	0.9	—	13,630	—	
Sec. 35, T. 19 N., R. 2 W.	prospect drift	1	A46367	14.8	33.9	41.4	9.9	5.5	52.8	1.1	29.5	1.2	9.9	8,910	2,280	Allison Member, Casement prospect; sample may have been somewhat weathered.
		2	—	—	39.8	48.6	11.6	4.5	62.0	1.3	19.2	1.4	11.6	10,460	—	
		3	—	—	45.1	54.9	—	5.1	70.2	1.4	21.7	1.6	—	11,840	—	

[1] Condition: 1, as received; 2, moisture-free; 3, moisture-and ash-free.
[2] Analyses by U. S. Bureau of Mines Laboratory, published in U. S. Bur. Mines Tech. Paper 569.

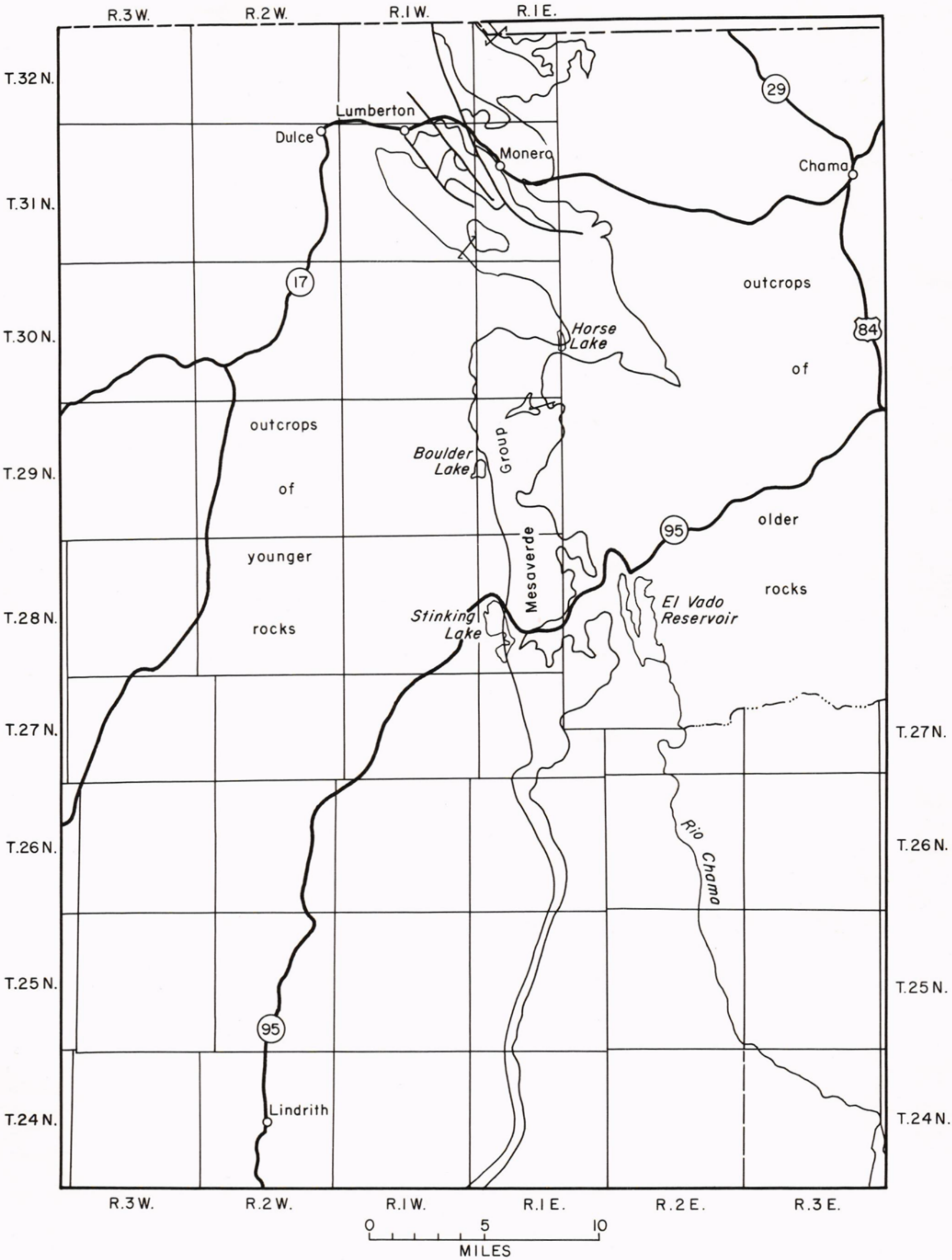

Figure 43
INDEX MAP OF MONERO MESAVERDE FIELD

TABLE 7. REPRESENTATIVE ANALYSES OF COAL SAMPLES FROM MONERO MESAVERDE FIELD

LOCATION	KIND OF SAMPLE	CONDITION[1]	PROXIMATE, PERCENT: LABORATORY NUMBER[2]	PROXIMATE, PERCENT: MOISTURE	PROXIMATE, PERCENT: VOLATILE MATTER	PROXIMATE, PERCENT: FIXED CARBON	PROXIMATE, PERCENT: ASH	ULTIMATE, PERCENT: HYDROGEN	ULTIMATE, PERCENT: CARBON	ULTIMATE, PERCENT: NITROGEN	ULTIMATE, PERCENT: OXYGEN	ULTIMATE, PERCENT: SULFUR	HEATING VALUE: BRITISH THERMAL UNITS PER POUND	FUSIBILITY OF ASH, °F: INITIAL DEFORMATION TEMP.
Sec. 7, T. 31 N., R. 1 E.	channel	1	2122	4.0	39.0	51.1	5.9	—	—	—	—	1.0	—	—
		2	—	—	40.7	53.1	6.2	—	—	—	—	1.1	—	—
SW¼ Sec. 7, T. 31 N., R. 1 E.	channel	1	29279	7.2	37.1	50.4	5.3	—	—	—	—	0.7	12,160	2340
		2	—	—	40.0	54.3	5.7	—	—	—	—	0.7	13,100	—
NW¼ NE ¼ Sec. 20, T. 31 N., R. 1 E.	channel	1	A-37774	3.9	37.8	48.4	9.9	5.5	69.2	1.4	10.5	3.5	12,740	2230
		2	—	—	39.4	50.3	10.3	5.2	72.1	1.5	7.3	3.6	13,260	—
		3	—	—	43.9	56.1	—	5.8	80.3	1.7	8.2	4.0	14,790	—
Sec. 8, T. 31 N., R. 1 W.	channel	1	5761	1.7	36.3	55.1	6.9	5.2	75.4	1.6	10.2	0.7	13,730	—
		2	—	—	36.9	56.1	7.0	5.1	76.7	1.6	8.9	0.7	13,960	—
		3	—	—	39.7	60.3	—	5.5	82.5	1.7	9.6	0.7	15,020	—
NE¼ Sec. 10, T. 31 N., R. 1 W.	channel	1	A-37934	3.3	36.1	50.2	10.4	5.4	70.5	1.5	11.3	0.9	12,950	2820
		2	—	—	37.4	51.8	10.8	5.3	72.9	1.6	8.5	0.9	13,390	—
		3	—	—	41.9	58.1	—	5.9	81.7	1.8	9.6	1.0	15,020	—

[1] Condition: 1, as received; 2, moisture-free; 3, moisture- and ash-free.
[2] All analyses by U. S. Bureau of Mines.

northwest-trending faults in the vicinity of Monero and Lumberton, the coal-bearing unit is disposed on the backslope of a one- to three-mile-wide cuesta for the entire length of the field. Near the north end of the field, the Menefee consists almost entirely of sandstone, and is almost indistinguishable from the underlying Point Lookout Sandstone and the overlying La Ventana Tongue of the Cliff House Sandstone. Near and south of Monero, the Menefee contains much more shale and coal, and can be separated from the other units. The sandstones of the Menefee form the capping of much of the cuesta south of Monero, and the dips are commonly less than five degrees. North of Boulder Lake, dips are three degrees or less over large areas.

The combined thickness of the Menefee Formation and the overlying La Ventana Sandstone Tongue is slightly more than 250 feet (Dane, 1948). Because of the topography and the fact that Lewis Shale covers only a very small part of the backslope of the cuesta, the full thickness is present in only small areas. Thus, any coal present in the Menefee will be beneath less than 250 feet of overburden.

Thin, discontinuous coals have been measured near the western edge of the Mesaverde Group outcrop at Stinking Lake, Boulder Lake, and several places along the eastern face of the cuesta between Horse Lake and Monero. Except for the measurement along the mesa front about four miles east-southeast of Horse Lake, at which five feet were measured (Muehlberger, 1967), the coals are not of strippable thickness.

Near Monero and Lumberton, bed thicknesses up to 7.3 feet have been measured (U.S. Bur. Mines, 1936), but dip angles and faulting probably preclude stripping over any significant area.

COAL QUALITY

Five representative analyses, from mines near Lumberton and Monero, are shown in Table 7. These, plus other published analyses (U.S. Bureau of Mines, 1936), indicate that the coal is of high-volatile bituminous B or C rank with relatively low ash and moisture content and somewhat higher sulfur content than most other San Juan Basin Menefee coals. Sulfur content ranges up to 3.5 percent, but is seemingly very erratic even in samples from the same mine.

PAGOSA SPRINGS CRETACEOUS AREA

by John W. Shomaker

The Pagosa Springs Cretaceous area (fig. 44) is a narrow, arcuate outcrop of the Upper Cretaceous coal-bearing rocks which trends from the Florida River east of Durango to the Colorado-New Mexico state line southeast of Pagosa Springs. The area lies along the northern rim of the San Juan Basin in La Plata and Archuleta Counties, Colorado. The evaluation of strippable-coal potential is based on field examination and on reports by Zapp (1949), Barnes (1953), and Wood, Kelley, and MacAlpin (1948).

GEOLOGIC SETTING

At the western end of the area, the geologic section consists, in ascending order, of the Point Lookout Sandstone, the Menefee Formation, the Cliff House Sandstone, the Lewis Shale, the Pictured Cliffs Sandstone, and the Fruitland Formation, all of Late Cretaceous age. The Point Lookout Sandstone consists primarily of sandy shales interbedded with fine- to coarse-grained sandstone. The sandstone beds increase in thickness and in grain size from bottom to top. The unit is about 400 feet thick. Overlying it is the Menefee Formation which consists also of sandy shales, carbonaceous shales, and sandstones with numerous lenticular coal beds. The thickness of the Menefee is highly variable, but at the western limit of the Pagosa Springs area it is about 175 feet thick. The Cliff House Sandstone consists almost entirely of sandy shale in that area, and is barren of coal. The Lewis Shale is a dark-gray marine clay-shale about 2,000 feet thick. It is believed to intertongue with the overlying Pictured Cliffs Sandstone which is a uniform coarse-grained sandstone about 200 to 250 feet thick. Above the Pictured

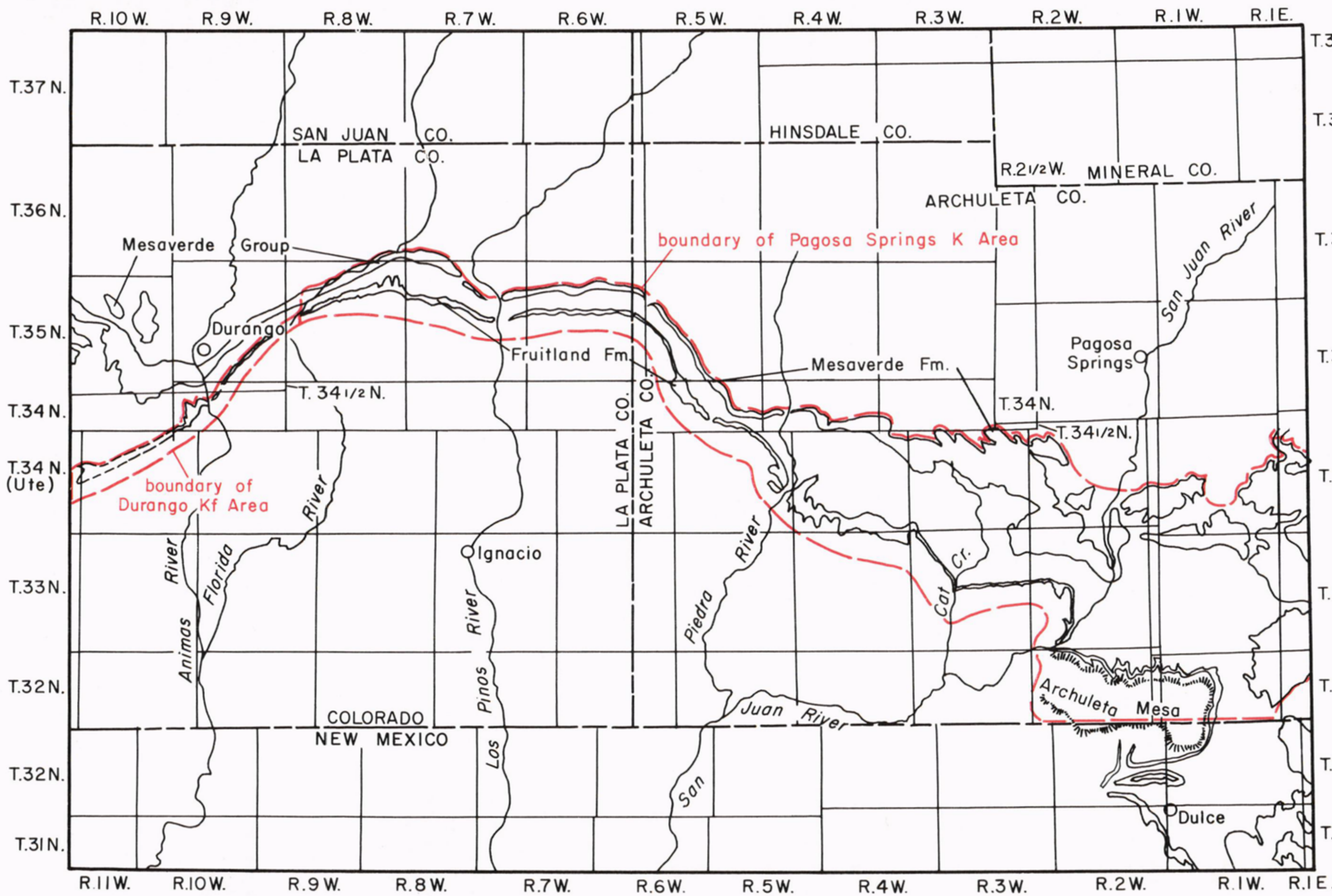

Figure 44

INDEX MAP OF PAGOSA SPRINGS AND DURANGO AREAS SHOWING OUTCROPS OF MESAVERDE AND FRUITLAND FORMATIONS

TABLE 8. REPRESENTATIVE ANALYSES OF COAL SAMPLES FROM PAGOSA SPRINGS AREA AND ADJOINING AREAS

LOCATION	CONDITION[1]	LABORATORY NUMBER[2]	PROXIMATE, PERCENT: MOISTURE	VOLATILE MATTER	FIXED CARBON	ASH	ULTIMATE, PERCENT: HYDROGEN	CARBON	NITROGEN	OXYGEN	SULFUR	HEATING VALUE: BRITISH THERMAL UNITS PER POUND
Fruitland Formation												
NE¼ SW¼ Sec. 13, T. 35 N., R. 6 W.	1	—	3.6	—	—	—	—	—	—	—	—	12,650
	2	—	—	38.6	50.9	10.5	—	—	—	—	0.6	13,120
	3	—	—	—	—	—	—	—	—	—	—	14,660
NW¼ NE¼ Sec. 15, T. 35 N., R. 6 W.	1	9146	3.3	34.6	50.7	11.4	5.4	69.1	1.3	11.9	0.9	12,510
	2	—	—	35.8	52.4	11.8	5.2	71.5	1.4	9.2	0.9	12,930
	3	—	—	40.6	59.4	—	5.9	81.0	1.6	10.5	1.0	14,660
NE¼ SW¼ Sec. 14, T. 35 N., R. 7 W.	1	A3404	2.5	32.4	41.7	23.4	—	—	—	—	1.7	10,890
	2	—	—	33.2	42.8	24.0	—	—	—	—	1.7	11,170
Mesaverde Group (Menefee Formation)												
NW¼ SE¼ Sec. 13, T. 35 N., R. 9 W.	1	B41137	1.5	33.3	58.9	6.3	—	—	—	—	—	14,160
	2	—	—	33.8	59.8	6.4	—	—	—	—	—	14,380
	3	—	—	36.2	63.8	—	5.9	86.1	1.6	5.6	0.8	15,370

[1] Condition: 1, as received; 2, moisture-free; 3, moisture- and ash-free.
[2] All analyses by U. S. Bureau of Mines.

Cliffs Sandstone is the Fruitland Formation which consists of fine- to medium-grained crossbedded sandstone, sandy shale, shale, and coal. The coals are very erratically distributed through the section and are ordinarily quite dirty but in places are unusually thick. The well-known Carbonero bed near the base of the formation reaches a thickness of nearly 100 feet in one section, but it contains many shale partings and much bony coal.

Eastward from the western edge of the Pagosa Springs area at the Florida River, the abundance of coal in the Menefee Formation decreases markedly. In the Florida River Valley, the Menefee contains at least twelve beds of coal up to three feet in thickness. Six miles farther east, no coal is found in the Menefee. At this point it consists almost entirely of even-bedded, medium- to coarse-grained sandstone similar to that of the overlying Cliff House Sandstone and the underlying Point Lookout Sandstone. Farther eastward, all three formations are considered to have merged and are mapped simply as the Mesaverde Formation. The Mesaverde maintains a thickness of about 350 feet throughout the remainder of its outcrop to the east end of the Pagosa Springs area. The Lewis Shale is also generally consistent throughout the remainder of the area at a thickness of about 2,400 feet. The Pictured Cliffs Sandstone continues through the area generally as a single massive bed of fine- to medium-grained, buff to brown sandstone. The Fruitland Formation and the overlying barren Kirtland Formation, also of Late Cretaceous age, thin to the east until toward the east end of the area they have a combined thickness of only 70 to 100 feet. This thickness does not include tongues of the Kirtland and Fruitland which interfinger with tongues of the Animas Formation of latest Cretaceous and early Tertiary age. The coal zone at the base of the Fruitland Formation persists but the number and thickness of coal beds diminish until at the east end of the area only one bed a few feet thick remains.

From the Florida River to the Piedra River, the resistant sandstones of the Mesaverde Formation stand as a steep hogback between the overlying Lewis Shale and the underlying Mancos Shale. East of the Piedra River, the dip becomes less steep and the outcrop becomes much broader and very irregular owing to the effect of structural deformation. The Fruitland Formation, supported by the resistant Pictured Cliffs Sandstone, forms a long sinuous hogback all the way from the Florida River to the Colorado-New Mexico state line. For the most part, the outcrop of the Fruitland is less than 1,000 feet wide; however, just east of the Piedra River a local flattening of structure causes the outcrop band to widen until at one or two localities it is more than a mile wide.

A few commercial mines have opened the Menefee Formation coal just east of the Florida River. Owing to the rapid transition of the Menefee to barren sandstone in this area, however, little extensive development has been done. The Fruitland Formation, on the other hand, has been mined extensively from the western edge of the Pagosa Springs area to about the La Plata-Archuleta county line.

COAL QUALITY

No samples of the Menefee coal from this area have been analyzed but it is probably similar to coals of similar stratigraphic position just west of the Florida River. A coal sample from the Fireglow mine about a mile west of the river yielded 14,160 Btu per pound and contained about 6.3 percent ash on an as-received basis, and 0.8 percent sulfur on a moisture-and-ash-free basis. Analyses of Fruitland Formation coal from the vicinity of the Los Pinos River indicate heating values ranging from 10,890 to 12,650 Btu per pound, ash content ranging from 11.4 to 23.4 percent, and sulfur content ranging from 0.9 percent to 1.7 percent—all on an as-received basis (table 8).

EVALUATION OF STRIPPABLE COAL POTENTIAL

As indicated by the foregoing, the Menefee Formation contains coal only in the extreme western part of the Pagosa Springs area, and there it dips steeply to form a prominent hogback. In fact, in the area where the Menefee does contain coal, the dips are generally on the order of 40° and rarely less than 20°; thus strippable coal is not a possibility. The same situation prevails for the Fruitland Formation from the Florida River to the Piedra River; in this area the dips seldom are less than 9° and they are often more than 30°. Just east of the Piedra River in the southwestern part of T. 34 N., R. 4 W. (Ute), the Fruitland outcrop locally broadens into an irregular patch encompassing several square miles in total. Even here the dips are six to eight degrees.

In section 30 of that township, a small strip mine is being operated by the Colorado Highway Department for coal to spread on icy roads. The pit is limited on all sides by topography, and little increase in its size is likely.

Another irregular patch of about three square miles lies along the southern boundary of this township and in the northeast corner of T. 33 N., R. 4 W.; dips are again 6° or more. From the western edge of R. 3 W. eastward to the San Juan River, the Fruitland consistently contains coal beds of minable thickness but is exposed on a sinuous ridge at dips from 7° to more than 3o°. From the San Juan River eastward around the east side of Archuleta Mesa and to the New Mexico state line, dips are much less steep, being 3° to 6°. The Fruitland outcrop, however, lies in the face of Archuleta Mesa within which it is covered by 200 or more feet of overburden.

DURANGO FRUITLAND AREA

by Robin C. Lease

The Durango Fruitland area is a northeasterly trending outcrop of Late Cretaceous strata along the northern edge of the San Juan Basin. It is bounded on the east by the Florida River and on the west by 108° W. Long. (fig. 44).

The Fruitland Formation is a series of lenticular sandstone, shale, and coal beds resting conformably on the Pictured Cliffs Sandstone. The lower Fruitland sequence of brown and gray shale with interbedded sandstone and coals locally intertongues with the underlying Pictured Cliffs Sandstone. In the central part of the area, the Carbonero coal bed is associated with this intertonguing and is locally 80 feet thick (Zapp, 1949). The upper Fruitland is a nonmarine sequence of sandstone, coal, and gray to gray-green shale. The coal beds in the upper Fruitland are lenticular and range up to 20 feet in thickness.

The Fruitland coals in the Durango region are of poor quality owing to many thin shale partings and a high ash content. The poor quality, together with the nearby availability of the higher quality Menefee Formation coals, has discouraged mining of the Fruitland coal beds since the late 1800's.

An analysis of coal from the La Plata mine (SE1/4SE1/4 section 27, T. 35 N., R. 9 W.) gave an as-received 3.1 percent moisture, 32.7 volatile matter, 47.4 fixed carbon, 16.8 percent ash, 11,900 Btu, and a calculated 1.3 percent sulfur (U.S. Bur. Mines, 1937). A moisture-free analysis yielded 33.7 percent volatile matter, 49.0 percent fixed carbon, 17.3 percent ash, and 12,270 Btu; and a moisture-and-ash-free analysis gave 40.8 percent volatile matter, 59.2 percent fixed carbon, 5.5 percent hydrogen, 80.1 percent carbon, 1.8 percent nitrogen, I1.0 percent oxygen, 1.6 percent sulfur, and 14,840 Btu. The coal is thus a high-ash and medium-low-sulfur coal.

The Fruitland Formation crops out along a southeastward-dipping monocline. Dips average 24 degrees along the outcrops. No strippable-coal reserve has been calculated for the area due to the steep rate of dip and the poor quality of the coal.

RED MESA FRUITLAND AREA

by William R. Speer

The evaluation of strippable reserves of coal in this area (fig. 45) utilizes geologic maps and sections of Barnes, Baltz, and Hayes (1954), drill-hole data of the Peabody Coal Co., subsurface well-log studies, and field examination. Data were compiled on preliminary maps of the U.S. Geological Survey's 7 1/2-minute topographic quadrangle series.

The Fruitland Formation in the Red Mesa area crops out as a relatively narrow band trending northeast-southwest along the northwestern margin of the San Juan Basin. This edge of the structural basin is defined by the Hogback monocline, as designated by Kelley and Clinton (1960), which separates the Basin from the adjacent Four Corners platform. The monocline is most prominently expressed topographically by Rocky Ridge, the outcrop of the Pictured Cliffs Sandstone. The narrowness of this outcrop band and that of the stratigraphically overlying Fruitland Formation is attributable to the relatively steep monoclinal dip of the beds. Dips of these strata range from 5° to as high as 23°, depending upon their position on the flexure.

The steepness of the dip generally precludes consideration of strip-mining practices, particularly in the northern half of the area, where the steeper dips are prevalent. Stripping would be hampered also by the ruggedness of terrain. Although coal-bed thicknesses are attractive for mining, particularly in the basal portion of the Fruitland, the upper portion contains a number of thick-bedded sandstones. These resistant sandstones form substantial hogback ridges which create an overburden problem detrimental to stripping operations.

The generally steep dip is modified somewhat in the southern portion of the area, near the state line, by a subsidiary structural feature. This anticlinal or terrace feature, termed the Red Mesa anticline (Barnes, et al., 1954) has a northeast-southwest axis trending through sections x and 2 of T. 32 N., R. 13 W., section 3 of T. 32 N., R. 12 W., and section 35 0f T. 33 N., R. 12 W., which parallels the monocline along its northwestern edge. The flattening of dip on the flank of this feature modifies the anticlinal bend of the monocline, resulting in shallower dips in the Fruitland Formation of from 5° to 8° in the region of the Cinder Buttes. The Cinder Buttes, located in sections 11, 14, 15, and 22 of T. 32 N., R. 12 W., are isolated remnants of burned lower Fruitland Formation protruding above the dip slope of the Pictured Cliffs, and are upheld by capping beds of resistant clinker shale.

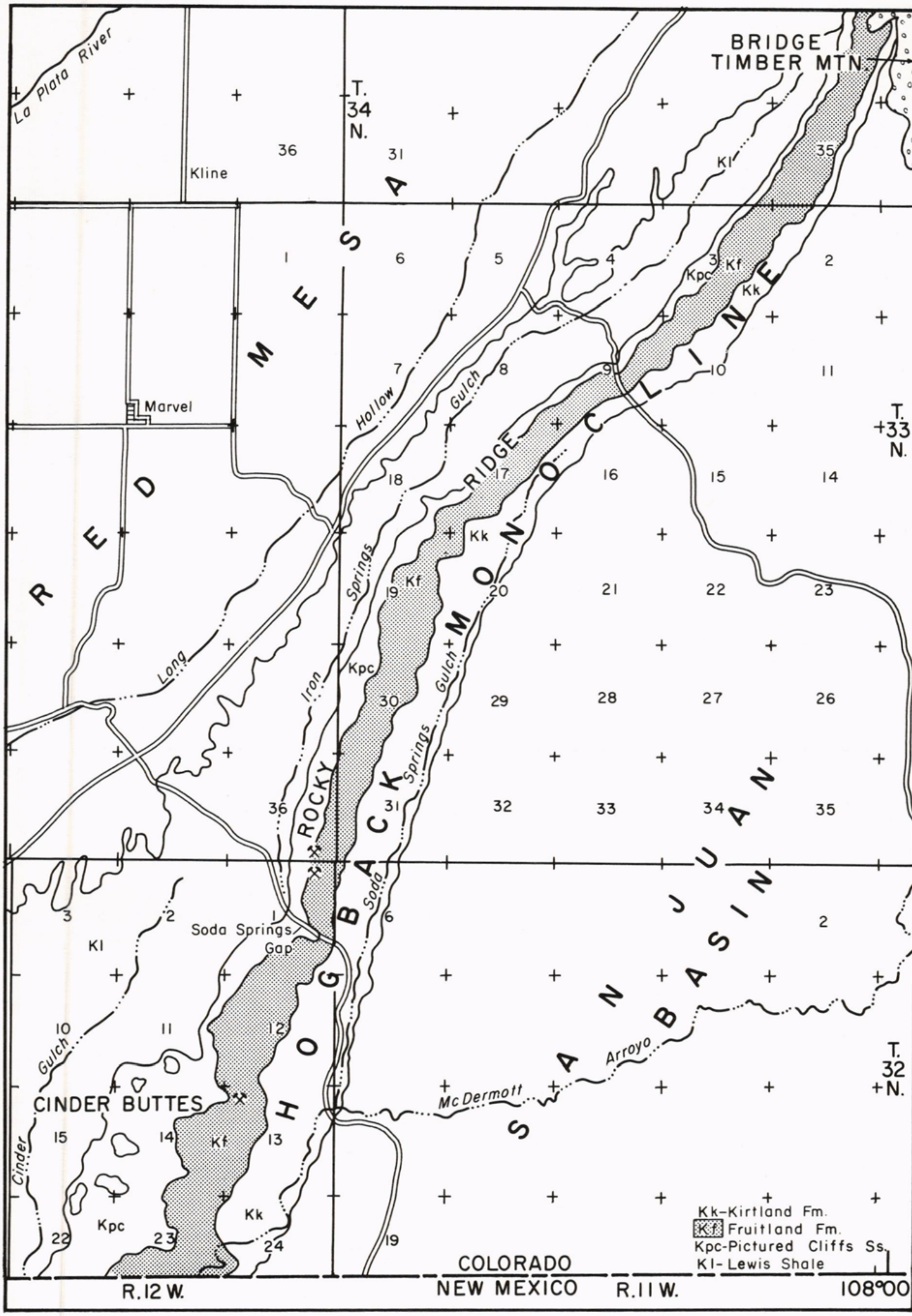

Figure 45
INDEX MAP OF RED MESA FRUITLAND AREA

Consideration of strippable reserves of coal in the Red Mesa area would be impractical were it not for the substantial thicknesses of coal found in the lower 90 to 125 feet of the Fruitland Formation. These coal beds, abundant and relatively thick, are lenticular and interbedded irregularly with carbonaceous shales and shaly sandstones. They are typical of a sedimentary sequence resulting from deposits in a fluctuating coastal-swamp environment. One measured surface section in the N1/2 of section 30, T. 33 N., R. II W., (No. 39 of Barnes et al.) indicates that approximately two-thirds of the lower 91 feet of Fruitland consists of coal. A drill hole in the NE1/4 of section 23, T. 32 N., R. 12 W., is described as penetrating 61 feet of coal in the lower 214 feet of the 275 feet drilled to reach the Pictured Cliffs Sandstone. More significant is the persistence of a single substantial coal bed immediately on top of the Pictured Cliffs in the southern half of the area. This bed consistently exceeds 20 feet in thickness and contains very few measured shale partings more than 0.7 foot thick.

An estimation of the strippable reserves available from this bed alone, to a maximum stripping depth of 250 feet and extending along the outcrop from the state line to the north line of section 30 of T. 33 N., R. I I W., results in a reserve of some 40.6 million tons. While this calculation gives some idea of magnitude of the possible reserves, the geometry of the deposit and the resultant pit-design problems and mining expense would make strip mining a doubtful economic consideration. The steepness of dip of the Fruitland Formation along its outcrop in the northern half of the area would definitely preclude stripping considerations.

Analyses of Fruitland coals from previously worked underground mines in the Red Mesa area indicate a rank of high-volatile C bituminous, approaching subbituminous rank in the Cinder Buttes area (Barnes et al., 1954). The analyses show a uniformly low sulfur content, ranging from 0.6 to 1.1 percent and an ash content ranging from 8.8 to 19.1 percent. No underground mines are currently operative in the Red Mesa area. Drill-hole sample analyses show an ash content of approximately 12 percent and a sulfur content of 0.77 percent, consisting predominantly of organically combined sulfur. The heating values of all samples range from a low of 8,300 Btu per pound to a high of 54,820 Btu with a mean average near 12,400 Btu.

DESCRIPTIONS OF TOWNSHIPS

T. 32 N., R. 12 W.

The Fruitland crops out over most of this shortened township. The outcrop trends north-northeastward through portions of sections 1, I I, 12, 13, 14, 23, and 24 and exists as isolated remnants farther westward, upholding the Cinder Buttes. This township encompasses m0re than 95 percent of the 40.6 million tons of calculated strippable reserves described in the introduction. As such, it is the only area of possible consideration for strip mining in the Red Mesa area. The relatively steep dip and the presence of numerous prominent sandstone-capped ridges in the overlying sedimentary sequence would result in a deep, narrow, linear pit of doubtful workability.

The area is presently accessible to four-wheel-drive vehicles by a network of drill-hole roads along the back slopes of the Pictured Cliffs Sandstone, both north and south of the all-weather road cutting through the Soda Springs gap in section 1. In the NW1/4NW1/4 of section I is the abandoned Ft. Lewis underground mine workings which, though extensively caved, expose a substantial portion of the lower Fruitland coal bed which was being mined.

T. 33 N., R. 12 W.

The Fruitland crops out in only a small area of this township in the extreme southeastern corner of section 36. It is in this area, however, that the abandoned Henderson mine is located. The face of the mine's main entry effectively exposes the lower Fruitland coal unit.

T. 33 N., R. 11 W.

The Fruitland Formation crops out diagonally across this township from section 3 to section 31 in an irregularly narrow band of increasingly steeper dip in a northward direction. The increasing dip and overburden thickness combined to preclude consideration of strippable reserves.

T. 34 N., R. II W.

The steep dip of the Fruitland lessens somewhat through sections 13 and 24 of this township, but is still too steep for strip-mining considerations. The outcropping Fruitland band extending through sections 35 and 26 is interrupted in the northern portion of sections 25 and 26 and the southern portion of section 24 by an overstepping remnant of the San Juan peneplain, called Bridge Timber Mountain. This mesa-like feature of 8,300 feet altitude, capped by Pliocene-Pleistocene gravels, is an erosional remnant of a once extensive Cenozoic pediment surface which covered the area, but presently obscures only a minor portion of the Late Cretaceous outcrops.

No strippable reserves are estimated for this township.

SUMMARY

The coal beds of the Red Mesa area occur in the Fruitland Formation in a narrow outcrop band which dips relatively steeply into the San Juan Basin along the marginal Hogback monocline. The steep dips, together with excessive overburden thicknesses, combine to make strip-mining possibilities limited. The coal-bed thicknesses and continuity in the lowermost portion of the formation are positive factors, particularly in the southern half of the area, where structural modifications make stripping operations more feasible. Strippable reserves in this portion of the area are on the order of 40 million tons to a pit depth of 250 feet when considering only the main coal bed immediately overlying the Pictured Cliffs Sandstone. Mining considerations may make strip recovery of these resources economically impractical.

FRUITLAND FRUITLAND FIELD

by Edward C. Beaumont

The Fruitland field includes the shallow coal in the Fruitland Formation between the San Juan River and the Colorado-New Mexico state line. The surface of the southern part of the Fruitland field is characterized by broad alluviated flats interrupted by sharp sandstone-capped cuestas with relief varying from a few feet to a few tens of feet. Linear gravel-capped terraces of several levels parallel, and are restricted to the areas marginal to the valleys of the San Juan and the La Plata Rivers. As the dip of the beds increases northward along the Hogback monocline, the surface is marked by narrow ridges and valleys near the flexure and high, tilted mesas away from the fold.

STRUCTURE

In the southern part of the field, the easterly dips are low, 1 1/2 to 3 degrees, and the area of potential stripping coal is about two miles wide. The dip of the strata increases very gradually northward from the San Juan River for a distance of about six miles at which point the Fruitland sequence becomes involved in the steeply dipping, northeast-trending flexure known as the Hogback monocline. The outcrop band of the Fruitland is abruptly narrowed in the southernmost portion of the Ute Mountain Indian Reservation. For the next several miles the strike swings eastward and slightly south of east before again resuming a northeasterly trend. Near the La Plata River the trend is more easterly as the outcrop band approaches the Colorado line. From near the south boundary of Ute Mountain Indian Reservation, where the Fruitland Formation first becomes involved in the Hogback monocline, to the north end of the area, the outcrop of the formation gradually diagonals across the monocline. At the south end, the coal-bearing strata are in the synclinal bend such that the dip decreases rapidly away from the Fruitland-Pictured Cliffs contact. As the beds trend easterly and northeasterly, the entire formation is caught up in the steep flank of the monocline, but near the La Plata River the exposed portion of the Fruitland begins to rise above the monocline, into the zone of the anticlinal bend. Under the latter circumstances, the dip of the strata increases rapidly downdip.

Within the influence of the Hogback monocline, dips on the Pictured Cliffs Sandstone range from 18 degrees near the south boundary of the Ute Mountain Indian Reservation to a maximum of 4o degrees near the east boundary of the reservation. Eastward from the La Plata River, the dip of the beds in the Pictured Cliffs and the Fruitland averages about nine degrees.

DISTRIBUTION OF THE COAL

The Fruitland Formation in the southern part of the Fruitland field contains one principal coal bed at the base and another bed of less commercial consequence from 90 to 130 feet above the lower bed. In the s0uthern half of T. 30 N., R. 15 W., the lower bed, known locally as the "main bed," ranges in thickness from a maximum of about 19 feet to a minimum of about one foot near the El Paso Natural Gas Co. pipeline (fig. 46). The average thickness of this bed is about 16 feet. In this same area the "upper bed" varies in thickness from about two feet near the pipeline to as much as six feet. The average thickness is about 4.5 feet.

In the northern parts of sections 21 and 22 of T. 30 N., R. 15 W. the "main bed" remains quite thin. It begins to thicken again northward in the north half of section 16, and in section 9 the bed is split by a thin shale parting that gradually increases to a thickness of eight feet in the northeast corner of section 3. Preliminary drilling on the Ute Mountain Indian Reservation indicates that the separation between the two coal splits continues to thicken and the coal continues to thin to the point of having no commercial value.

The "upper bed" in this northern part of T. 30 N., R. 15 W., increases from a minimum of two feet in section 16 to a maximum of 6.5 feet in section 2. This bed continues onto the Ute Reservation with about this same thickness and increases to about 13 feet on the east side of section 25, T. 31 N., R. 15 W. (projected). In this area the coal is intercalated with numerous thin shale and siltstone partings and is of questionable value.

In section 25, T. 31 N., R. 15 W. (projected), Hayes and Zapp (1955) indicated a stratigraphic rise in the Fruitland-Pictured Cliffs contact of about 180 feet (their "shoreline N"). Beginning at about this position they mapped three coal beds about 5.5, 6.5, and 12.0 feet thick in ascending order. These units are traceable eastward in the outcrop with reasonable reliability to section 28, T. 31 N., R. 14 W. (projected), beyond which they are covered. Another stratigraphic rise of about 40 feet in the base of the Fruitland ("shoreline P" of Hayes and Zapp) confuses the correlation of the foregoing units with those in the next area of exposure.

Beginning in section 27, there is a basal coal about 6.5 feet thick separated by an interval of about 60 feet from a stratigraphically higher 7- to 8-foot-thick bed that contains numerous partings. The lower bed is traceable northeastward to just beyond the east boundary of the Ute Mountain Indian Reservation. According to Hayes and Zapp (1955), the stratigraphically higher bed thickens to about 20 feet near the reservation boundary and continues to thicken northeastward to a measured culmination in section 21, T. 32 N., R. 13 W. of 43 feet, 32 feet of which is coal and 11 feet shale or bony coal. The lack of adequate exposure precludes defining this bed in its full detail at the surface, but the implication from the measured sections of Hayes and Zapp (1955) is that the bed may have a maximum thickness of 50 feet in section 15, T. 32 N., R. 13 W. An exploration hole drilled by Peabody Coal Co. near this locality, close to the north line of section 22, revealed a 25.3-foot-thick coal bed with 21.9 feet described as coal and 3.4 feet as shale and bone. Hayes and Zapp (1955) continued to show this bed, on a somewhat reduced scale, eastward and northward to the Colorado line. Within a mile of the Colorado line, two measured sections of this basal coal bed, at this point resting directly on the Pictured Cliffs, show the thickness to be 31.4 and 34.3 feet.

In the eastern part of the Ute Mountain Indian Reservation and northeastward to the Colorado line, there are several higher lenticular coal beds in the Fruitland distributed through an interval of about 230 feet above the top of the thick bed described above.

EXPLORATION AND DEVELOPMENT

All of the potentially strippable coal in the Fruitland Formation in T. 30 N., R. 15 W. has been explored in con-

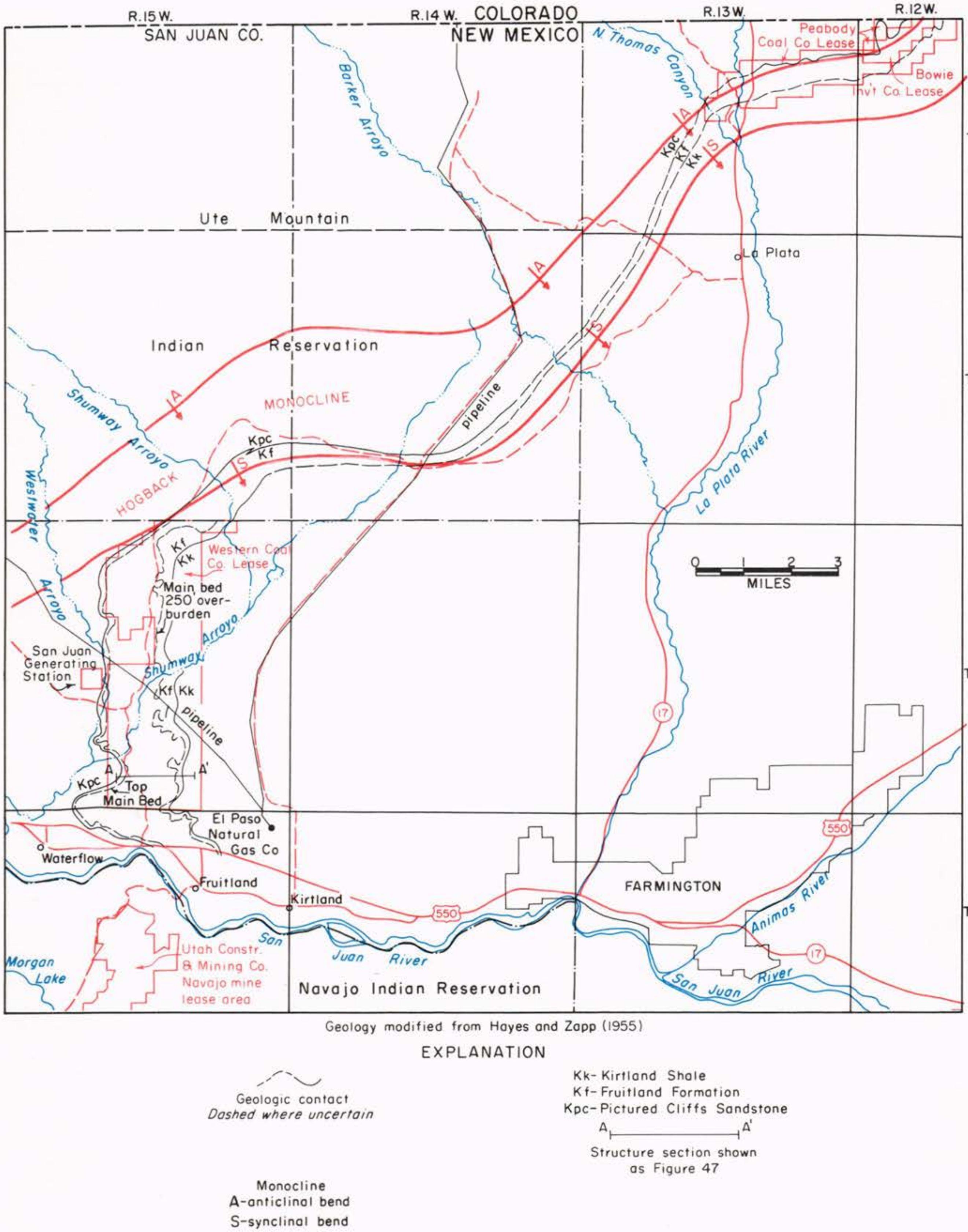

Figure 46
INDEX MAP OF FRUITLAND FRUITLAND FIELD

siderable detail by Western Coal Co., a subsidiary of Public Service Co. of New Mexico and Tucson Gas & Electric Co., which will be putting this area into production to supply the power plant that is presently under construction as a joint venture by these two companies (fig. 47). The first 345-megawatt unit of the new San Juan power plant is to be operational in early 1973. The area was first explored in connection with this venture by surface geologic investigation and reconnaissance core drilling in 1959. Detailed core and noncore drilling was done in 1969-70 on a 1,320-foot grid spacing with 660-foot locations in the shallow area.

At the north end of the Fruitland field, Peabody Coal Co. has leases under the major portion of the shallow-coal lands for a distance of about five miles southwest along the Fruitland trend from the Colorado state line. Approximately 480 acres in the midst of the Peabody holdings immediately adjacent to the state line is controlled by Bowie Investment Co.

Numerous small underground mines supplying coal for local consumption have been in operation from time to time in the south end of the coal field. None of the earlier mines is still active, but it is reported (W. R. Speer, personal communication) that a small surface-mining operation has been active in early 1971 in section 4, T. 29 N., R. 15 W. The same operator had previously attempted to open a pit in the basal Fruitland coal where the bed lies immediately beneath terrace gravels in section 32, T. 30 N., R. 15 W. Weathering of the coal beneath the preterrace surface made it infeasible to reach fresh coal at this locality. To both the west and east of the La Plata River, there have been a number of small mining operations in the past. None of these, however, were active at the time of this investigation.

COAL RESERVES

T. 29, 3o, and 3 i N., R. i 5 W.

Strippable-coal reserves have been calculated in detail for the Western Coal Co. holdings in T. 30 N., R. 15 W. This constitutes the major portion of the minable coal considered within the scope of this investigation. Adjacent to these holdings, there is a very narrow strip of land underlain by coal in T. 29 N., R. 15 W. between the valley of the San Juan River and the Western Coal Co. holdings that might be considered strippable reserves; and in the southern part of the Ute Mountain Indian Reservation, there is an area of about 2.5 miles in length along the Fruitland trend (from the south boundary to the east line of section 25, T. 31 N., R. 15 W.) that might be considered to have some minor potential for stripping coal. Inasmuch as the reserves in these two small areas are considered by the writer to have potential value only as adjuncts to the Western Coal Co. operation, the reserves in T. 29 and 31 N., R. 15 W. are treated together with the major reserves in T. 30 N., R. 15 W.

The "main bed," the basal coal seam in this area, constitutes the bulk of the reserve. The "upper bed" may have some value but it is considered marginal. For this reason, it provides reserve tonnage only within the area of consideration of the "main bed." Strippable coal reserves for these townships are placed at 82 million tons in the interval from 0 to 150 feet of overburden and 58 million tons in the 150 to 250 feet of overburden category.

T. 32 N., R. 12 and 13W.

The coal in the Fruitland Formation on the remaining part of the Ute Mountain Indian Reservation and northeastward to section 21, T. 32 N., R. 13 W. cannot be considered to have a stripping potential, regardless of the thick coal, in view of the inclination of the strata in the heart of the Hogback monocline. About 2.5 miles south of the Colorado line, the outcrop band of the Fruitland bends to the east, and, according to the mapping of Hayes and Zapp (1955), the coal-bed outcrops deviate slightly from the main trend of the Hogback monocline in such a manner that at the surface they are structurally above the zone of maximum folding. Bed inclinations in this area are nevertheless quite steep for strip-mine consideration, the range being from about 23 degrees maximum at the south end to about eight degrees near the Colorado line.

Data regarding any of the beds above the basal bed in this area are scattered, and from the small amount of data available (Hayes and Zapp, 1955), it appears that the upper beds contain abundant partings. The lower bed is also interrupted at frequent intervals by shale bands and other impurities, but it would appear that if partings of 0.8 foot or less were included in the bed and partings of greater than 0.8 foot were considered to be extractable in mining, an average thickness of 25 feet could be projected for the lower bed. Using this figure, the lower bed can be calculated to contain about 11 million tons of coal in the 0- to 150-foot overburden range and 7 million tons in the 150- to 250-foot range.

COAL QUALITY

All of the coal deposits in the Fruitland field can be classified as high-volatile C and B bituminous. This is in contrast to a rank classification given these deposits by Hayes and Zapp (1955) of subbituminous A. The higher rank classification is based on the ASTM specifications whereby the class and group are determined on a moist, mineralmatter-free basis (U.S. Office of Coal Research, 1967, p. 59). The writer, using one of the "Parr" formulae presented in the cited publication, converted 40 "as-received" analyses to the moist mineral-matter-free basis and found the calorific values to range from a low of 11,886 to a high of 13,880 Btu with an average value of 12,114 Btu. Samples from six localities were collected and analysed by the U.S. Bureau of Mines (1936, p. 58). Three of these came from mines in the northern part of the area, and in each instance the converted Btu value placed the coal in the high-volatile B bituminous range.

Within the area explored in detail by Western Coal Co., a distributed sampling of 70 partial and 24 complete proximate analyses of core samples appears to indicate a slight northward increase in the rank of coal. Along the southern margin of T. 3o N., R. 15 W. the average "as-received" calorific value is about 9,830 Btu, whereas in the northern part of the township, the average for two sets of samples ranges from 10,534 to 10,845 Btu. The average Btu value for 70 analyses covering the entire area is about 10,200. The principal factor affecting the northward increase in calorific value appears to be the decreasing ash content of the coal.

Along the southern margin of Western Coal Co.'s holdings, the coal has an average ash content of 17.42 percent. This quantity decreases northward to a minimum average of 12.61 percent in the northern part of the township. The moisture content of 70 samples varies only about one degree and averages 10.70 percent. On the basis of 24 analyses, volatile matter in the coal increases northward from a minimum average of 33.96 percent to a maximum average of 37.58 percent, and fixed carbon also increases northward from a minimum average of 37.02 to a maximum average of 40.46 percent. The average fixed carbon content for these 24 samples is 38.11 percent. Sulfur content of this coal averages 0.86 percent for 70 analyses and shows a definite increase from south to north in average values from 0.68 to 1.01 percent.

A group of ten mine, prospect, and tipple analyses taken from the U.S. Bureau of Mines records and published by Hayes and Zapp (1955) correspond closely to the core-hole analyses from the Western Coal Co. leases. The exception, as previously indicated, is in the northern part of the Fruitland field where the moisture and ash contents are lower and the volatile matter and fixed carbon contents are higher — conditions reflecting the somewhat higher rank classification of the coal along Hogback monocline.

SUMMARY

The Fruitland Formation in the Fruitland coal field trends northward from the San Juan River with low dips approximately as far as the south end of the Ute Mountain Indian Reservation. The coal-bearing strata from this position northward to the New Mexico-Colorado state line are involved in the sinuous, northeast-trending Hogback monodine. In the area of low dips (T. 30 N., R. 15 W.), the coal will be strip-mined for use in a power generating facility presently under construction. There is one principal and one secondary minable coal bed in this area. Northward the contact of the Fruitland with the underlying Pictured Cliffs Sandstone rises, and progressively higher coal beds appear. Relatively thick coal beds are present in the north half of the area, but with the possible exception of the northeastemmost few miles, the steep dips preclude surface development. All of the coal is either high-volatile C or B rank with an average sulfur content of about 0.80 percent. Reserves of strippable coal in both categories (o to 150 feet and 150 to 250 feet of overburden) are estimated to be 158 million tons.

NAVAJO FRUITLAND FIELD

by John W. Shomaker

The Navajo Fruitland coal field, at present the largest and best known coal field in the San Juan Basin, is defined as the area underlain by strippable coal of the Fruitland Formation within the Navajo Indian Reservation. It encompasses all or part of some 14 townships (fig. 48) in a belt that extends from the San Juan River on the north to Hunters Wash and Coal Creek on the south, bounded on the west by the outcrop of the Pictured Cliffs Sandstone and on the east by the eastern boundary of the Reservation.

The Fruitland Formation, of Late Cretaceous age, is a sequence of irregular gray, brown, and black shales; tan, yellowish-brown and white sandstones; and coal (pl. 4-D). The sandstones are generally fine grained and crossbedded, and tend to grade laterally to shale in short distances. The major coals occur near the base of the formation, just above the top of the underlying Pictured Cliffs Sandstone. The number of minable beds increases from north to south, and the lowest beds are apparently older at the south end owing to the regressive nature of the deposits.

The coal is of subbituminous rank, with a slight decrease in quality (owing to increase in ash content) from north to south. Sulfur content ranges from 0.3 percent to 3.3 percent with an average of somewhat less than 0.8 percent. Average coal analyses from the Utah Construction and Mining Co.'s lease, on an as-received basis are as follows:

Area	Btu	Ash	Moisture
T. 29 N., R. 15 W.	9,300	21.6%	12.8%
T. 28 N., R. 16 W.	9,400	17.4%	13.3%
T. 28 N., R. 15 W.	9,200	20.0%	13.0%
T. 27 N., R. 16 W.	9,200	19.5%	13.1%
T. 26 N., R. 16 W.	9,000	20.5%	13.2%
T. 25 N., R. 16 W.	9,000	20.9%	13.2%
Total	9,100	20.4%	13.2%

Average of all reserves: alkali as Na_2O (dry basis) = 0.51%, ash-softening temperature = 2,638°F, grindability index (Hardgrove) = 52.0.

Physiographically, the field is a broad, gently westward sloping plain dissected by tributaries to the Chaco River which parallels the west edge of the field. The northern part of the field in particular is broken by extensive badlands and low cuestas, while the southern part is characterized by low sandstone-capped mesas and gently undulating slopes. Most of the field is well disposed for strip mining and construction of haulage roads or railroads.

Utah Construction and Mining Co. obtained an exploration permit from the Navajo Tribe in 1953, and in 1957 negotiated a lease for 24,000 acres (pl. 4-E). The lease has since been expanded to 31,000 acres (fig. 48). In 1960, Utah completed an agreement with Arizona Public Service Co. to supply coal to the Four Corners power plant located adjacent to the lease. Coal deliveries began in 1963, and since the summer of 1964, the requirement has been increasing from about 2 1/2 million tons per year to a projected 1971 production on the order of 8 million tons.

Coal is stripped in successive 100-foot-wide cuts to a maximum depth of 120 feet. Overburden is stripped by a 48-yard Marion dragline and a 50-yard Bucyrus-Erie dragline, and coal is loaded by two 11-yard Marion shovels and one 16-yard Bucyrus-Erie shovel. A third 50-yard dragline is under construction.

The El Paso Natural Gas Co.-Consolidation Coal Co. lease, which encompasses virtually all of the remainder of the strippable coal in the Navajo area, has been thoroughly explored but mining has not begun. The original intent of El Paso Natural Gas Co. may have been to have a reserve suitable for gasification, but the association with Consolidation, a leader in coal-conversion technology, seems to indicate interest in a liquid-hydrocarbon-conversion project.

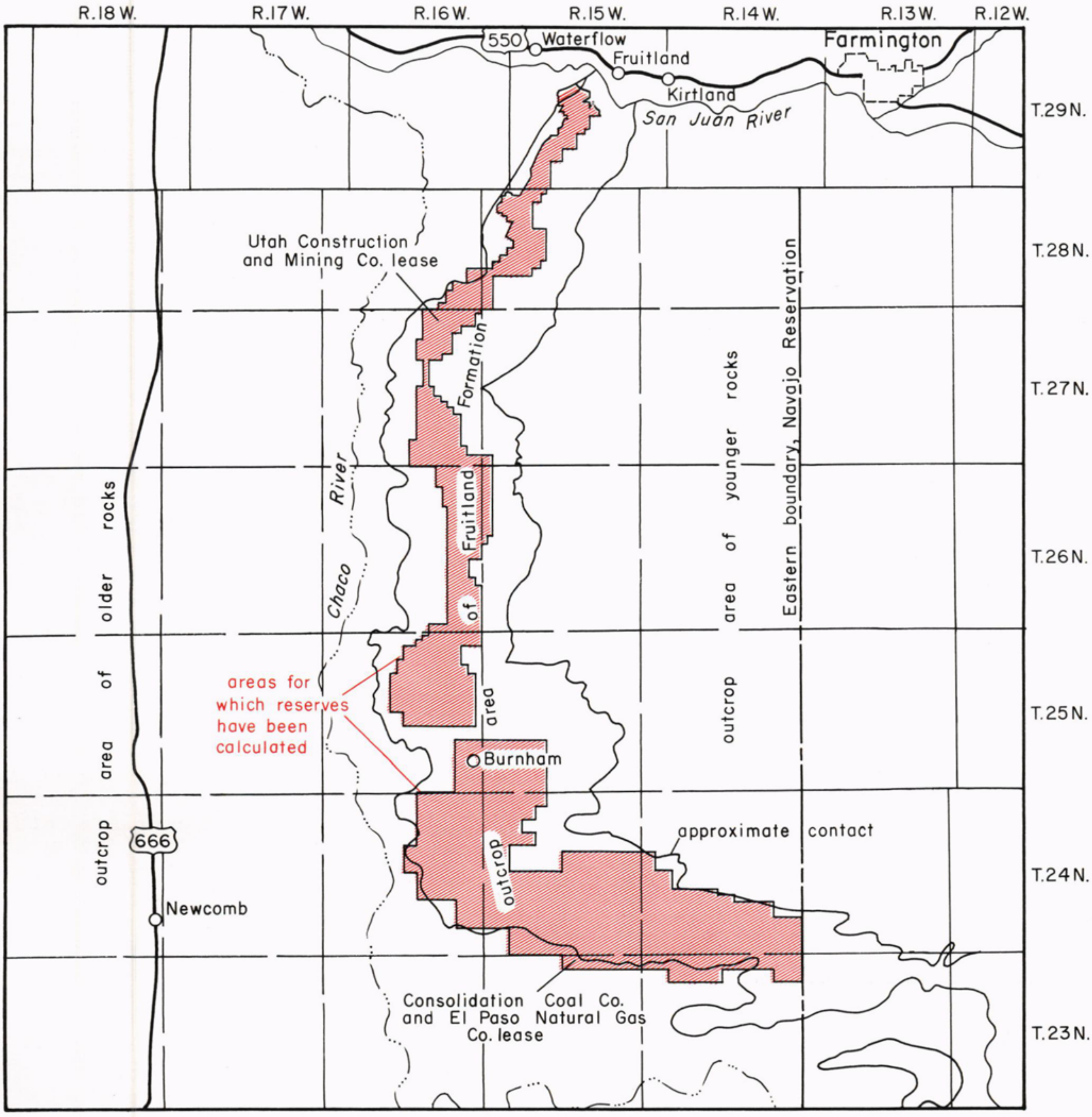

Figure 48
Map showing Navajo Fruitland field

All of the coal in the Navajo field considered strippable at present is leased from the Navajo Tribe by Utah Construction and Mining Co. (from the San Juan River south to near Burnham Trading Post) and by Consolidation Coal Co. and El Paso Natural Gas Co., in a joint venture, from Burnham Trading Post to Hunters Wash (fig. 48). The coal-reserve data shown in Table 9 were derived almost entirely from information provided by Utah Construction and Mining Co. and Consolidation Coal Co. No systematic field examination was made.

TABLE 9. SUMMARY OF COAL RESERVES IN NAVAJO FRUITLAND FIELD

Township T. N.	R. W.	Measured, indicated, and inferred reserves, millions of tons — Depths 10-150 feet		Depths 150-250 feet	
23	14				
23	15				
24	14				
24	15		482.9(1)		630.0(3)
24	16				
25	15				
25	16 (part)				
25	16 (part)	136.2		240.7	
26	16	252.2		322.5	
27	16	103.5		95.1	
28	15	9.8	541.8(2)	55.5	722.8(2)
28	16	25.4		9.0	
29	15	14.7		——	
			1,024.7		1,352.8

Note: (1) Includes coal seams thicker than 3.0 feet under less than 150 feet of overburden and possessing less than a 10:1 stripping ratio, plus seams thicker than 3.0 feet under less than 100 feet of overburden possessing less than a 20:1 stripping ratio.
(2) Limited by 10:1 stripping ratio.
(3) Estimate based on ratio of two stripping categories for area in which both are known from drilling.

BISTI FRUITLAND AREA

by John W. Shomaker

SUMMARY

The Bisti Fruitland area is thought to contain about 1,870 million tons of subbituminous, high-ash, low-sulfur coal beneath less than 250 feet of overburden. Of the total, about 958 million tons is estimated to be beneath less than 150 feet of overburden. The reserve estimates are based on drilling data of widely varying density, and are therefore less reliable in some areas than in others.

Sulfur content averages about 0.7 percent, and ash content ranges as high as 36 percent. Overburden, largely shale and soft sandstone, should be relatively inexpensive to mine. At present transportation is not available; providing it will be expensive.

INTRODUCTION

The Bisti Fruitland area represents the greatest undeveloped reserve in the San Juan Basin. In terms of gross tonnage it is on the same order of magnitude as the Navajo Fruitland field; preliminary estimates indicate about 1,870 million tons. Of that total, only about 142.6 million tons has been delineated by closely spaced drilling and later leased. Most of the remainder is beneath unleased federal and state land, and is in the earliest stages of exploration by holders of short-term exploration permits.

The area lies 30 to 55 miles south of Farmington in a band parallel to the Chaco River (see fig. 49).

The economically valuable coals are found in the lower 150 feet of the Upper Cretaceous Fruitland Formation. The Fruitland is a sequence of highly lenticular nonmarine clay-stones, silty and sandy shales, and soft crossbedded sandstones, with coal; the overlying Kirtland Shale is of similar lithology but lacks coal. The Fruitland is underlain by the marine Pictured Cliffs Sandstone, also of Late Cretaceous age.

The estimates of strippable reserves are based on drill-hole data provided by Public Service Coal Co. (a subsidiary of Public Service Co. of New Mexico), and by several of the exploration permit holders, as well as on oil tests, published geologic data (Bauer and Reeside, 1921), and drilling (pl. 4-F) and mapping by the New Mexico State Bureau of Mines and Mineral Resources. Public Service Coal Co.'s original area of consideration encompassed nearly all of the coal to an overburden thickness of 160 feet in T. 23 N., R. 13 W. and T. 24 N., R. 13 W. That reserve was examined in 1961 and 1962 by E. C. Beaumont (Beaumont, 1962); 39 holes were drilled. For the present study, the additional coal available to an overburden thickness of 250 feet was determined by projection of structure contours and thickness trends shown in Beaumont's work.

Evaluation of the coal in Ranges I0 W., xi W., and 12 W. was based primarily upon logs of 29 drill holes (pl. 3) kindly furnished by permit holders. Though virtually all of the coal is beneath federal or state land, the drilling data does not become public information, and because of competitive pressure in obtaining additional permits and leases, much drilling data was withheld or released on condition that parts of it be held in confidence. Thus, the evaluation in this report is not as complete as it might have been and much basic data cannot be included. Fortunately, the distribution of data is such that it can be effectively supplemented by oil and gas test data and outcrop measurements to yield reasonable results. In addition, the New Mexico State Bureau of Mines drilled one small-diameter (2 1/8-inch) and two large diameter (5 7/8-inch) core holes (see pl. 3) to aid in reserve calculations and to obtain samples for washability studies.

The drill-hole density, and correspondingly the reliability of estimates, is greatest in T. 23 N., R. 12 W. and decreases southeastward until, at Betonnie Tsosie Wash (Escavada Wash of earlier usage), so little data are available that no reserves were estimated beyond except for very speculative amounts based solely on outcrop measurements.

Where possible, outcrop positions were projected from drill-hole data, then checked against published maps and field observation. The "crop line" actually used for calculations was arrived at by projecting a 1 0-foot overburden line. In areas where no outcrop is visible on the surface, an approximate outcrop was projected from drill-hole data and used directly under the assumption that the precision of such a projection is not sufficient to allow a meaningful further refinement to the 10-foot overburden line.

The general areas underlain by strippable coal are shown

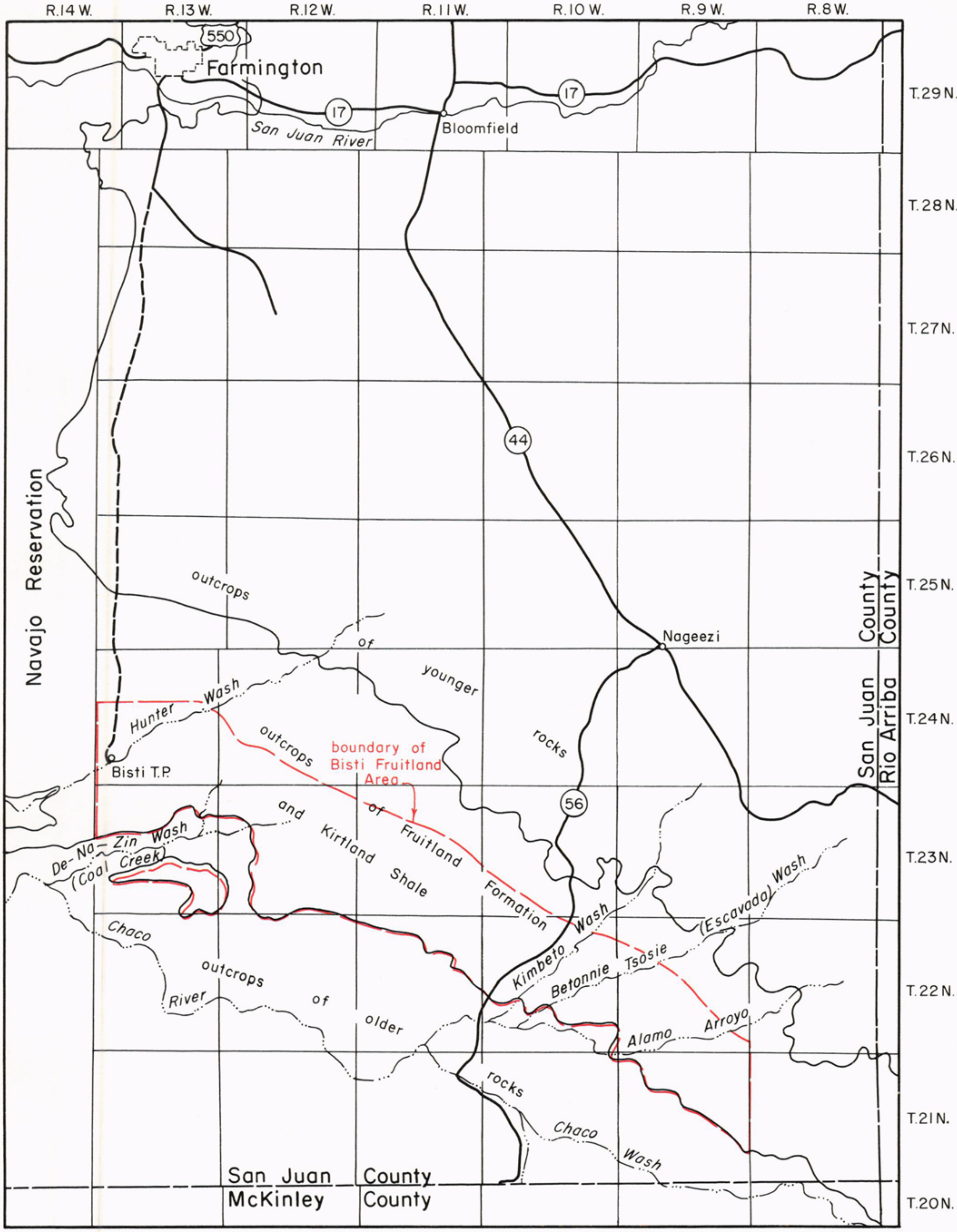

Figure 49
MAP SHOWING LOCATION OF BISTI FRUITLAND AREA

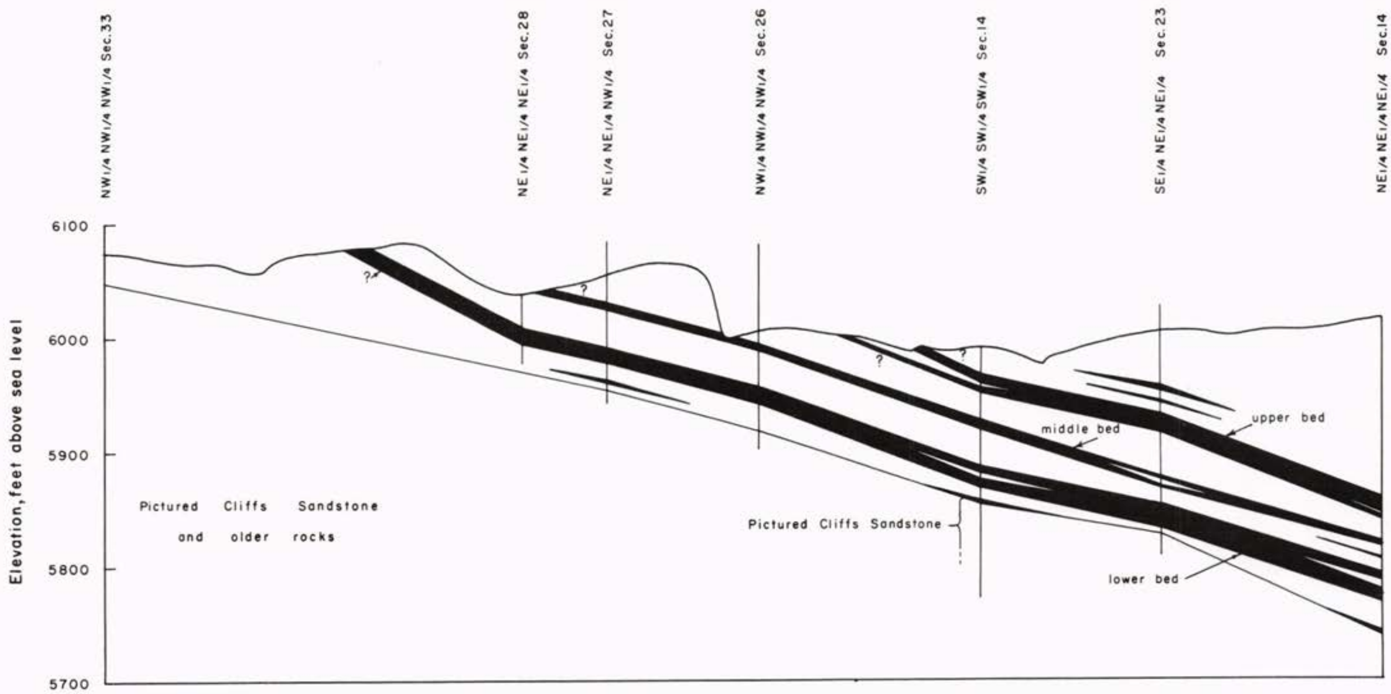

Figure 50

DIAGRAMMATIC CROSS-SECTION OF COAL BEDS IN FRUITLAND FORMATION, T. 23 N., R. 12 W. PLANE OF CROSS-SECTION IS PARALLEL TO DIRECTION OF DIP, AND DATA FOR DRILL HOLES IN SECTIONS 23, 26, AND 27 HAVE BEEN PROJECTED. VERTICAL EXAGGERATION 20X. SEE PLATE 3 FOR LOCATION

on Plate 3 by means of outcrop lines, 1 o-foot, 150-foot, and 250-foot overburden cutoff lines on selected beds, and 3-foot coal thickness cutoff lines. Figure 5o is a representative diagrammatic cross section across one of the richest parts of the area, and illustrates the complexity of the coal distribution.

Similar overburden conditions apply throughout the area. The fluviatile, lagoonal, and nearshore marine origin of the Fruitland Formation resulted in great variation of lithology in short distances, both laterally and vertically, and in a wide range of clastic rock types. The variation is on such a small scale relative to the size of the stripping area, however, that at any point the overall mix of rock types is about the same as at any other. The rocks are predominantly claystone and silty and sandy shale, with lenses of soft irregularly bedded or crossbedded, clayey, fine-grained sandstone.

The topography of the western part of the area is a rugged badland (the Bisti) carved in soft shales and sandstones in the Hunter Wash and De-Na-Zin Wash (Coal Creek) drainages. In R. 12 W. and eastward, the topography is one of gently sloping or rolling plains broken by low, south-facing scarps and broad sandy washes. For the most part, the surface is sandy, but fairly well covered with grass. Access is easy, and except for widely scattered Navajo hogans and a few pipeline and powerline rights-of-way, there are virtually no improvements on any of the acreage underlain by strippable coal.

The Bisti area is rather remote from a transportation standpoint. From Bisti Trading Post to the nearest point on a railroad (in the vicinity of Thoreau) is about 6o miles airline distance (see fig. 2), and distances from other parts of the area would be greater.

DESCRIPTIONS OF

TOWNSHIPS T. 21 N., R. 9 W.

The Fruitland Formation underlies about one-half of the township, in the northeastern part. A bed, likely to be correlative with the bed measured in T. 22 N., R. 9 W., has been measured at four places in section 4 and its thickness is consistent at six feet (Bauer and Reeside, 1921). Applying that thickness as an average and an area derived from the dip, position of the outcrop, and topographic configuration, a reserve of 58.2 million tons can be estimated beneath less than 150 feet of overburden. Perhaps another 6o million tons will lie beneath 15o to 25o feet of overburden. These figures are actually based on far too few data to be considered reliable.

T. 22 N., R. 9 W.

Based upon surface measurements by Bauer and Reeside (1921) and on surface examination during this project, it is very likely that some strippable coal exists in sections 27 through 34. The entire township is underlain by the Fruitland Formation, and a bed 4.3 to 5.o feet thick has been measured some distance above the base of the formation in section 32. Drilling has been done by the permit holder to determine the reserves, but the information has not been made available to the New Mexico State Bureau of Mines.

To arrive at some sort of estimate for this report, an average thickness of four feet was assumed, and the area beneath which the coal might lie at depths less than 150 feet was estimated from the position of the outcrop, the dip, and the configuration of the topography. The amount thus obtained is 22 million tons; the area is shown on Plate 3. There is a likelihood that some reserves exist in the 150- to 250-foot overburden range, but there is little evidence that the bed thickness exceeds five feet. No reserves were estimated.

T. 22 N., R. 10 W.

The Fruitland Formation underlies all but about three square miles in the southwest corner of the township. Reserve estimates were made for the area west of Betonnie Tsosie Wash from three coal tests drilled by permit holders, one test drilled (fig. 51) by the New Mexico State Bureau of Mines (No. 15A), and one oil test, together with data projected into the township from the west. While five data points cannot be considered sufficient for an accurate estimate, the ease of correlation and distribution of control make the estimate seem fairly reliable.

In this township, there is one main coal bed beneath most of the area. Two higher beds, both present and of economic importance in areas farther west, pinch out near the western boundary of T. 22 N., R. 10 W. The exact locations of the pinchouts are not known, but for the sake of conservative reserve estimation, they are placed a mile or less east of the easternmost wells in which the beds appear. A fourth and still higher bed is well developed in the northwest corner of section 18, but appears nowhere else; in all probability it is a split of the uppermost of the three beds described in T. 22 N., R. 11 W.

The reserve estimate for T. 22 N., R. 10 W. is made up of the following components: main bed west of Betonnie Tsosie Wash, additional coal in the upper two beds plus the fourth bed present in section 18, and a small area in sections 25, 26, 35, and 36 which is not represented by drill-hole data. In addition, some coal may exist in the southeastern corner of the township east of Betonnie Tsosie Wash, but there are no data available upon which to base an estimate.

The main bed ranges from 14 to 3o feet in thickness and averages 25 feet in five drill holes. The estimate of reserves was arrived at by contouring the top of the bed, which lies directly upon or just a few feet above the Pictured Cliffs Sandstone, then locating the projected outcrop and the 150-foot and 250-foot overburden cutoffs by intersection with the topographic map. The 25-foot average thickness was applied throughout and yields a reserve of 196.5 million tons beneath 150 feet or less overburden and 167.0 million tons beneath 150 to 25o feet.

The aggregate thickness of minable beds above the main bed west of the pinchout near the western boundary of the township is 29 feet in the northwest corner of section 18 (where the 17-foot upper split or fourth bed is present) and 10 feet in a hole 7,600 feet northwest where the fourth bed is absent. In order to allow for all of the upper coal, a thickness of 29 feet was applied against an arbitrarily chosen area of one square mile to yield a reserve estimate of 34.6 million tons.

The area in sections 25, 26, 35, and 36 is not known to have been explored by drilling, but isolated outcrops and evidence of burning of coal on the outcrop indicate the presence of strippable coal. Outcrop measurements, probably including more than one bed, range from 1.4 feet to 6.8 feet; since outcrops cannot be traced continuously, only a very rough approximation of strippable area can be made. Using a thickness of four feet, a reserve of about three million tons is reasonable.

T. 22 N., R. 11 W.

In this township, three beds are well defined. The lowest lies just above the Pictured Cliffs Sandstone, and is apparently continuous with the main bed described in T. 22 N., R. 10 W. A second bed lies 25 to 4o feet above it, and may be shown by further drilling to be a split of the lower bed. The third bed lies 5o to 10o feet above the second.

Outcrop data, together with two drill-hole logs, have been used to define and evaluate the coal. The lowest bed is present in the northeastern part of the township, in sections through 4 and 10 through 15. Its thickness in a drill hole in the northwest corner of section 12 1s 13 feet and in a drill hole near the west quarter of section 4 is two feet. In sections 10 and 15, outcrop measurements of an apparently correlative bed gave thicknesses of 1.1 to 3.3 feet. For purposes of calculating reserves, an attempt was made to delineate areas in which the thickness is less than three feet and exclude them.

The middle bed is five and four feet thick, respectively, in the drill holes in sections 4 and 12, and 4.5 to 8.5 feet thick in published measured sections in sections 10 and 11. For the reserve calculation, the lower and middle beds were combined and an estimated average combined thickness of 13 feet applied. The combination is arbitrary, and in fact the middle bed seen in drill-hole logs in the western part of T. 23 N., R. 1 W. appears to have closer affinity with (and is probably part of, in one drill hole) the uppermost bed.

The upper bed is nine and six feet thick in the two drill holes, and 3.9 to 8.4 feet thick on the outcrop in sections 3, 10, and 11. An average of eight feet was used in the reserve calculation because of the thickening of the bed farther north in T. 23 N., R. 1 W.

The dip of the beds is slightly less than one degree, based on the available data. It is very likely that the apparently uniform dip is interrupted by structural deformation on a scale too small to be detected with so little control.

The combined lower and middle beds appear to contain about 56.9 million tons to an overburden thickness of 150 feet, and about 43.6 million tons between 150 feet and 25o feet of overburden. The upper bed probably contains about 44.6 million tons beneath less than 150 feet, and about 14.8 million tons between 15o and 25o feet. The estimated total for the township in all categories is 159.9 million tons.

T. 23 N., R. 11 W.

Three coal beds, correlative with those of T. 22 N., R. W. are present beneath almost all of T. 23 N., R. 1I W., and are strippable near the western and southern boundaries (see pl. 3). There is some evidence that the two upper beds merge in at least one area in section 29 (see log of

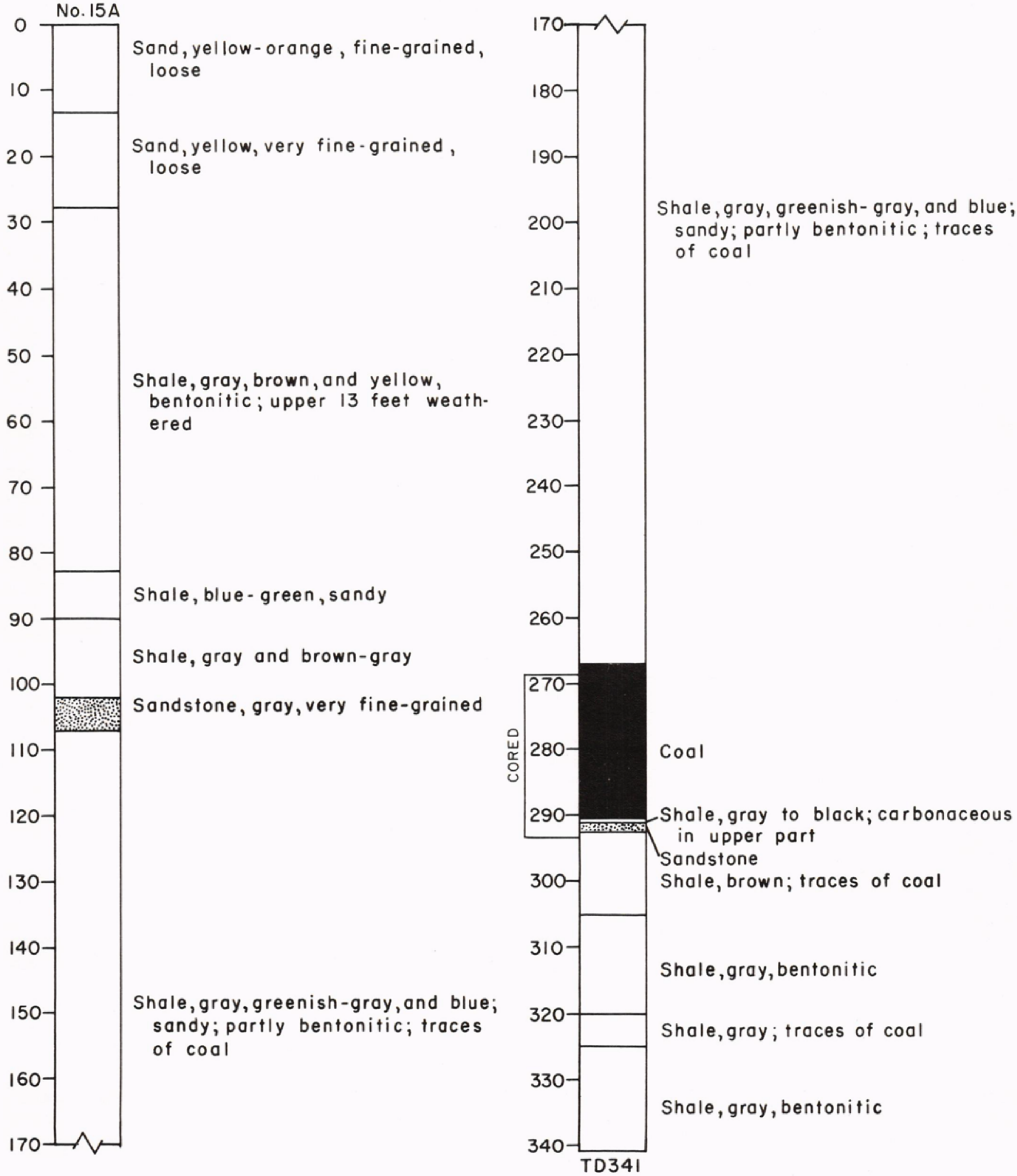

Figure 51

Graphic log of test hole No. 15A, SE¼SE¼SE¼ section 15, T. 22 N., R. 10 W., San Juan Co., N.M.
Logged by R. C. Lease

N.M.S.B.M. test hole No. 12, fig. 52), and that consideration plus the fact that the barren section between them is only 17 to 21 feet thick in the two holes in which it was found, led to combining the two for purposes of reserve calculation. The aggregate thickness is 28 to 47 feet where penetrated. The lower bed, treated separately, ranges from 9 to 15 feet in thickness in four holes (pl. 3), but because of outcrop data a probable area in which it is less than three feet thick was determined and excluded from the calculations.

The upper beds are estimated at 25.8 million tons in the 10- to 150-foot overburden range and 250.0 million tons in the 50- to 250-foot range. The corresponding figures for the lower bed are 18.8 million tons and 52.4 million tons.

T. 23 N., R. 12 W.

The three-bed coal section is clearly developed in this township. The lower bed underlies about 27 square miles including a small area in sections 3 and 4 of T. 22 N., R. 12 W. (see pl. 3) and ranges from 9 to 32 feet in thickness. The bed apparently thickens northeastward from the outcrop to a maximum near the position of the 250-foot overburden cut-off line. The thickness of the middle bed is much less, and in large areas the middle bed is not considered economic either because it is less than three feet thick or because it is split into two beds each less than three feet thick separated by barren rock thicker than either coal. The areas excluded from reserve calculation for these reasons are necessarily arbitrary, but were chosen rather conservatively. The upper bed underlies about half the area underlain by the lower bed, and varies from 0 to 21 feet with the thickest measurements along the east side of the township and the thinnest along the north line. An effort was made, based on the larger number of drill holes (including N.M.S.B.M. test hole No. 13, fig. 53) than in townships discussed previously, to delineate areas for all three beds within which a fairly narrow range of thickness might apply, and to use average thicknesses for these areas in reserve calculations.

The lower bed is estimated to contain 205.2 million tons in the 10- to 150-foot overburden range, and 154.8 million in the 150- to 250-foot range. The middle bed is estimated to contain some 35.4 and 4.0 million tons in the corresponding ranges, but these figures are highly conjectural because of the arbitrary thickness cutoffs. The upper bed is estimated at 114.0 and 32.2 million tons; the latter figure is quite speculative owing to the great thickness variation (3 to 21 feet) involved. If the reserves estimated for T. 23 N., R. 12 W. prove to be nearly correct or conservative, this township will rival the most coal-rich single township in the Navajo Fruitland field, and may well surpass it in terms of coal available at less than 150 feet.

T. 23 N., R. 13 W., and T. 24 N., R. 13 W.

The reserve data for this area were taken from a consultant's report by Edward C. Beaumont for Public Service Coal Co. (Beaumont, 1962). The criteria followed by Beaumont were slightly different from those outlined for the present study, but not sufficiently different to warrant a complete recalculation from the original data. The tonnage figures in Beaumont's report apply to all coal in three beds (correlative with those of T. 23 N., R. 12 W.) beneath an overburden thickness less than that represented by 160 feet of overburden on the lowest bed. Coal under less than ten feet of cover is excluded, as is that in beds less than three feet thick. Partings thinner than eight inches were considered coal; those thicker than eight inches were excluded. For the present report, a projection of drill-hole data (thickness trends and structure contours on the top of the upper bed) was used to estimate coal beneath between 160 and 250 feet of overburden. A combined coal thickness of 21.3 feet, the average for the 0- to 160-foot range, was applied.

Thus, several simplifying assumptions were made; the outcome, however, is probably as close to the truth as is possible without additional drilling.

For the shallower reserve category, considered about equivalent to the 10- to 150-foot normally used in the CLEANAIR tabulations, a reserve of 142.6 million tons is estimated. For the deeper category, a reserve of 133.0 million tons is projected.

In addition to the area included in the Public Service Co. of New Mexico's report, an outlier of Fruitland Formation lies in sections 20 through 29, 35, and 36 (see fig. 49). It contains at least three beds of coal, according to measurements made by Bauer and Reeside (1921); one of the beds reaches a thickness of over six feet. The measurements do indicate, however, that all three beds are extremely lenticular, and though overburden thicknesses are generally less than 50 feet it is not likely that significant strippable reserves exist. No drilling data are available to indicate the thickness trends away from the outcrop, and for that reason the area is shown on Plate 3 as a marginal prospect pending results of further exploratory work.

TABLE 10. SUMMARY OF STRIPPABLE-COAL RESERVES IN BISTI FRUITLAND AREA

Township T. N.	R. W.	Measured, indicated, and inferred reserves, millions of tons: Overburden 10-150 feet	Overburden 150-250 feet
21	9	58.2	60.0
22	9	22.0	?
22	10	234.0	167.0
22	11	101.5	58.4
23	11	44.6	302.4
23	12	354.6	191.0
23	13	143.0*	133.0*
24	13		
		957.9	911.8

* Computed on a slightly different basis. See text.

COAL QUALITY

The Bisti Fruitland coal is of subbituminous A rank, and is presumed to be nonagglomerating as are the Fruitland coals further west and north. Twenty selected representative analyses are shown in Table 11, and as-received heating value and ash content are shown for 64 additional samples on Figure 54. In both Table 1 and Figure 54, data are presented as furnished by the individual or concern for whom the samples were analyzed, and except for the three

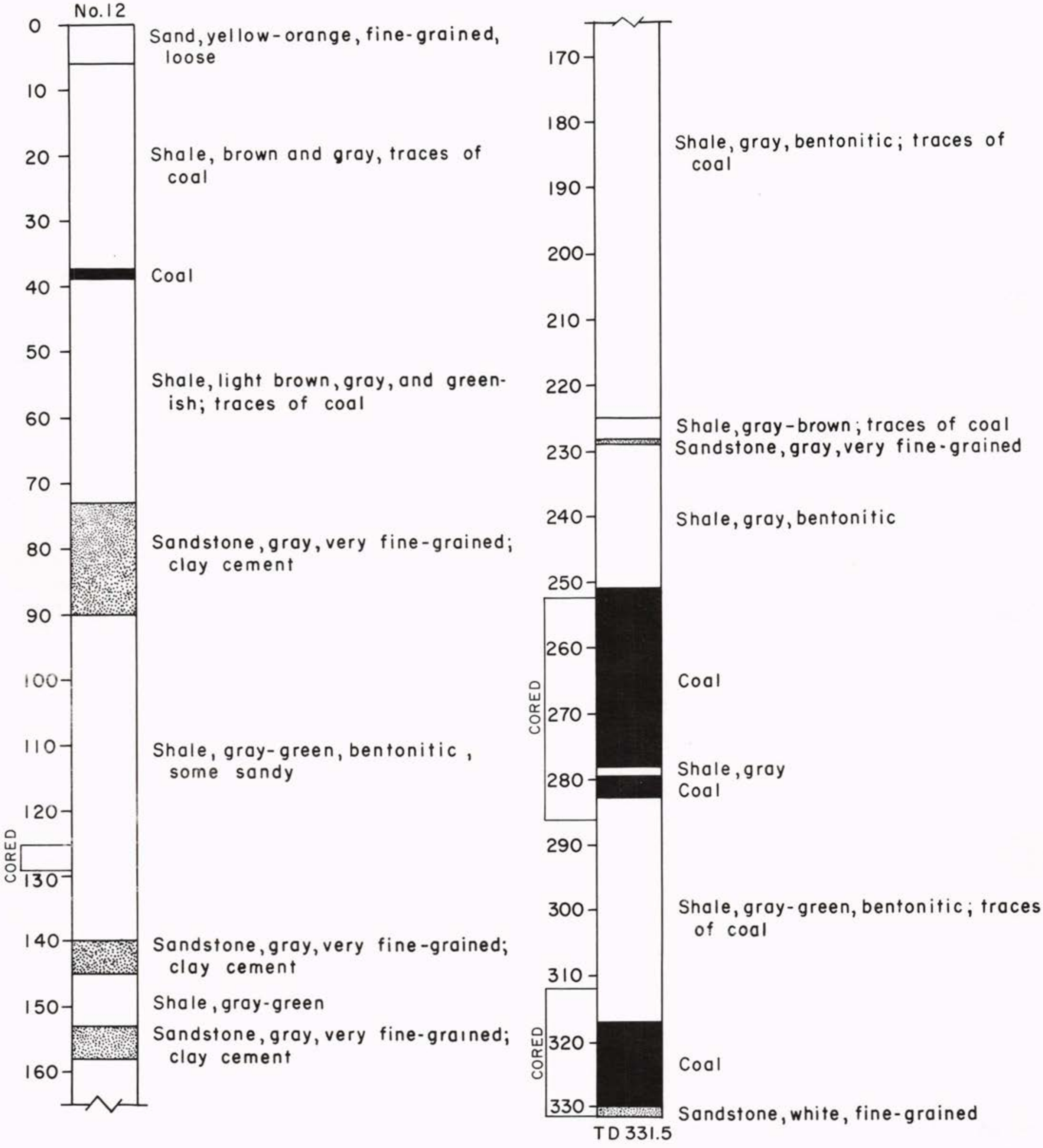

Figure 52

Graphic log of test hole No. 12, NW¼SE¼NE¼ section 29, T. 23 N., R. 11 W., San Juan Co., N.M. Logged by R. C. Lease

test holes drilled by the New Mexico State Bureau of Mines and Mineral Resources, do not represent original sampling work by the Bureau. Thus, no comment about their reliability can be made.

For a given moisture content, heating value and ash content are almost directly proportional. It is also apparent from Figure 54 that ash content is extremely variable; the lowest value noted was 8.5 percent and the highest was 35.14 per-

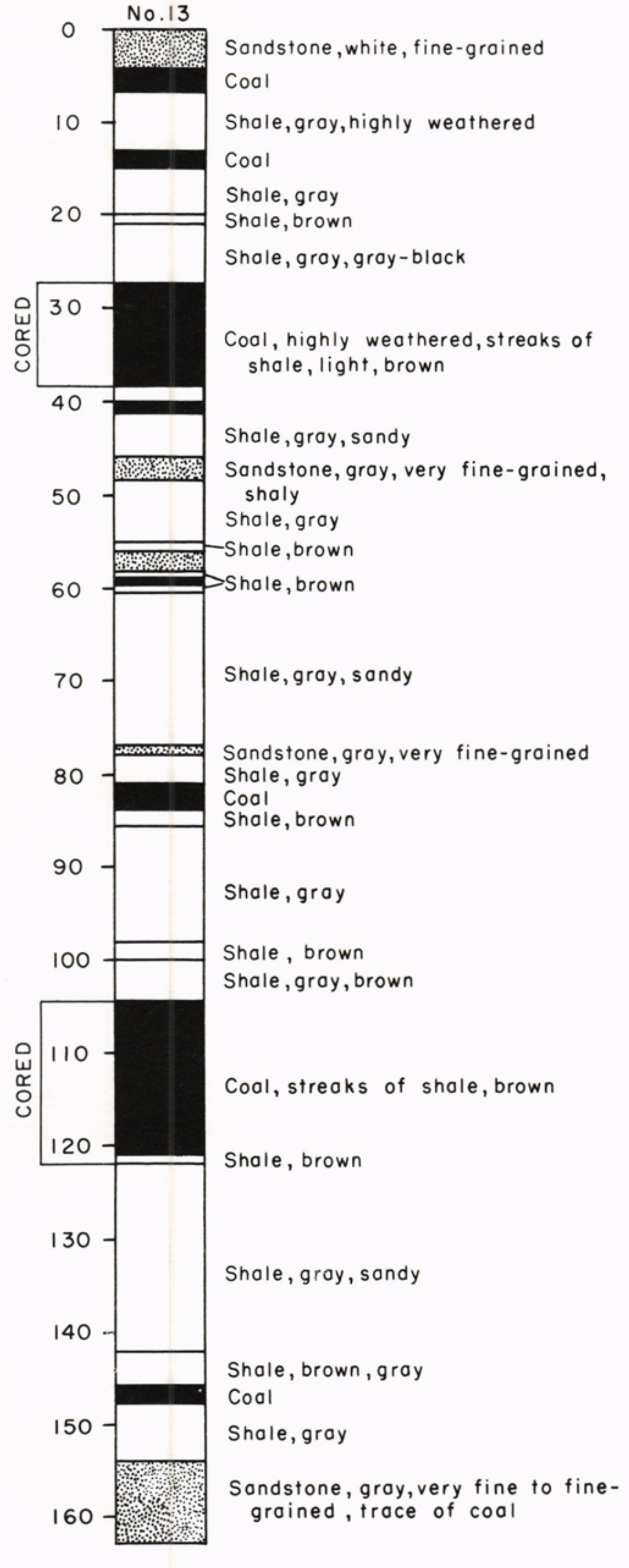

Figure 53

Graphic log of test hole No. 13, SW¼NE¼NE¼ section 27, T. 23 N., R. 12 W., San Juan Co., N.M. Logged by R. C. Lease

cent. The average ash content of all samples considered was 18.5 percent.

Most of the analyses (all but one of those containing more than ten percent moisture) are from core samples; most samples which contained less than ten percent moisture were from washed drill-cuttings samples. Although there is no more direct evidence to support the conclusion, it would seem likely that the most nearly representative range of moisture-content values would be 13 to 16 percent. From this it would follow that the practical range in heating value is 7,500 to 10,000 Btu per pound, with an average near 8,850 Btu per pound. The, moist, mineral-matter-free heating value averages 10,870 Btu per pound for the coals containing more than ten percent moisture (Beaumont, 1962).

The ash content is present as thin partings or intimately mingled with the coal itself, and thus would not be extractable during mining. Washability studies by the U.S. Bureau of Mines (see section entitled "Drilling and Washability Testing") indicate that, in general, the coal could be substantially upgraded by washing in a dense-medium washing device. Yields at a specific gravity separation of 1.50 (or in one case, 1.60) are 73.6 to 89.7 percent of the original sample, and contain 9.4 to 11.8 percent ash. The heating values of these washed products ranged from 11,248 to 12,364 Btu per pound.

Sulfur content ranges between 0.4 and 0.9 percent, and averages about 0.6 percent. Of total sulfur content, 7 to 30 percent is "pyritic"; it occurs principally in the form of the iron sulfide marcasite, which is distributed as a very fine crystalline aggregrate in thin, mostly vertical veinlets. Most of the remainder of the sulfur is in organic material intimately mixed in the coal.

Volatile matter content ranges between 16.4 and 31.8 percent, and averages 24.9 percent. Only four determinations out of 65 indicated less than 22.0 percent. Fixed carbon ranges between 30.3 and 50.8 percent and averages 39.8 percent in 65 determinations.

Ash-fusion analyses are available for 63 samples in Range 13 W., and for one sample each in T. 23 N., R. 12 W., and T. 22 N., R. 10 W. Initial softening temperatures range from 2,185°F to values in excess of 2,800°F, and most are 2,500°F or more. Almost all fluid temperatures are 2,700°F or more.

STAR LAKE FRUITLAND AREA

by John W. Shomaker and Robin C. Lease

The Star Lake area (fig. 55) includes all potentially strippable coal resources in the Fruitland Formation east of the eastern edge of R. 9 W. (the eastern boundary of the Bisti Kf area). Physiographically, the Star Lake area is similar to the Fruitland Formation terrain farther west, being characterized by generally gentle relief, with low southward-facing cuestas broken by broad sandy arroyos. The area is almost utterly barren except for sparse grass cover, and, aside from an occasional dwelling, trading post, or petroleum-pipeline facility, there is little to prevent strip mining wherever the coal is suitable.

The Fruitland Formation is comprised largely of soft, gray and brown shales, and soft white, fine-grained sand-

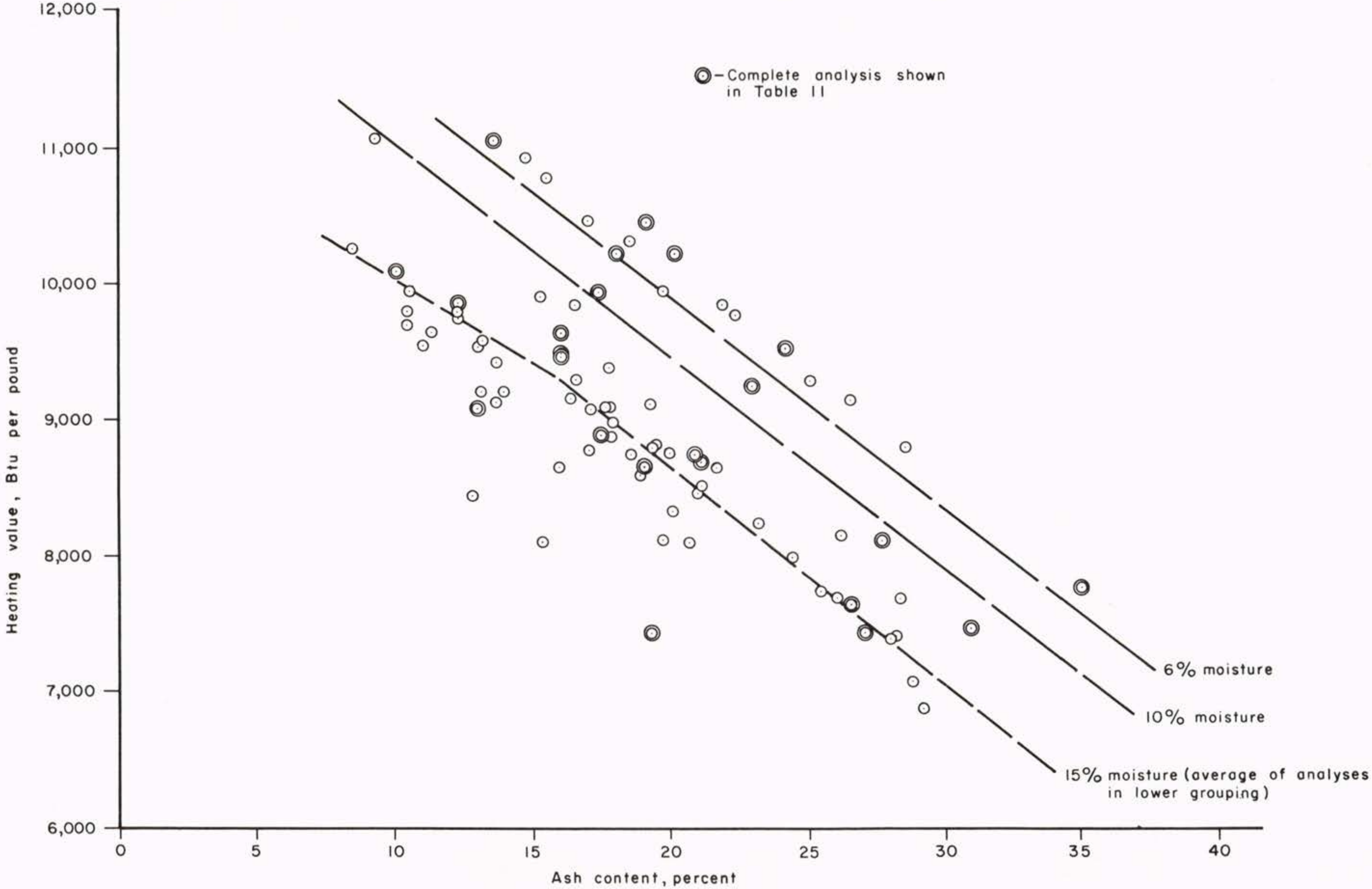

Figure 54

GRAPH SHOWING RELATIONSHIP OF HEATING VALUE, ASH CONTENT, AND MOISTURE CONTENT OF COAL FROM BISTI FRUITLAND AREA ON AS-RECEIVED BASIS

TABLE 11. REPRESENTATIVE ANALYSES OF COAL SAMPLES FROM BISTI FRUITLAND AREA.

LOCATION	KIND OF SAMPLE	PROXIMATE, PERCENT: CONDITION[1]	SAMPLE NO.	LABORATORY NUMBER[3]	MOISTURE	VOLATILE MATTER	FIXED CARBON	ASH	ULTIMATE, PERCENT: HYDROGEN	CARBON	NITROGEN	OXYGEN	SULFUR	HEATING VALUE: BRITISH THERMAL UNITS PER POUND	FUSIBILITY OF ASH, °F: INITIAL DEFORMATION TEMP.	SOFTENING TEMP.	FLUID TEMP.
NW¼ NW¼ NW¼ Sec. 5,	drill cuttings	1	29	—	4.52	—	—	13.65	—	—	—	—	0.59	11,035	—	—	—
T. 22 N., R. 10 W.		2	—	—	—	—	—	14.30	—	—	—	—	0.62	11,577	—	—	—
		3	—	—	—	—	—	—	—	—	—	—	—	13,485	—	—	—
SE¼ SE¼ SE¼ Sec. 9,	drill cuttings	1	34	—	9.28	29.26	38.42	23.04	—	—	—	—	0.54	9,240	2,420	2,720	2,720+
T. 22 N., R. 10 W.		2	—	—	—	32.25	42.35	25.40	—	—	—	—	0.60	10,185	—	—	—
		3	—	—	—	—	—	—	—	—	—	—	—	13,653	—	—	—
NE¼ NE ¼ NE¼ Sec. 15,	core sample	1	15-A	J-63526	12.4	33.9	37.6	16.1	5.6	54.7	1.0	22.1	0.49	9,630	2,910+	—	—
T. 22 N., R. 10 W.		2	—	—	—	38.7	42.9	18.4	4.8	62.4	1.1	12.7	0.56	10,990	—	—	—
		3	—	—	—	47.5	52.5	—	5.9	76.4	1.3	15.7	0.68	13,470	—	—	—
NE¼ NW¼ NW¼ Sec. 12,	drill cuttings[2]	1	27	—	5.01	—	—	35.14	—	—	—	—	0.44	7,740	—	—	—
T. 22 N., R. 11 W.	104 to 110 feet	2	—	—	—	—	—	36.99	—	—	—	—	0.46	8,148	—	—	—
		3	—	—	—	—	—	—	—	—	—	—	—	12,931	—	—	—
NE¼ NW¼ NW¼ Sec. 12,	drill cuttings	1	—	—	5.42	—	—	19.41	—	—	—	—	0.66	10,427	—	—	—
T. 22 N., R. 11 W.	155 to 159 feet	2	—	—	—	—	—	20.52	—	—	—	—	0.70	10,835	—	—	—
		3	—	—	—	—	—	—	—	—	—	—	—	13,634	—	—	—
NE¼ SE¼ NE¼ Sec. 29,	core sample	1	12-A	J-63220	12.7	31.9	34.3	21.2	5.3	49.5	0.9	22.9	0.3	8,680	—	—	—
T. 23 N., R. 11 W.		2	—	—	—	36.5	39.3	24.2	4.6	56.7	1.1	13.0	0.4	9,940	—	—	—
		3	—	—	—	48.2	51.8	—	6.1	74.8	1.4	17.2	0.5	13,120	—	—	—
NE¼ SE¼ NE¼ Sec. 29,	core sample	1	12-B	J-61645	14.6	30.8	38.6	16.0	5.7	54.4	1.1	22.5	0.34	9,440	2,910+	—	—
T. 23 N., R. 11 W.		2	—	—	—	36.1	45.2	18.7	4.7	63.6	1.2	11.4	0.40	11,050	—	—	—
		3	—	—	—	44.4	55.6	—	5.0	78.3	1.5	13.9	0.49	13,600	—	—	—
SE¼ NE¼ SW¼ Sec. 9,	drill cuttings	1	21-A	—	5.28	—	—	18.09	—	—	—	—	0.59	10,206	—	—	—
T. 23 N., R. 12 W.		2	—	—	—	—	—	19.10	—	—	—	—	0.62	10,775	—	—	—
		3	—	—	—	—	—	—	—	—	—	—	—	13,319	—	—	—
NE¼ NE¼ NE¼ Sec. 10,	core sample	1	23	—	9.39	30.11	43.10	17.41	—	—	—	—	0.72	9,915	2,505	2,720+	2,720+
T. 23 N., R. 12 W.		2	—	—	—	33.23	47.56	19.21	—	—	—	—	0.79	10,942	—	—	—
		3	—	—	—	—	—	—	—	—	—	—	—	13,544	—	—	—
SE¼ NW¼ SE¼ Sec. 1,	core, 80′-87′	1	14	—	15.4	24.8	40.7	19.1	4.4	46.4	1.07	28.4	0.64	8,652	2,410	2,500	2,760
T. 23 N., R. 13 W.		2	—	—	—	29.3	48.1	22.6	5.2	54.8	1.26	15.4	0.76	10,227	—	—	—
SE¼ NW¼ SE¼ Sec. 1,	core, 97′-116′	1	15	—	15.8	22.2	35.4	26.6	2.9	42.3	0.88	26.8	0.48	7,630	2,800	2,800	2,800
T. 23 N., R. 13 W.		2	—	—	—	26.4	42.0	31.6	3.4	50.2	1.04	13.2	0.57	9,062	—	—	—
SE¼ NW¼ SE¼ Sec. 1,	core, 192′-209′	1	1	—	13.0	23.5	36.4	27.1	3.7	43.5	0.5	22.8	0.6	7,410	2,800	2,800	2,800
T. 23 N., R. 13 W.		2	—	—	—	27.0	41.8	31.2	4.3	52.1	0.6	11.1	0.7	8,520	—	—	—
SW¼ SW¼ SW¼ Sec. 4,	core, 33′-40′	1	53	—	17.6	20.7	34.0	27.7	4.1	44.6	0.12	21.8	0.71	8,098	2,650	2,690	2,800
T. 23 N., R. 13 W.		2	—	—	—	25.1	41.3	33.6	5.0	54.1	0.15	7.2	0.86	9,828	—	—	—
SW¼ SW¼ SW¼ Sec. 4,	core, 132′-140′	1	54	—	16.4	27.8	45.7	10.1	3.2	58.6	0.05	27.3	0.70	10,075	2,185	2,225	2,540
T. 23 N., R. 13 W.		2	—	—	—	33.2	54.7	12.1	3.8	70.1	0.06	13.1	0.84	12,051	—	—	—
SW¼ NE¼ SW¼ Sec. 8,	core, 72′-81′	1	63	—	13.2	26.0	47.8	12.3	6.8	55.9	0.49	23.9	0.63	9,851	2,580	2,640	2,730
T. 23 N., R. 13 W.		2	—	—	—	30.2	55.5	14.3	7.8	64.4	0.57	12.2	0.73	11,349	—	—	—
SE¼ SW¼ NW¼ Sec. 11,	core, 80′-95′	1	3	—	10.3	23.3	35.6	30.8	4.4	42.3	0.2	21.6	0.7	7,436	2,800+	2,800+	2,800+
T. 23 N., R. 13 W.		2	—	—	—	26.0	39.7	34.3	4.9	47.9	0.2	12.0	0.7	8,290	—	—	—
SE¼ SW¼ NW¼ Sec. 11,	core, 105′-108′	1	4	—	14.5	20.9	43.8	20.8	4.8	52.4	0.3	20.9	0.8	8,721	2,800+	2,800+	2,800+
T. 23 N., R. 13 W.		2	—	—	—	24.5	51.2	24.3	5.0	61.3	0.3	8.3	0.8	10,200	—	—	—
SE¼ SW¼ NW¼ Sec. 11,	core, 147′-163′	1	5	—	14.9	24.4	44.5	16.1	3.5	54.4	1.0	24.4	0.6	9,470	2,800+	2,800+	2,800+
T. 23 N., R. 13 W.		2	—	—	—	28.7	52.4	18.9	4.1	63.9	1.2	11.2	0.7	11,140	—	—	—
SW¼ NE¼ SE¼ Sec. 32,	core, 17′-21′	1	28	—	14.4	31.8	40.7	13.1	4.7	48.1	1.14	32.4	0.58	9,067	2,535	2,600	2,800
T. 24 N., R. 13 W.		2	—	—	—	37.1	47.6	15.3	5.5	56.2	1.33	21.0	0.68	10,592	—	—	—
NW¼ SW¼ SW¼ Sec. 17,	drill cuttings	1	19	—	5.39	—	—	24.23	—	—	—	—	0.46	9,497	—	—	—
T. 23 N., R. 12 W.		2	—	—	—	—	—	25.61	—	—	—	—	0.49	10,038	—	—	—
		3	—	—	—	—	—	—	—	—	—	—	—	13,494	—	—	—
SW¼ NE¼ SE¼ Sec. 25,	drill cuttings	1	7	—	4.98	—	—	20.21	—	—	—	—	0.57	10,222	—	—	—
T. 23 N., R. 12 W.		2	—	—	—	—	—	21.27	—	—	—	—	0.60	10,758	—	—	—
		3	—	—	—	—	—	—	—	—	—	—	—	13,664	—	—	—
SW¼ NE¼ SE¼ Sec. 27,	core sample	1	13-A	J-62865	19.4	29.4	31.9	19.3	5.3	44.1	0.9	29.9	0.5	7,420	2,910+	—	—
T. 23 N., R. 12 W.		2	—	—	—	36.5	39.5	24.0	3.9	54.7	1.1	15.7	0.6	9,210	—	—	—
		3	—	—	—	48.0	52.0	—	5.2	72.0	1.5	20.5	0.8	12,110	—	—	—
SW¼ NE¼ SW¼ Sec. 27,	core sample	1	13-B	J-62275	16.6	29.3	36.5	17.6	5.5	50.8	1.0	24.7	0.46	8,880	—	—	—
T. 23 N., R. 12 W.		2	—	—	—	35.2	43.7	21.1	4.4	60.9	1.2	11.9	0.53	10,640	2,910+	—	—
		3	—	—	—	44.6	55.4	—	5.5	77.1	1.5	15.2	0.68	13,480	—	—	—

[1] Condition: 1, as-received; 2, moisture-free; 3, moisture- and ash-free.
[2] May be weathered sample.
[3] Laboratory number indicates analyses by U. S. Bureau of Mines.

stone, with coal. All of the beds are irregular as to thickness, and few can be traced more than a mile or two without significant change in thickness, or lithologic makeup. Shale and coal content diminish toward the eastern end of the area, and the increasingly sandy formation thins to disappearance in the vicinity of Cuba. The coals reach thicknesses of at least 15.9 feet (New Mexico State Bureau of Mines and Mineral Resources test hole No. 11 penetrated two coal beds, one 13 and the other 15.9 feet thick). Typically, the coals contain a great many thin partings (fig. 56).

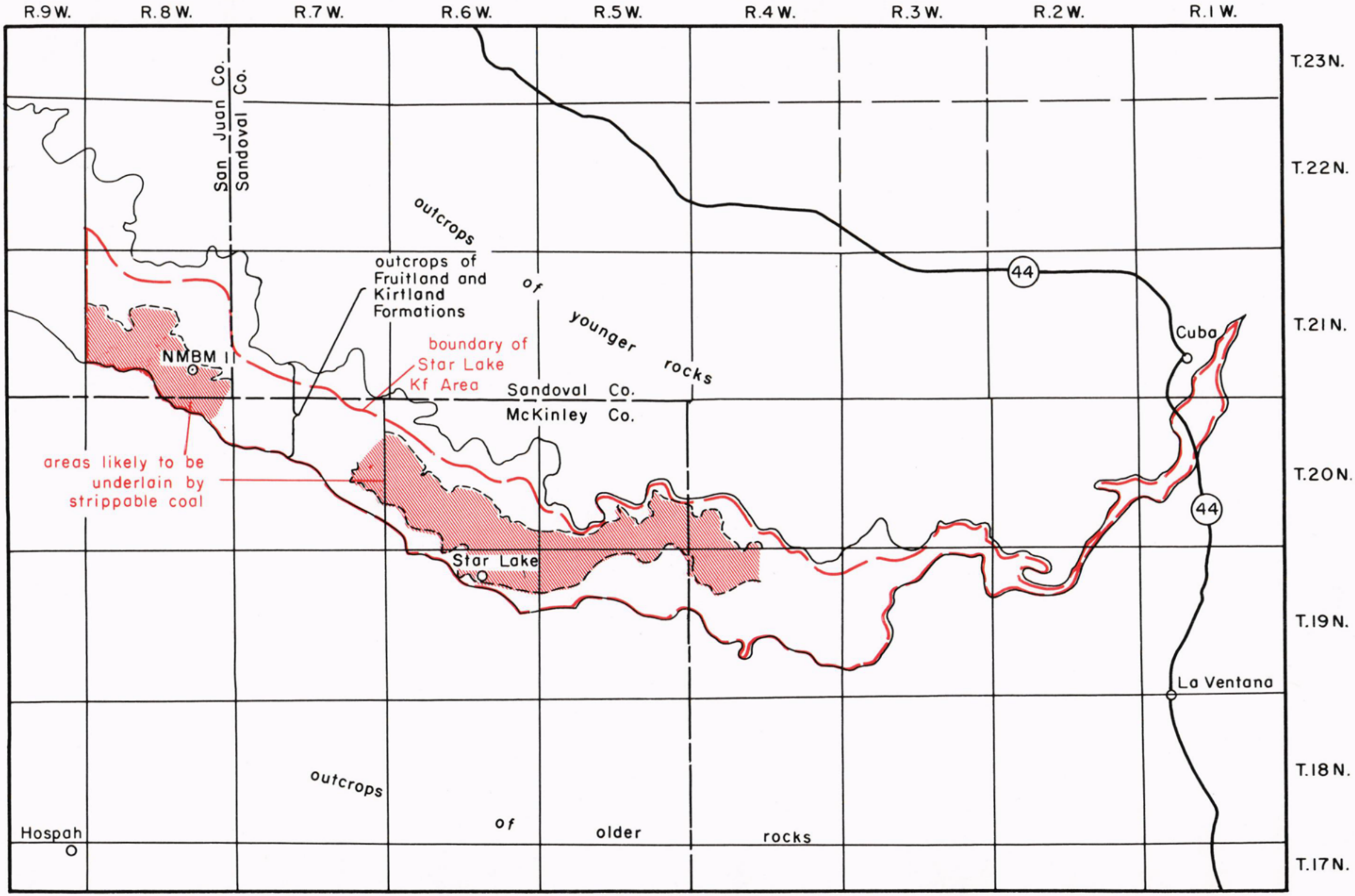

Figure 55

INDEX MAP SHOWING LOCATION OF STAR LAKE FRUITLAND AREA AND AREAS LIKELY TO BE UNDERLAIN BY STRIPPABLE COAL

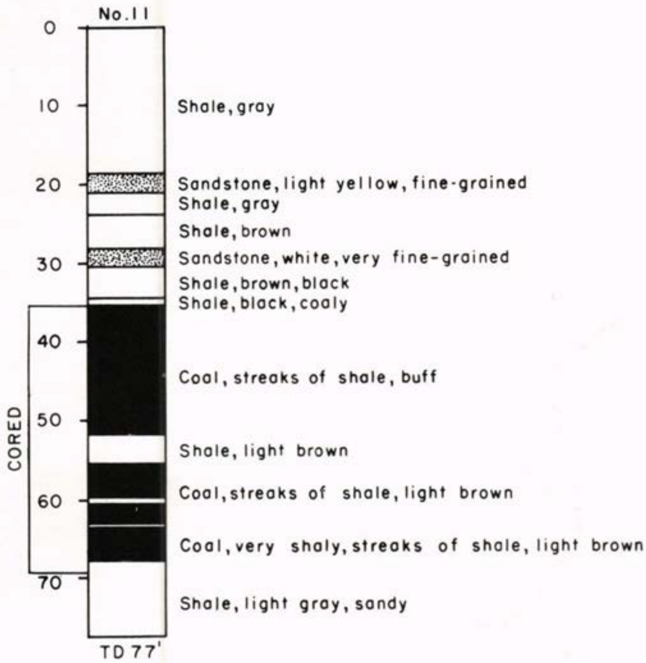

Figure 56

GRAPHIC LOG OF TEST HOLE No. 11, NE¼SW¼SW¼ SECTION 26, T. 21 N., R. 8 W., SAN JUAN CO., N.M. LOGGED BY R. C. LEASE

COAL RESERVES

The Star Lake area is the most recently explored part of the Fruitland Formation coal belt, and only fragmentary information is available from the permit and lease holders. Almost no drilling data were released, and tonnage figures that were released are very generalized. The reserve estimates in this report are thus based upon oil and gas test logs (confined almost entirely to R. 8 W.), reserve totals based on drilling by a lessee in T. 19 N., R. 5 W., a single test hole (No. 11, see fig. 56) drilled by the New Mexico State Bureau of Mines and Mineral Resources, consulting reports prepared for Public Service Co. of New Mexico (Beaumont, 1960a; Beaumont, 1960b), and miscellaneous published geologic reports (Dane, 1936; and Hinds, 1966). Unfortunately, since all of the information taken together is still insufficient for an accurate calculation of reserve, the total given is only a speculation. The intent, however, is to give a conservative estimate and it is hoped that further work by developers of these deposits will reveal more coal than has been estimated.

It seems likely that about 385 million tons lie beneath less than 250 feet of overburden in the general vicinity of Star Lake, including the west half of R. 4 W. and all of Ranges 5 W. and 6 W. Of that amount, perhaps 245 million tons are present beneath less than 150 feet of overburden. Through the use of a few oil and gas tests, an estimate of 120 million tons to 150 feet of overburden, and perhaps an additional 130 million tons between 150 feet and 250 feet, has been made for R. 8 W. Virtually no data are available for R. 7 W., and such surface mapping as is available for the part of the area east of the center of R. 4 W. seems to indicate that no important reserves exist there. Thus the aggregate estimate is about 635 million tons to a depth of 250 feet.

Overburden consists of alternate beds of soft shale and sandstone. The sandstone beds are commonly only a few feet thick and should present little difficulty in stripping.

COAL QUALITY

The rank of Star Lake coals for which analyses are available (see table 12) is near the borderline between subbituminous A and high-volatile bituminous C. The rank, based on moist, mineral-matter-free coal, was determined from Figure 57 by extrapolation of the heating value-ash content relationship and ignoring sulfur content (seldom as much as 0.7 percent). At the most nearly representative moisture content in analyses available, on the order of 10.7 to 11.5 percent, the moist, mineral-matter-free heating value was determined as 12,170 Btu per pound, well above the 11,500 Btu lower limit of the high-volatile C bituminous category. The two equilibrium moisture determinations for New Mexico State Bureau of Mines and Mineral Resources test hole No. 11 indicate moisture contents of 13.45 and 13.77 percent, however (table 12), and the corresponding moist, mineral-matter-free heating value is 11,530 Btu, or almost exactly the same as the lower limit. Thus it would appear that the rank is near the borderline for nonagglomerating coals.

The most pronounced grouping of analytical results is in the range of 9,400 to 10,200 Btu per pound and 15 to 20 percent ash; sulfur content is most commonly 0.4 to 0.7 percent. Ash-fusion temperatures are quite high (table 12). Results of washability testing of samples from New Mexico State Bureau of Mines test hole No. 1 are in the section entitled "Drilling and Washability Testing."

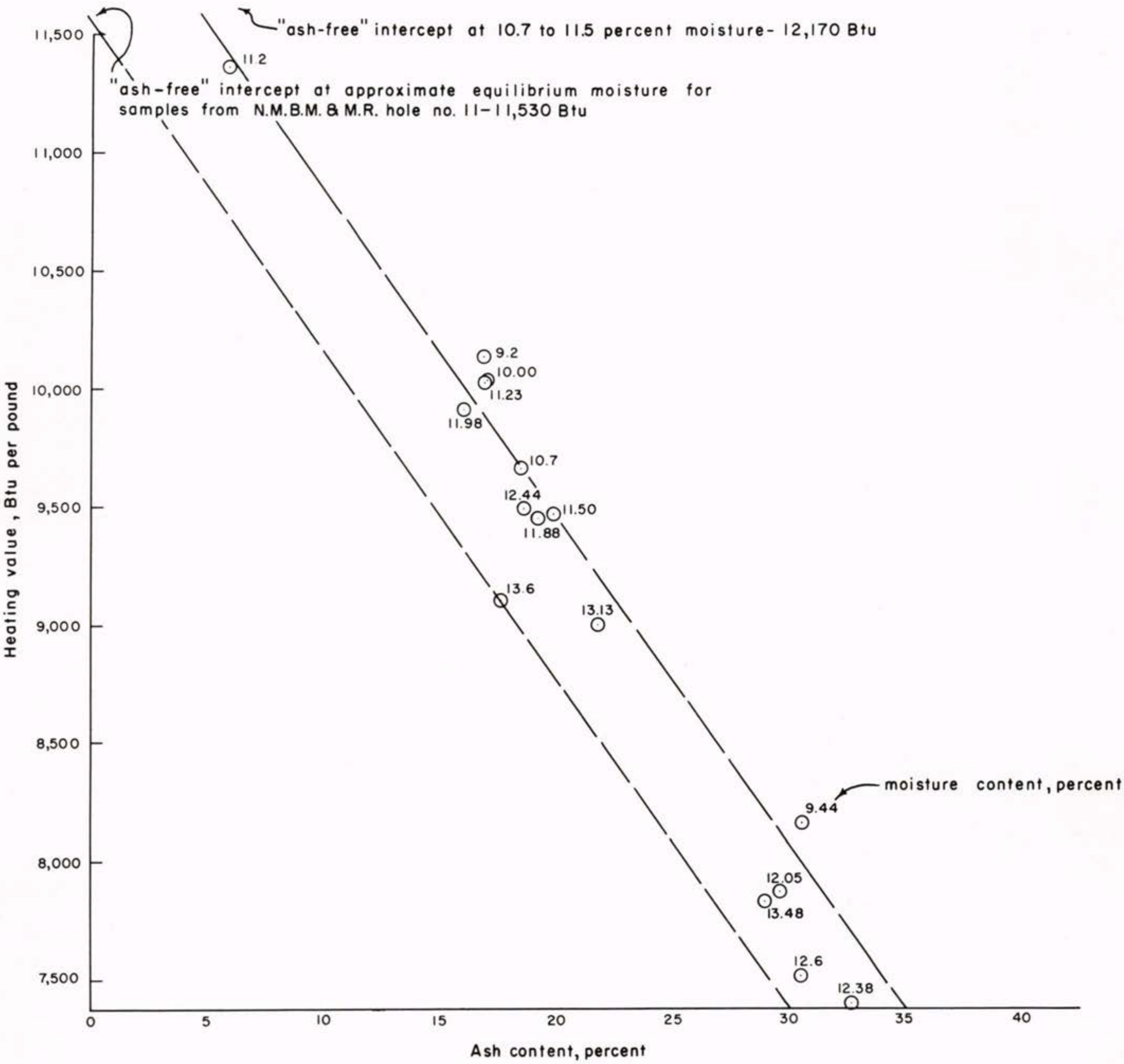

Figure 57

Graph showing heating value, ash content, and moisture content of coals, Star Lake Fruitland area

TABLE 12. ANALYSES OF COAL SAMPLES FROM STAR LAKE FRUITLAND AREA

LOCATION	KIND OF SAMPLE	CONDITION[1]	SAMPLE NO.	PROXIMATE, PERCENT: LABORATORY NUMBER	MOISTURE	VOLATILE MATTER	FIXED CARBON	ASH	ULTIMATE, PERCENT: HYDROGEN	CARBON	NITROGEN	OXYGEN	SULFUR	HEATING VALUE: BRITISH THERMAL UNITS PER POUND	FUSIBILITY OF ASH, °F: INITIAL DEFORMATION TEMP.	SOFTENING TEMP.	FLUID TEMP.	REMARKS
T. 19 N., R. 3 W.	core sample	1	—	TH-55298	9.44	27.40	32.67	30.49	—	—	—	—	0.57	8,161	2750+	2750+	2750+	Analysis by Commercial Testing and Eng. Co.
		2	—	—	—	30.26	36.07	33.67	—	—	—	—	0.63	9,012	—	—	—	
T. 19 N., R. 4 W.	core sample	1	—	TH-55672	11.50	36.57	32.07	19.86	—	—	—	—	0.67	9,473	—	—	—	Analysis by Commercial Testing and Eng. Co.
		2	—	—	—	41.32	36.24	22.44	—	—	—	—	0.76	10,704	—	—	—	
T. 19 N., R. 5 W.	core sample	1	—	TH-57167	13.13	32.63	32.46	21.75	—	—	—	—	0.49	9,003	2750+	2750+	2750+	Analysis by Commercial Testing and Eng. Co. Equilibrium moisture—13.06%, grindability—50.1.
		2	—	—	—	37.56	37.37	25.07	—	—	—	—	0.56	10,364	—	—	—	
T. 19 N., R. 5 W.	core sample	1	—	TH-57168	12.05	30.39	27.96	29.60	—	—	—	—	0.59	7,870	2750+	2750+	2750+	Analysis by Commercial Testing and Eng. Co. Equilibrium moisture—12.47%, grindability—56.7.
		2	—	—	—	34.55	31.79	33.66	—	—	—	—	0.67	8,948	—	—	—	
T. 19 N., R. 5 W.	cuttings sample	1	—	TH-57166	13.48	29.55	28.05	28.92	—	—	—	—	0.50	7,829	2750+	2750+	2750	Analysis by Commercial Testing and Eng. Co.
		2	—	—	—	34.15	32.42	33.43	—	—	—	—	0.58	9,049	—	—	—	
T. 19 N., R. 6 W.	cuttings sample	1	—	TH-54419	12.38	28.21	26.73	32.68	—	—	—	—	0.46	7,393	2655	2700+	2700+	Analysis by Commercial Testing and Eng. Co. Equilibrium moisture—13.42% weighted average of 2 analyses.
		2	—	—	—	32.20	30.51	37.29	—	—	—	—	0.52	8,438	—	—	—	
T. 19 N., R. 6 W.	cuttings sample	1	—	TH-54321	11.88	35.58	33.37	19.17	—	—	—	—	0.40	9,455	2700+	2700+	2700+	Analysis by Commercial Testing and Eng. Co. Equilibrium moisture—12.82%, grindability 52.4.
		2	—	—	—	40.37	37.87	21.76	—	—	—	—	0.45	10,730	—	—	—	
T. 19 N., R. 6 W.	core sample	1	—	TH-53401	11.98	35.63	36.43	15.96	—	—	—	—	0.48	9,915	2700+	—	—	Analysis by Commercial Testing and Eng. Co.
		2	—	—	—	40.48	41.39	18.13	—	—	—	—	0.55	11,265	—	—	—	
T. 19 N., R. 6 W.	core sample	1	—	C-14106	9.2	34.5	39.5	16.8	—	—	—	—	0.57	10,141	—	—	—	Analysis by Illinois Geological Survey.
		2	—	—	—	38.0	43.5	18.5	—	—	—	—	0.63	11,168	—	—	—	
		3	—	—	—	46.7	53.3	—	—	—	—	—	0.77	13,701	—	—	—	
T. 19 N., R. 6 W.	core sample	1	—	TH-53399	11.23	35.86	36.05	16.86	—	—	—	—	0.49	10,030	2250	2700+	—	Analysis by Commercial Testing and Eng. Co. Equilibrium moisture—13.46%, grindability—45.4.
		2	—	—	—	40.40	40.61	18.99	—	—	—	—	0.55	11,299	—	—	—	
T. 19 N., R. 6 W.	core sample	1	—	C-14107	10.00	34.3	38.8	16.9	—	—	—	—	0.57	10,042	—	—	—	Analysis by Illinois State Geological Survey.
		2	—	—	—	38.1	43.1	18.8	—	—	—	—	0.63	11,163	—	—	—	
		3	—	—	—	46.9	53.1	—	—	—	—	—	0.77	13,738	—	—	—	
NW¼ Sec. 11 T. 19 N., R. 6 W.	outcrop sample	1	—	A-23141	11.2	40.0	43.0	5.8	5.9	64.2	1.3	22.3	0.5	11,360	—	—	—	Analysis by U.S. Bureau of Mines.
		2	—	—	—	45.1	48.4	6.5	5.3	72.3	1.4	14.0	0.5	12,800	—	—	—	
		3	—	—	—	48.2	51.8	—	5.6	77.3	1.5	15.0	0.6	13,690	—	—	—	
T. 20 N., R. 6 W.	core sample	1	—	TH-53400	12.44	34.95	34.05	18.56	—	—	—	—	0.56	9,499	2220	2700+	—	Analysis by Commercial Testing and Eng. Co.
		2	—	—	—	39.91	38.89	21.20	—	—	—	—	0.64	10,848	—	—	—	
T. 20 N., R. 6 W.	core sample	1	—	C-14108	10.7	33.4	37.5	18.4	—	—	—	—	0.65	9,667	—	—	—	Analysis by Illinois Geological Survey.
		2	—	—	—	37.4	42.0	20.6	—	—	—	—	0.72	10,826	—	—	—	
		3	—	—	—	47.1	52.9	—	—	—	—	—	0.91	13,637	—	—	—	
NE¼ SW¼ SW¼ Sec. 26,[2] T. 21 N., R. 8 W.	core sample	1	11-A	J-62557	13.6	33.4	35.4	17.6	5.5	52.5	1.0	22.9	0.53	9,110	2910+	—	—	Analysis by U.S. Bureau of Mines. Equilibrium moisture—13.77%, grindability index—55, free-swelling index—noncaking. Top size—⅜"x 0. Pyritic sulfur—0.10%.
		2	—	—	—	38.6	41.0	20.4	4.6	60.8	1.1	12.5	0.62	10,540	—	—	—	
		3	—	—	—	48.5	51.5	—	5.7	76.4	1.4	15.7	0.77	13,240	—	—	—	
NE¼ SW¼ SW¼ Sec. 26,[2] T. 21 N., R. 8 W.	core sample	1	11-B	J-62604	12.6	28.7	28.2	30.5	4.8	43.0	0.8	20.4	0.49	7,510	—	—	—	Analysis by U.S. Bureau of Mines. Equilibrium moisture—13.45%, grindability index—51, free-swelling index—noncaking. Pyritic sulfur—0.12%.
		2	—	—	—	32.8	32.4	34.8	3.9	49.2	0.9	10.6	0.56	8,590	2910+	—	—	
		3	—	—	—	50.3	49.7	—	6.0	75.5	1.4	16.2	0.86	13,180	—	—	—	

[1] Condition: 1, as received; 2, moisture-free; 3, moisture- and ash-free.
[2] N. M. State Bureau of Mines and Min. Res. test hole No. 11.

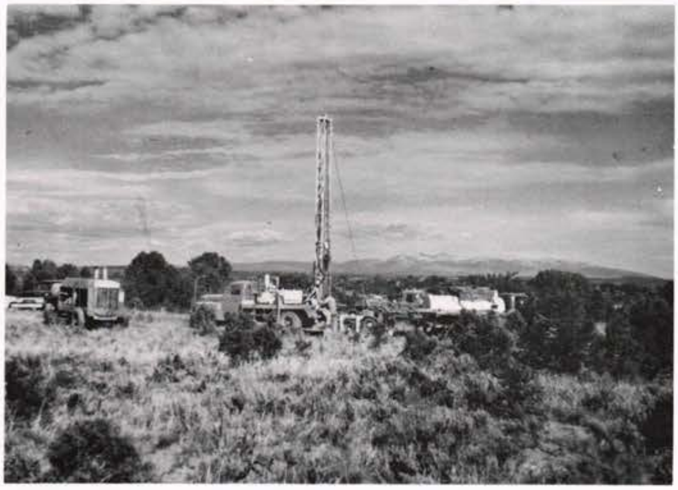

PLATE 4-A

PLATE 4-D

PLATE 4-B

PLATE 4-E

PLATE 4-C

PLATE 4-F

Plate 4

PHOTOGRAPHS OF COAL MINES, COAL OUTCROPS, AND COAL-BEARING STRATA

Summary of Strippable Coal Resources

Table 13 presents a summary of original reserves considered strippable under criteria designed to include coal within stripping range using current mining techniques, and in a somewhat deeper category expected to represent feasible stripping coal in a few years.

The first category includes coal in beds three feet thick or thicker beneath less than 150 feet of overburden, and the second includes beds five feet thick or thicker covered by more than 150 but less than 250 feet of overburden. As a rule, partings thinner than 0.7 foot were considered coal. A coal bed was considered part of a thicker coal above or below if the intervening parting was thinner than either, but for reserve calculations, the net coal thickness of the assemblage was used. In areas in which data were insufficient to allow accurate correlation, thicknesses of several coal beds were added and the aggregate treated as one hypothetical bed whose top coincided with the top of the uppermost actual bed.

In the early part of the study, an effort was made to restrict reserves to those minable at a stripping ratio or better. As data were assembled, however, it became evident that such a restriction was not reasonable because thickness could not be determined accurately enough between data points. Accordingly, no stripping ratio limitation was placed on calculations made for the report. Data obtained as complete tonnage figures from coal lessees, however, are limited by various stripping ratios; these situations are explained in full in the appropriate coal field or area sections of this report.

The reserve tabulation was further divided where possible into "measured" and "inferred" categories, defined as follows: measured reserves are those determined from drill-hole or outcrop measurements on approximately one-mile centers or better, and where beds can be correlated with some accuracy. Inferred reserves are based on drill-hole or outcrop measurements more than a mile apart, and involve considerable extrapolation of data and projection of geologic evidence. The inferred category encompasses a wide range of reliability, from that in areas in which drilling density is almost one hole per square mile but thickness variations are too great to permit accurate thickness contouring, to that in areas in which the reserve estimate is a speculation based on only a few measurements per township.

Reserves are to be considered "original," in that no account has been taken of tonnage mined, but in fact such a small percentage of the total in any one field or area has been mined that the reserves can be thought of as "remaining." To avoid the problem of deciding on a reasonable recoverability factor, the full tonnage is reported without deduction for mining losses.

TABLE 13. ORIGINAL STRIPPABLE RESERVES, MILLIONS OF SHORT TONS

Coal Field or Area	Overburden less than 150 feet		Overburden 150 feet to 250 feet	
	Measured[1]	Inferred[1]	Measured[1]	Inferred[1]
Cortez	13.1	115.2	–	29.5
Gallup	270.0[2]		88.0[2]	
Durango and Mesa Verde	–	–	–	–
Barker Creek	–	–	–	–
Hogback	–	–	–	–
Toadlena	–	–	–	–
Newcomb	–	78.5	–	6.3
Chaco Canyon	–	31.0	–	–
Chacra Mesa	–	–	–	–
San Mateo	–	21.2	–	–
Standing Rock	–	63.5	–	75.0
Zuni	–	6.2	–	–
Crownpoint	–	15.0	–	–
South Mount Taylor	–	1.4	–	–
East Mount Taylor	–	–	–	–
Rio Puerco	–	–	–	–
La Ventana	–	15.0	–	–
Tierra Amarilla	–	–	–	–
Monero	–	–	–	–
Pagosa Springs	–	–	–	–
Durango	–	–	–	–
Red Mesa	–	22.0	–	18.0
Fruitland	93.0[2]	–	65.0[2]	–
Navajo	1,024.7[2]		1,352.8[2]	
Bisti	–	958.0	–	912.0
Star Lake	–	365.0	–	270.0
Totals	3,092.8		2,816.6	
Grand Total			5,909.4	

[1] See text for definitions.
[2] Some portion limited by stripping ratio. See appropriate field or area section of report.

Drilling and Washability Testing

By John W. Shomaker and Robin C. Lease

On July 21, 1970, a 15-hole drilling program was begun by the New Mexico State Bureau of Mines and Mineral Resources under a supplemental matching grant from the U.S. Department of Health, Education, and Welfare NAPCA Project 69-3401 D-0. The purposes of the program were to provide information as to coal thickness and depth in several areas in which geologic data suggested strippable coal could be reasonably expected (fig. 58), and to provide core samples for washability analyses.

The actual drilling was done by Kenneth Harlan of Farmington, N.M., under the supervision of Robin C. Lease of the New Mexico State Bureau of Mines. Electrical logs of all of the holes were made by the U.S. Geological Survey, Water Resources Division, and analyses of cores recovered were made by the Pittsburgh Energy Research Center of the U.S. Bureau of Mines. A. W. Deurbrouck of the Pittsburgh Energy Research Center supervised the analytical work and contributed much to the planning of the project and the interpretation of the results.

The general plan of the operation was to drill, at each of *5* locations, a 4%-inch hole with a rock bit, preferably with air, and prepare a detailed log of the cuttings descriptions. If a significant quantity of coal were found in drilling of the pilot hole, a second hole was drilled in which the coal beds were cored. The core was to be 2 1/8 inches in diameter except for three holes drilled specifically for washability testing in known large reserves in the Fruitland Formation. Core 5 7/8-inches in diameter was taken in these holes. Gamma ray and spontaneous potential logs were run in all of the pilot holes, and resistivity, neutron, gamma-gamma (density), and caliper logs were run in some. Core samples were described in detail, the coal was placed in sealed plastic sacks, and then in sealed steel drums for shipment to the U.S. Bureau of Mines Laboratory.

The results of the program are summarized in Table 14. A graphic log for each of the test holes is inserted in the appropriate coal area or field section of the report.

Each coal bed (or group of beds capable of being mined as a unit; that is, separated by partings less than 0.7 foot thick) was submitted to the U.S. Bureau of Mines laboratory as a separate sample. Full proximate and ultimate analyses, with grindability, ash fusion, forms of sulfur, equilibrated moisture, and free-swelling index determinations were made for each. In addition, sink-float washability tests were made at 0.1 (or 0.05 in some cases) specific-gravity-unit steps for coal crushed to 3/8-inch top size for each sample. For the 5 7/8-inch core, similar tests were made at 1 1/2-inch top size as well and screen analyses were made of 3/8-inch top size materials. Ash analyses were made for all samples, and several carbonaceous partings between sampled coal beds were analyzed for ash content, sulfur content, and heating value.

The results of the sink-float washability testing are shown in Tables 15-45. The chemical analyses (tables 46-49) of the core samples have been included in the appropriate tables in sections of the report dealing with the various coal fields and areas. Interpretive comments concerning the washability testing are included in the following section written with the guidance and advice of A. W. Deurbrouck.

LABORATORY TEST PROCEDURE

The varied size and weight of the core samples collected made it necessary to set up a test program which could be modified readily to accommodate the samples received.

The raw samples were received in plastic bags to preserve the natural bed moisture. The samples were weighed and crushed to 1 1/2 inches or 3/8-inch top size, depending on core size and weight; a head sample was riffled out and sent to the analytical laboratory in plastic bags for equilibrium moisture content, ultimate and proximate analyses, pyritic sulfur content, fusibility of ash, free-swelling index number, Hardgrove grindability index (H.G.I.), and British thermal units (Btu).

The remaining portion of the sample was air dried and weighed. Where adequate material was available the sample was riffled into three parts for:

1. Float-and-sink testing of material 1 1/2-inches top size after the minus 100 mesh material was screened out,
2. Float-and-sink testing of material crushed to 3/8-inch top size after the minus 100 mesh material was screened out, and
3. Screen analysis after material was crushed to 3/8-inch top size.

If the remaining portion of the sample was not sufficiently large to treat in this manner, the material was crushed to 3/8-inch top size and screened at 100 mesh. The plus mesh material was then float-sink tested.

Regardless of the procedure followed, all float-sink and screen size fractions were analyzed for ash, pyritic sulfur, total sulfur, and Btu contents. A similar analysis was made on the minus 100 mesh material removed before float-sink testing, as this dust may influence the final product in commercial practice.

The float-sink testing procedure consisted of separating the coal into a desired number of specific gravity fractions in organic liquids ranging from 1.30 to 1.80 specific gravity. The specific gravity in each solution was checked immediately before adding coal; changes in specific gravity due to carryover of the solution and temperature changes were 0.001 specific gravity points or less. Certigrav* (a patented standardized-gravity organic heavy liquid) was the organic liquid used.

Each sample to be tested was processed through the specific gravity solutions progressing from the lightest to the heaviest. The sample was placed in the 1.30 specific gravity

*** Reference to trade names is made for identification only and does not imply endorsement by the U.S. Bureau of Mines.**

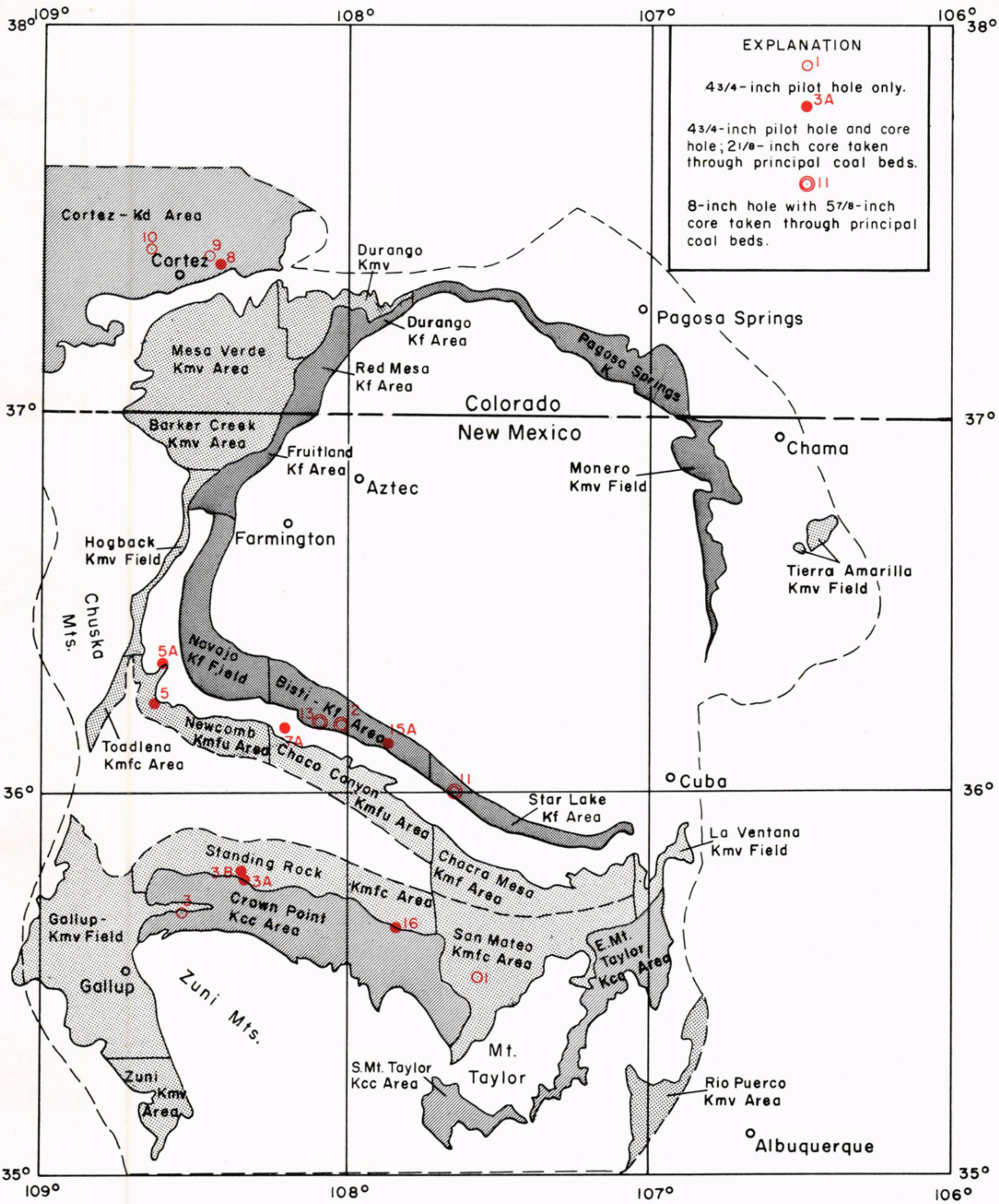

Figure 58

MAP SHOWING COAL FIELDS AND COAL AREAS, AND LOCATIONS OF COAL-TEST HOLES DRILLED BY THE NEW MEXICO STATE BUREAU OF MINES AND MINERAL RESOURCES

TABLE 14. SUMMARY OF RESULTS OF DRILLING PROGRAM

HOLE NO.	LOCATION	COAL AREA OR FIELD	MINERALS OWNER	PILOT HOLE DEPTH	COAL BEDS ENCOUNTERED IN PILOT HOLE, THICKNESSES AND TOPS IN FT.[1]	FORMATION[2]	COAL INTERVALS CORED FOR ANALYSES	SAMPLE DESIGNATION	CORE DIAMETER INCHES	ELECTRICAL LOGS RUN[3]	REMARKS
1	NW¼ SW¼ SW¼ Sec. 9, T. 15 N., R. 7 W.	San Mateo	Santa Fe Pacific Railroad Co.	218.7	3.0-56.5; 0.8-89.6; 3.0-93.8; 1.5-98.5	Kmfc	none			GR, SP, R	No core hole drilled
3	NE¼ NW¼ NE¼ Sec. 21, T. 17 N., R. 16 W.	Crownpoint	The Navajo Tribe	297.0	1.0-27.0; 2.0-196.5	Kmfc Kcg	none			GR, SP, R	No core hole drilled
3A	NW¼ SW¼ NE¼ Sec. 16, T. 18 N., R. 14 W.	Standing Rock	The Navajo Tribe	217.0	2.0-56; 3.0-107; 1.0-120; 3.5-128; 3.5-141.3; 4.7-150.8; 4.3-157.9	Kmfc	128.1-131.6; 141.3-145.8; 150.8-155.5 157.9-162.2 155.5-157.9	A B C D	2⅛	GR, SP, R	Sample D—parting
3B	NW¼ NE¼ NE¼ Sec. 8, T. 18 N., R. 14 W.	Standing Rock	The Navajo Tribe	112.6	1.0-50.5; 3.0-63.5; 2.0-72; 6.5-82.5; 12.1-91.5	Kmfc	82.5-89.0; 89.0-91.5 91.5-103.6	A B C		GR, SP, R	Pilot hole cored below 82.5. Sample B—parting
5	NW¼ SW¼ SW¼ Sec. 2, T. 23 N., R. 17 W.	Newcomb	The Navajo Tribe	320.0	2.4-80.2; 1.5-84.0; 3.3-97.0; 2.3-101.5; 3.5-144; 4.5-152; 4.0-168; 2.0-190; 1.0-194; 5.5-249.5	Kmf	80.2-82.6; 97.0-100.3; 101.5-103.8		2⅛	GR, SP, R	Three intervals combined for sample
5A	SW¼ SW¼ Sec. 36, T. 25 N., R. 17 W.	Newcomb	The Navajo Tribe	327.0	5.5-31.5; 9.0-55; 5.5-68; 2.0-77.5; 1.0-81.5; 6.0?-264; 3.0-292; 2.0?-302.5	Kmf	57.0-64.4; 69.7-73.1	A B	2⅛	GR, N, SP, R	
7A	SE¼ SE¼ NW¼ Sec. 34, T. 23 N., R. 13 W.	Chaco Canyon	The Navajo Tribe	305.0	1.6-171.4	Kmf	171.4-173.9		2⅛	GR, SP, N	No core hole drilled; pilot hole cored below 155
8	NE¼ NE¼ NE¼ Sec. 18, T. 36 N., R. 14 W.	Cortez	Frances B. Toelle	168.0	2.0-55; 1.5-63.5; 9.7-74.3; 2.5-85	Kd	74.3-83.4		2⅛	GR, SP, R, N, D	
9	NW¼ NE¼ NW¼ Sec. 12, T. 36 N., R. 15 W.	Cortez	Edgar C. Hoxsie	228.0	1.8-41.0; 1.5-60; 1.0-62; 4.5-126; 1.0-132.5	Kd	none			GR, SP, R, D, N, C	No core hole drilled
10	SW¼ SW¼ Sec. 32, T. 37 N., R. 16 W.	Cortez	Jewel L. Gardner	231.0	4.5-76; 5.0-132; 3.5-153	Kd	none			GR, SP, R, D, N, C	No core hole drilled
11	NE¼ SW¼ SW¼ Sec. 26, T. 21 N., R. 8 W.	Star Lake	U.S. Gov't.	77.0	16.0-35.5; 13.3-55.5	Kf	35.8-51.5; 55.5-68.6	A B	5⅞	GR, SP, R by Century Geophysical Corp.	No core hole drilled; pilot hole cored below 35.8
12	NW¼ SE¼ NE¼ Sec. 29, T. 23 N., R. 11 W.	Bisti	U.S. Gov't.	331.5	29.5-252.5; 13.0-317.0	Kf	252.5-283.0; 321.5-330.0;	A B	5⅞	GR, SP, R	No core hole drilled; pilot hole cored below 225; 8.5 ft. of 2⅛-inch core cut to locate top of lower bed, then reamed through
13	SW¼ NE¼ NE¼ Sec. 27, T. 23 N., R. 12 W.	Bisti	U.S. Gov't.	163.0	9.5-28.0; 2.5-39; 2.5-81; 12.3-109.5; 1.5-148	Kf	28.0-37.5; 109.5-121.8	A B	5⅞	GR, SP, R, N	
15A	NE¼ NE¼ NE¼ Sec. 15, T. 22 N., R. 10 W.	Bisti	U.S. Gov't.	341.0	22.2-267; 3.0-296; 1.5-317; 2.0-323; 1.5-328.5	Kf	269.0-290.2		2⅛	GR, SP, R, D, N	No core hole drilled; pilot hole cored below 269
16	SW¼ NW¼ NE¼ Sec. 36, T. 17 N., R. 10 W.	Standing Rock	State of New Mexico	263.0	3.0-65; 4.0-135; 4.0-164; 3.0-179; 11.2-184.7; 1.4-199.7	Kmfc	179.0-182.0; 184.7-195.9; 199.7-201.1		2⅛	GR, SP, D, N	Three intervals combined for sample

[1] May not agree with coal interval as found in core because of delay in circulating samples to surface, cavings from hole wall, or lost circulation.

[2] Kd, Dakota Sandstone; Kcg, Gibson Member of Crevasse Canyon Formation; Kmf, Menefee Formation; Kmfc, Cleary Member of Menefee Formation; Kf, Fruitland Formation.

[3] Logs run by U. S. Geological Survey, Water Resources Division, unless otherwise noted. GR, gamma ray; SP, spontaneous potential; R, resistivity; N, neutron; D, gamma gamma density; C, caliper.

bath in small quantities to prevent entrapment, stirred, and allowed to settle. The floating coal was then removed with a screen wire strainer. The sink portion, having settled into a container with a screen bottom in the bath, was raised above the liquid level and allowed to drain. The container was then placed into the next denser solution, and the process was repeated. This was continued until the sample was separated into the desired specific gravity fractions.

The float-sink data from core samples are not to be construed as representing the quality of the total coal bed, but rather as indicating the quality of the bed in that particular geographical location. Float-sink data are based upon perfect specific gravity separations that are approached, but not equaled, in commercial practice.

EXPERIMENTAL RESULTS

FLOAT-SINK TEST RESULTS

All analytical results are given on a moisture free basis unless otherwise noted. Depth intervals sampled are given in Table 14.

Cortez Area

The washability results for hole No. 8, Tables 15 and 16, show this sample to be of high-ash and low sulfur content. This coal contains almost no low-density material, float 1.40 specific gravity, but contains about 45 percent sink 1.80 specific gravity material. The equilibrium moisture of this sample was only 3.8 percent.

The carbonaceous shale noted in the core log is reflected in the high percentage of intermediate-density material (1.40 to 1.80 specific gravity). The recovery of low-ash coal obtainable here would be too low for a commercial operation.

Crushing the sample from 1% inches to 3/8-inch top size was of no value in releasing the impurities or increasing yield.

Newcomb Area

The washability results for hole No. 5, given in Table 17, show this coal contains more than 50 percent of intermediate-density material (1.40 to 1.80 specific gravity) resulting in a high-ash, low-Btu product that contains only 2.1 percent sink 1.80 specific gravity material. Because of the large percentage of near-gravity material (± 0.10 specific gravity units) present, washing of this coal anywhere from 1.40 to 1.50 specific gravity would require a dense-medium washer. The resulting product would be, at best, 13.4 percent ash at a 60.3 percent yield.

The washability results for hole No. 5A, given in Tables 18 and 19, show the two samples collected from this hole are of low-ash, rather high sulfur, and high-Btu contents as received. Removal of the sink 1.60 specific gravity material would result in the removal of only 5 to 8 percent of the raw coal, but a reduction of about 35 percent in the total sulfur content of the samples plus a significant reduction in ash content. These coals are basically identical and because of the low percentage of near-gravity material (± 0.10 specific gravity units) present at 1.60 specific gravity, would be easy to wash in a jig.

Bisti Area

The washability results for hole No. 12, of sample A, given in Tables 20 and 21, show this sample to be of high-ash and low-sulfur content. Removal of the sink 1.50 specific gravity material from the sample crushed to 1 1/2 inches top size would result in a 74.0 percent product yield analyzing 11.8 percent ash, 0.50 percent sulfur (total), and 11,939 Btu. Because of the large percentage of near-gravity material present at 1.50 specific gravity a dense-medium coal washing device would be required. Crushing of the sample to 3/8-inch top size would release some impurities but not enough to make such a step feasible.

The washability results of sample B, located 34.0 feet below sample A, are summarized in Tables 22 and 23. The quality of the raw coal is much better here owing to the appreciable reduction of the heaviest impurities and less intermediate-density material. Washing this coal, when crushed to 1 1/2 inches top size, at 1.60 specific gravity would provide an 89.7 percent product yield of 11.3 percent ash, 0.52 percent sulfur, and 12,123 Btu. A jig could efficiently be used for such a separation. Crushing of this sample to 3/8-inch top size would release some impurities, not enough however, to make such a step feasible.

The washability results of hole No. 13, samples A and B, given in Tables 24, 25, 26, and 27 show both samples to be of high-ash and low-sulfur content. Removal of the sink 1.50 specific gravity material from sample A would provide a 73.6 percent product yield of 9.4 percent ash, 0.65 percent sulfur, and 11,248 Btu. Removal of the same material from sample B would provide a 77.3 percent product yield of 10.2 percent ash, 0.56 percent sulfur, and 11,885 Btu. The percentage of near-gravity material present in these samples 'at 1.50 specific gravity would dictate the use of a dense-medium process to obtain an effective separation.

Crushing of sample A to 3/8-inch top size and washing at 1.60 specific gravity would result in a 4.5 percent increase in yield at constant Btu contents over the 1 1/2 inches top size material washed at 1.50 specific gravity. Similar treatment of sample B would result in a 3.4 percent yield increase at constant Btu but an ash increase in excess of one percentage point.

The washability results for hole No. 15A, given in Table 28, show this coal to be rather high-ash but low-sulfur content. Removal of the sink 1.50 specific gravity material would provide a product yield of 80.6 percent, containing 9.5 percent ash, 0.67 percent sulfur, and 12,364 Btu. In commercial practice this would be an easy separation for a dense-medium washer to make. The near-gravity material is rather high for a jig.

Chaco Canyon Area

The washability results for hole No. 7A, given in Table 29, show this to be a high-ash high-sulfur content sample containing no more than 19.3 percent recoverable coal. Such a seam could not be economically washed.

Star Lake Area

The washability results of sample A of hole No. 11 crushed to 1½ inches top size are given in Table 30. Removal of the sink 1.40 specific gravity material would provide a 67.8 percent product yield of 9.5 percent ash, 0.62 percent sulfur, and 12,378 Btu. If a 12.4 percent ash would be acceptable, the yield could be increased to 81.4 percent by removal of only the sink 1.50 specific gravity material.

Crushing of this sample to 3/8-inch top size released some impurities as shown in Table 31; removal of the sink 1.50 specific gravity material would provide a 78.5 percent yield product containing 10.1 percent ash, 0.76 percent sulfur, and 12,092 Btu.

Sample A would require a dense-medium washer to effectively separate the coal from its ass0ciated impurities because of the high percentage of intermediate-density material (1.40 to 1.80 specific gravity) present.

The washability results of sample B are shown in Tables 32 and 33. This is consistently a lower quality coal containing more intermediate- and high-density material than the overlying sample A. To obtain a product of 11.8 percent ash and 12,144 Btu would require washing at 1.40 specific gravity, thus providing a yield of only 46.6 percent. However, because the bed lies so close to the surface and the overlying sample is of much better quality, it is possible such a low recovery would be acceptable. Crushing of this sample from 11/2 inches to 3/8-inch top size would be of limited value, and probably not economically practical.

Standing Rock Area

The washability results for hole No. 3A, samples A and B, are given in Tables 34 and 35. These are exceptionally clean coals as received, both containing large percentages of 1.30 specific gravity float coal and almost no high-density impurities. Upgrading of these coals would not be necessary.

Sample C, Table 36, is a composite of two core samples taken on either side of a shale parting which analyzed 79.1 percent ash and contained only 1,990 Btu. Sample C, as received, is of intermediate-ash and high-sulfur content; however, removal of the sink 1.60 specific gravity material would provide an 87.5 percent product yield of 8.5 percent ash, 0.64 percent sulfur, and i1,597 Btu. Such a separation could easily be made in a jig owing to the paucity of near-gravity ± 0.10 specific gravity material.

Hole No. 3A produced 17.1 vertical feet of good quality coal in a 34.1 foot interval.

The washability of sample A, hole No. 3B, is given in Table 37. This is a relatively clean coal containing about 20 percent of high-density impurities which can be readily removed by jig washing as little near-gravity material is present. The 1.60 specific gravity float coal contains 9.7 percent ash, 0.46 percent sulfur and 12,141 Btu at an 80.5 percent recovery.

Sample C contains about 20 percentage points more of the float 1.30 specific gravity material than does sample A as shown in Table 38. This coal may be easily upgraded by removal of the sink 1.80 specific gravity material, thus providing an 89.8 percent product yield of 9.4 percent ash, 0.65 percent sulfur, and 12,409 Btu. A jig washer could be used efficiently to upgrade this sample and sample A.

Hole 3B produced 18.6 vertical feet of good coal separated by only one 2.5-foot parting which analyzed 81.9 percent ash and 1,570 Btu.

The washability of coal sampled in hole No. 16 is given in Table 39. It was a reasonably clean coal as received. The removal of the sink 1.80 specific gravity material would provide a final product of 9.4 percent ash, 0.86 percent sulfur, and 12,148 Btu at a 96.7 percent yield. The sulfur content of this coal is somewhat higher than most samples collected for this study.

Screen Analyses

Core samples 5%8 inches in diameter were collected from two areas, the Bisti and the Star Lake. These larger cores provided sufficient sample so that screen analyses could be made.

Tables 40, 41, 42, and 43 are screen analyses of core samples from the Bisti area. The finer size fractions appear to be somewhat higher in ash and sulfur content than the coarser material.

Tables 44 and 45 are screen analyses of core samples from the Star Lake area. Generally, the finer material contains more impurities but sample B, Table 45, contains excessive percentages of impurities throughout its entire size range.

All the screen analyses indicate these coals are rather hard. Only sample A, hole No. 13, contains more than 5 percent minus 100 mesh material. This same sample contained only 50.6 percent plus 7 mesh material, approximately 10 percentage points less of this coarse material than any other sample screened.

SUMMARY TABLES

To further characterize the core samples collected, summary tables were made of the ultimate and proximate analyses of the core samples (tables 46 and 47), analyses of the ash constituents of the core samples (table 48), and analyses of additional physical properties of the core samples (table 49).

CONCLUSIONS

The washability of these core samples indicated most of the samples could be substantially upgraded by removal of the sink 1.50 or 1.60 specific gravity material, and generally the loss in yield was less than 20 percent. Only 6 of the 18 samples tested contained more than 10 percent ash after the sink 1.50 specific gravity material was removed. The samples from the Standing Rock area were of especially good quality as received.

Crushing from 1 1/2 inches to 3/8-inch top size to release impurities was of limited value in improving product quality or yield.

Of the 18 samples tested only one (hole 7A) contained in excess of 1 percent sulfur and that was a sample which provided a yield of float 1.50 specific gravity coal of only 14.7 percent.

The coals ranged in rank from subbituminous C to high-volatile C; eleven of the samples were subbituminous A.

TABLE 15. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 8, CORTEZ AREA, 1½ INCHES BY 0

SPECIFIC GRAVITY FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	1.2	5.6	0.35	1.30	14,120	1.2	5.6	0.35	1.30	14,120
1.30–1.40	13.1	10.0	.17	.47	13,420	14.3	9.6	.18	.54	13,479
1.40–1.50	15.8	18.2	.05	.28	12,000	30.1	14.1	.11	.40	12,702
1.50–1.60	13.6	27.1	.12	.31	10,530	43.7	18.2	.12	.37	12,026
1.60–1.80	11.8	40.4	.05	.28	8,270	55.5	22.9	.10	.35	11,228
Sink –1.80	44.5	79.3	.20	.20	1,810	100.0	48.0	.14	.28	7,037
Minus– 100	1.3	29.8	1.69	2.73	9,660	100.0	47.8	.16	.32	7,070

TABLE 16. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 8, CORTEZ AREA, ⅜ INCH BY 0

SPECIFIC GRAVITY FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	2.3	5.4	0.16	1.04	14,190	2.3	5.4	0.16	1.04	14,190
1.30–1.40	14.2	9.1	.07	.60	13,560	16.5	8.6	.08	.66	13,648
1.40–1.50	14.9	16.8	.01	.45	12,200	31.4	12.5	.05	.56	12,961
1.50–1.60	9.1	26.6	.09	.45	10,530	40.5	15.6	.06	.54	12,415
1.60–1.80	12.9	39.7	.08	.30	8,320	53.4	21.5	.06	.48	11,425
Sink –1.80	46.6	79.6	.21	.21	1,750	100.0	48.6	.13	.35	6,917
Minus– 100	2.7	41.3	.89	1.56	7,930	100.0	48.4	.15	.38	6,943

TABLE 17. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 5, NEWCOMB AREA, ⅜ INCH BY 0

SPECIFIC GRAVITY FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	15.5	6.0	0.08	0.68	12,280	15.5	6.0	0.08	0.68	12,280
1.30–1.40	30.3	11.7	.13	.69	11,480	45.8	9.8	.11	.69	11,750
1.40–1.50	14.5	24.8	.14	.71	9,660	60.3	13.4	.12	.69	11,248
1.50–1.60	11.4	36.2	.22	.78	7,900	71.7	17.0	.14	.71	10,716
1.60–1.80	26.2	49.2	.25	.54	6,020	97.9	25.6	.17	.66	9,459
Sink –1.80	2.1	57.7	.70	1.01	4,680	100.0	26.3	.18	.67	9,358
Minus– 100	1.6	35.8	.55	1.18	8,200	100.0	26.4	.18	.68	9,340

TABLE 18. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 5A, SAMPLE A, NEWCOMB AREA, ⅜ INCH BY 0

SPECIFIC GRAVITY FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	43.5	6.0	0.07	0.77	12,830	43.5	6.0	0.07	0.77	12,830
1.30–1.40	36.6	11.2	.18	.87	11,990	80.1	8.4	.12	.82	12,446
1.40–1.50	6.2	23.1	.64	1.32	10,070	86.3	9.4	.16	.85	12,275
1.50–1.60	6.0	35.6	.46	1.01	8,280	92.3	11.1	.18	.86	12,015
1.60–1.80	4.4	45.3	.62	.93	6,870	96.7	12.7	.20	.86	11,781
Sink –1.80	3.3	66.6	14.34	14.95	3,380	100.0	14.5	.66	1.33	11,504
Minus– 100	2.3	23.0	.11	1.78	10,320	100.0	14.7	.65	1.34	11,477

TABLE 19. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 5A, SAMPLE B, NEWCOMB AREA, 3/8 INCH BY 0

	DIRECT					CUMULATIVE				
SPECIFIC GRAVITY FRACTION	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	52.4	5.4	0.11	0.88	12,870	52.4	5.4	0.11	0.88	12,870
1.30–1.40	34.5	12.6	.13	.96	11,680	86.9	8.2	.12	.91	12,397
1.40–1.50	4.9	22.6	1.00	1.92	10,130	91.8	9.0	.16	.96	12,276
1.50–1.60	3.4	34.0	2.05	2.87	8,460	95.2	9.9	.23	1.03	12,140
1.60–1.80	1.7	37.7	5.37	6.33	7,680	96.9	10.4	.32	1.13	12,062
Sink –1.80	3.1	64.8	16.28	16.69	3,220	100.0	12.1	.82	1.61	11,788
Minus– 100	1.8	20.5	1.21	2.11	10,650	100.0	12.2	.82	1.62	11,767

TABLE 20. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 12, SAMPLE A, BISTI AREA, 1½ INCHES BY 0

	DIRECT					CUMULATIVE				
SPECIFIC GRAVITY FRACTION	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	32.3	6.6	0.01	0.53	12,780	32.3	6.6	0.01	0.53	12,780
1.30–1.35	22.3	10.7	.04	.55	12,060	54.6	8.3	.02	.54	12,486
1.35–1.40	8.3	16.5	.06	.49	11,150	62.9	9.4	.03	.53	12,309
1.40–1.50	11.1	25.7	.04	.32	9,840	74.0	11.8	.03	.50	11,939
1.50–1.60	7.6	37.9	.04	.35	8,000	81.6	14.2	.03	.49	11,572
1.60–1.80	6.5	48.9	.08	.30	6,210	88.1	16.8	.03	.47	11,177
Sink –1.80	11.9	73.3	.03	.12	2,350	100.0	23.5	.03	.43	10,126
Minus– 100	.5	31.7	.16	.70	8,590	100.0	23.6	.03	.43	10,119

TABLE 21. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 12, SAMPLE A, BISTI AREA, 3/8 INCH BY 0

	DIRECT					CUMULATIVE				
SPECIFIC GRAVITY FRACTION	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	29.1	5.4	0.04	0.51	12,930	29.1	5.4	0.04	0.51	12,930
1.30–1.35	21.3	9.2	.07	.54	12,340	50.4	7.0	.05	.52	12,680
1.35–1.40	10.9	15.0	.06	.38	11,410	61.3	8.4	.05	.50	12,455
1.40–1.50	10.4	23.8	.03	.42	10,080	71.7	10.6	.05	.49	12,110
1.50–1.60	7.2	34.2	.08	.38	8,430	78.9	12.8	.05	.48	11,774
1.60–1.80	7.9	46.2	.03	.31	6,580	86.8	15.8	.05	.46	11,302
Sink –1.80	13.2	72.5	.11	.15	2,450	100.0	23.3	.06	.42	10,133
Minus– 100	3.6	29.5	.09	.40	9,200	100.0	23.5	.06	.42	10,101

TABLE 22. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 12, SAMPLE B, BISTI AREA, 1½ INCHES BY 0

	DIRECT					CUMULATIVE				
SPECIFIC GRAVITY FRACTION	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	42.4	6.0	0.06	0.59	12,930	42.4	6.0	0.06	0.59	12,930
1.30–1.35	24.9	10.4	.06	.45	12,290	67.3	7.6	.06	.54	12,693
1.35–1.40	11.5	16.5	.19	.50	11,330	78.8	8.9	.08	.53	12,494
1.40–1.50	6.4	24.2	.14	.46	10,190	85.2	10.1	.08	.53	12,321
1.50–1.60	4.5	35.3	.14	.31	8,380	89.7	11.3	.09	.52	12,123
1.60–1.80	5.0	50.6	.14	.21	6,210	94.7	13.4	.09	.50	11,811
Sink –1.80	5.3	71.8	.33	.45	2,550	100.0	16.5	.10	.50	11,320
Minus– 100	.4	22.4	1.55	2.61	10,610	100.0	16.5	.11	.50	11,317

TABLE 23. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 12, SAMPLE B, BISTI AREA, ⅜ INCH BY 0

Specific gravity fraction	Direct: Weight, percent	Direct: Ash, percent	Direct: Pyritic sulfur, percent	Direct: Total sulfur, percent	Direct: British thermal units	Cumulative: Weight, percent	Cumulative: Ash, percent	Cumulative: Pyritic sulfur, percent	Cumulative: Total sulfur, percent	Cumulative: British thermal units
Float –1.30	34.0	5.0	0.16	0.48	13,030	34.0	5.0	0.16	0.48	13,030
1.30–1.35	25.1	8.3	.03	.50	12,480	59.1	6.4	.10	.49	12,796
1.35–1.40	14.5	12.7	.06	.51	11,790	73.6	7.6	.10	.49	12,598
1.40–1.50	9.4	19.6	.08	.44	10,640	83.0	9.0	.09	.49	12,376
1.50–1.60	4.4	32.1	.11	.37	8,680	87.4	10.2	.09	.48	12,190
1.60–1.80	5.3	45.4	.05	.27	6,780	92.7	12.2	.09	.47	11,880
Sink –1.80	7.3	71.3	.05	.39	2,640	100.0	16.5	.09	.46	11,206
Minus–100	3.4	21.1	.87	1.13	10,720	100.0	16.6	.11	.48	11,190

TABLE 24. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 13, SAMPLE A, BISTI AREA, 1½ INCHES BY 0

Specific gravity fraction	Direct: Weight, percent	Direct: Ash, percent	Direct: Pyritic sulfur, percent	Direct: Total sulfur, percent	Direct: British thermal units	Cumulative: Weight, percent	Cumulative: Ash, percent	Cumulative: Pyritic sulfur, percent	Cumulative: Total sulfur, percent	Cumulative: British thermal units
Float –1.30	25.1	5.6	0.03	0.68	12,560	25.1	5.6	0.03	0.68	12,560
1.30–1.35	21.0	7.5	.01	.63	11,360	46.1	6.5	.02	.66	12,013
1.35–1.40	19.1	11.5	.01	.64	10,260	65.2	7.9	.02	.65	11,499
1.40–1.50	8.4	20.9	.01	.60	9,300	73.6	9.4	.02	.65	11,248
1.50–1.60	4.9	35.8	.01	.55	7,350	78.5	11.1	.02	.64	11,005
1.60–1.80	6.2	53.5	.06	.48	4,840	84.7	14.2	.02	.63	10,554
Sink –1.80	15.3	74.3	.03	.35	2,300	100.0	23.4	.02	.58	9,291
Minus–100	.6	40.7	.35	1.12	7,120	100.0	23.5	.02	.59	9,278

TABLE 25. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 13, SAMPLE A, BISTI AREA, ⅜ INCH BY 0

Specific gravity fraction	Direct: Weight, percent	Direct: Ash, percent	Direct: Pyritic sulfur, percent	Direct: Total sulfur, percent	Direct: British thermal units	Cumulative: Weight, percent	Cumulative: Ash, percent	Cumulative: Pyritic sulfur, percent	Cumulative: Total sulfur, percent	Cumulative: British thermal units
Float –1.30	24.2	4.5	0.01	0.62	12,810	24.2	4.5	0.01	0.62	12,810
1.30–1.35	17.9	6.1	.01	.60	11,790	42.1	5.2	.01	.61	12,376
1.35–1.40	18.9	9.4	.01	.71	10,680	61.0	6.5	.01	.64	11,850
1.40–1.50	12.3	18.0	.03	.56	9,610	73.3	8.4	.01	.63	11,475
1.50–1.60	4.8	31.7	.03	.47	7,760	78.1	9.8	.01	.62	11,246
1.60–1.80	5.8	48.9	.03	.45	5,330	83.9	12.5	.02	.61	10,837
Sink –1.80	16.1	72.7	.30	.47	2,290	100.0	22.2	.06	.58	9,461
Minus–100	6.5	32.4	.17	.96	7,830	100.0	22.8	.07	.61	9,361

TABLE 26. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 13, SAMPLE B, BISTI AREA, 1½ INCHES BY 0

Specific gravity fraction	Direct: Weight, percent	Direct: Ash, percent	Direct: Pyritic sulfur, percent	Direct: Total sulfur, percent	Direct: British thermal units	Cumulative: Weight, percent	Cumulative: Ash, percent	Cumulative: Pyritic sulfur, percent	Cumulative: Total sulfur, percent	Cumulative: British thermal units
Float –1.30	40.5	5.8	0.09	0.59	12,600	40.5	5.8	0.09	0.59	12,600
1.30–1.35	22.2	11.3	.04	.53	11,520	62.7	7.7	.07	.57	12,217
1.35–1.40	9.1	16.7	.11	.55	10,950	71.8	8.9	.08	.57	12,057
1.40–1.50	5.5	26.9	.07	.48	9,640	77.3	10.2	.08	.56	11,885
1.50–1.60	5.3	40.1	.04	.45	7,630	82.6	12.1	.07	.55	11,612
1.60–1.80	11.6	51.4	.01	.27	5,890	94.2	16.9	.07	.52	10,907
Sink –1.80	5.8	69.1	.11	.18	3,370	100.0	20.0	.07	.50	10,470
Minus–100	.3	26.0	.60	1.07	9,940	100.0	20.0	.07	.50	10,468

TABLE 27. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 13, SAMPLE B, BISTI AREA, ⅜ INCH BY 0

SPECIFIC GRAVITY FRACTION	DIRECT WEIGHT, PERCENT	DIRECT ASH, PERCENT	DIRECT PYRITIC SULFUR, PERCENT	DIRECT TOTAL SULFUR, PERCENT	DIRECT BRITISH THERMAL UNITS	CUMULATIVE WEIGHT, PERCENT	CUMULATIVE ASH, PERCENT	CUMULATIVE PYRITIC SULFUR, PERCENT	CUMULATIVE TOTAL SULFUR, PERCENT	CUMULATIVE BRITISH THERMAL UNITS
Float –1.30	38.1	5.3	0.04	0.56	12,900	38.1	5.3	0.04	0.56	12,900
1.30–1.35	18.9	10.1	.06	.52	11,990	57.0	6.9	.05	.55	12,598
1.35–1.40	11.2	15.3	.15	.50	11,240	68.2	8.3	.06	.54	12,375
1.40–1.50	7.3	22.7	.04	.55	10,090	75.5	9.7	.06	.54	12,154
1.50–1.60	5.2	36.7	.01	.36	8,110	80.7	11.4	.06	.53	11,893
1.60–1.80	12.4	49.4	.06	.23	6,070	93.1	16.5	.06	.49	11,118
Sink –1.80	6.9	69.7	.03	.14	3,150	100.0	20.1	.06	.46	10,568
Minus– 100	1.9	24.1	.44	.73	10,200	100.0	20.2	.06	.47	10,561

TABLE 28. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 15A, BISTI AREA, ⅜ INCH BY 0

SPECIFIC GRAVITY FRACTION	DIRECT WEIGHT, PERCENT	DIRECT ASH, PERCENT	DIRECT PYRITIC SULFUR, PERCENT	DIRECT TOTAL SULFUR, PERCENT	DIRECT BRITISH THERMAL UNITS	CUMULATIVE WEIGHT, PERCENT	CUMULATIVE ASH, PERCENT	CUMULATIVE PYRITIC SULFUR, PERCENT	CUMULATIVE TOTAL SULFUR, PERCENT	CUMULATIVE BRITISH THERMAL UNITS
Float –1.30	42.2	5.5	0.10	0.70	13,040	42.2	5.5	0.10	0.70	13,040
1.30–1.40	29.4	11.3	.10	.64	12,060	71.6	7.9	.10	.68	12,638
1.40–1.50	9.0	22.7	.10	.62	10,190	80.6	9.5	.10	.67	12,364
1.50–1.60	5.2	34.1	.08	.36	8,490	85.8	11.0	.10	.65	12,129
1.60–1.80	5.6	46.5	.19	.44	6,450	91.4	13.2	.10	.64	11,781
Sink –1.80	8.6	69.1	.35	.49	2,730	100.0	18.0	.12	.62	11,003
Minus– 100	3.8	28.1	.11	.76	9,500	100.0	18.4	.12	.63	10,948

TABLE 29. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 7A, CHACO CANYON AREA, ⅜ INCH BY 0

SPECIFIC GRAVITY FRACTION	DIRECT WEIGHT, PERCENT	DIRECT ASH, PERCENT	DIRECT PYRITIC SULFUR, PERCENT	DIRECT TOTAL SULFUR, PERCENT	DIRECT BRITISH THERMAL UNITS	CUMULATIVE WEIGHT, PERCENT	CUMULATIVE ASH, PERCENT	CUMULATIVE PYRITIC SULFUR, PERCENT	CUMULATIVE TOTAL SULFUR, PERCENT	CUMULATIVE BRITISH THERMAL UNITS
Float –1.30	5.1	4.4	0.33	1.30	12,860	5.1	4.4	0.33	1.30	12,860
1.30–1.40	4.3	11.3	.58	1.73	11,880	9.4	7.6	.44	1.50	12,411
1.40–1.50	5.3	26.9	.75	1.66	9,820	14.7	14.5	.55	1.56	11,477
1.50–1.60	4.6	37.2	.65	1.35	8,470	19.3	19.9	.58	1.51	10,760
1.60–1.80	10.9	35.1	.69	1.55	8,620	30.2	25.4	.62	1.52	9,988
Sink –1.80	69.8	70.6	1.59	2.01	3,390	100.0	57.0	1.30	1.86	5,382
Minus– 100	4.5	56.2	1.50	2.20	5,300	100.0	56.9	1.30	1.88	5,379

TABLE 30. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 11, SAMPLE A, STAR LAKE AREA, 1½ INCHES BY 0

SPECIFIC GRAVITY FRACTION	DIRECT WEIGHT, PERCENT	DIRECT ASH, PERCENT	DIRECT PYRITIC SULFUR, PERCENT	DIRECT TOTAL SULFUR, PERCENT	DIRECT BRITISH THERMAL UNITS	CUMULATIVE WEIGHT, PERCENT	CUMULATIVE ASH, PERCENT	CUMULATIVE PYRITIC SULFUR, PERCENT	CUMULATIVE TOTAL SULFUR, PERCENT	CUMULATIVE BRITISH THERMAL UNITS
Float –1.30	26.9	6.1	0.12	0.61	12,920	26.9	6.1	0.12	0.61	12,920
1.30–1.35	26.7	10.4	.07	.57	12,290	53.6	8.2	.10	.59	12,606
1.35–1.40	14.2	14.1	.10	.74	11,520	67.8	9.5	.10	.62	12,378
1.40–1.50	13.6	26.9	.10	.74	9,410	81.4	12.4	.10	.64	11,883
1.50–1.60	6.0	48.2	.14	.62	6,150	87.4	14.8	.10	.64	11,489
1.60–1.80	6.4	45.0	.14	.61	6,560	93.8	16.9	.10	.64	11,153
Sink –1.80	6.2	70.8	.29	.95	2,050	100.0	20.2	.11	.66	10,588
Minus– 100	.4	27.7	.50	1.34	9,230	100.0	20.3	.12	.66	10,583

TABLE 31. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 11, SAMPLE A, STAR LAKE AREA, ⅜ INCH BY 0

SPECIFIC GRAVITY FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	25.8	4.9	0.11	0.76	12,940	25.8	4.9	0.11	0.76	12,940
1.30–1.35	23.8	9.2	.20	.76	12,290	49.6	7.0	.15	.76	12,628
1.35–1.40	15.3	13.1	.14	.79	11,550	64.9	8.4	.15	.77	12,374
1.40–1.50	13.6	18.2	.11	.71	10,750	78.5	10.1	.14	.76	12,092
1.50–1.60	7.4	32.3	.22	.69	8,450	85.9	12.0	.15	.75	11,779
1.60–1.80	6.2	44.5	.38	.65	6,510	92.1	14.2	.16	.74	11,424
Sink –1.80	7.9	72.2	.37	.76	1,820	100.0	18.8	.18	.74	10,665
Minus– 100	4.0	25.8	.11	1.14	9,630	100.0	19.0	.18	.76	10,625

TABLE 32. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 11, SAMPLE B, STAR LAKE AREA, 1½ INCHES BY 0

SPECIFIC GRAVITY FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	14.8	6.9	0.13	0.70	12,850	14.8	6.9	0.13	0.70	12,850
1.30–1.35	20.6	11.5	.07	.78	12,200	35.4	9.6	.10	.75	12,471
1.35–1.40	11.2	18.9	.09	.75	11,110	46.6	11.8	.09	.75	12,144
1.40–1.50	12.8	28.2	.16	.62	9,770	59.4	15.3	.11	.72	11,633
1.50–1.60	6.9	38.6	.10	.40	8,110	66.3	17.8	.11	.69	11,265
1.60–1.80	10.7	52.2	.28	.45	5,930	77.0	22.6	.13	.65	10,524
Sink –1.80	23.0	79.3	.17	.21	1,510	100.0	35.6	.14	.55	8,450
Minus– 100	.4	37.9	.96	1.45	8,020	100.0	35.6	.14	.56	8,449

TABLE 33. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 11, SAMPLE B, STAR LAKE AREA, ⅜ INCH BY 0

SPECIFIC GRAVITY FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	19.0	5.7	0.10	0.74	13,040	19.0	5.7	0.10	0.74	13,040
1.30–1.35	17.2	10.6	.09	.70	12,250	36.2	8.0	.10	.72	12,665
1.35–1.40	10.4	17.3	.13	.65	11,200	46.6	10.1	.10	.70	12,338
1.40–1.50	12.9	25.5	.10	.67	9,890	59.5	13.4	.10	.70	11,807
1.50–1.60	7.4	36.3	.08	.54	8,340	66.9	16.0	.10	.68	11,423
1.60–1.80	10.6	50.9	.27	.39	6,080	77.5	20.7	.12	.64	10,693
Sink –1.80	22.5	78.7	.05	.15	1,630	100.0	33.8	.11	.53	8,653
Minus– 100	4.1	42.1	.48	.83	7,410	100.0	34.1	.12	.54	8,604

TABLE 34. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 3A, SAMPLE A, STANDING ROCK AREA, ⅜ INCH BY 0

SPECIFIC GRAVITY FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	77.0	4.4	0.07	0.49	13,140	77.0	4.4	0.07	0.49	13,140
1.30–1.40	17.0	15.5	.04	.32	11,410	94.0	6.4	.06	.46	12,827
1.40–1.50	4.5	22.1	.08	.49	10,270	98.5	7.1	.06	.46	12,710
1.50–1.60	.5	32.0	.10	.46	8,800	99.0	7.2	.06	.46	12,690
Sink –1.60	1.0	55.4	.62	.92	5,090	100.0	7.7	.07	.46	12,614
Minus– 100	1.8	14.8	1.51	2.44	11,840	100.0	7.9	.10	.50	12,601

TABLE 35. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 3A, SAMPLE B, STANDING ROCK AREA, 3/8 INCH BY 0

SPECIFIC GRAVITY FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	86.7	4.1	0.03	0.58	13,170	86.7	4.1	0.03	0.58	13,170
1.30–1.40	10.3	10.8	.26	.74	12,100	97.0	4.8	.05	.60	13,056
1.40–1.50	1.4	22.4	.87	1.27	10,430	98.4	5.1	.07	.61	13,019
1.50–1.60	.8	33.5	.84	1.07	[1]	99.2	5.3	.07	.61	12,978
Sink –160	.8	50.6	3.53	3.84	5,840	100.0	5.6	.10	.64	12,921
Minus– 100	1.6	10.5	.65	1.10	12,360	100.0	5.7	.11	.64	12,912

[1] Insufficient sample for analyses.

TABLE 36. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 3A, SAMPLE C, STANDING ROCK AREA, 3/8 INCH BY 0

SPECIFIC GRAVITY FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	60.4	5.2	0.04	0.48	11,710	60.4	5.2	0.04	0.48	11,710
1.30–1.40	21.0	11.6	.14	.63	11,980	81.4	6.8	.06	.52	11,779
1.40–1.50	3.5	26.1	1.16	1.68	9,800	84.9	7.6	.11	.57	11,698
1.50–1.60	2.6	35.8	2.53	2.99	8,320	87.5	8.5	.18	.64	11,597
1.60–1.80	6.0	50.7	2.51	2.86	6,170	93.5	11.2	.33	.78	11,249
Sink– 1.80	6.5	58.9	7.29	7.37	4,770	100.0	14.3	.78	1.21	10,828
Minus– 100	2.5	20.9	1.24	1.78	10,820	100.0	14.4	.80	1.22	10,828

TABLE 37. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 3B, SAMPLE A, STANDING ROCK AREA, 3/8 INCH BY 0

SPECIFIC GRAVITY FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	44.7	4.0	0.06	0.44	13,010	44.7	4.0	0.06	0.44	13,010
1.30–1.40	27.9	13.0	.06	.45	11,600	72.6	7.4	.06	.44	12,468
1.40–1.50	5.1	25.3	.30	.67	9,780	77.7	8.6	.08	.46	12,291
1.50–1.60	2.8	38.3	.35	.61	7,960	80.5	9.7	.08	.46	12,141
1.60–1.80	4.8	52.9	.81	.92	5,680	85.3	12.1	.13	.49	11,777
Sink –1.80	14.7	73.7	.84	1.19	2,360	100.0	21.2	.23	.59	10,393
Minus– 100	2.9	30.4	.32	.79	9,250	100.0	21.4	.23	.60	10,360

TABLE 38. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 3B, SAMPLE C, STANDING ROCK AREA, 3/8 INCH BY 0

SPECIFIC GRAVITY FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	63.6	4.4	0.07	0.53	13,180	63.6	4.4	0.07	0.53	13,180
1.30–1.40	16.2	11.8	.21	.70	12,020	79.8	5.9	.10	.56	12,944
1.40–1.50	4.4	26.8	.66	1.15	9,740	84.2	7.0	.13	.60	12,777
1.50–1.60	2.2	36.4	1.27	1.58	8,270	86.4	7.7	.16	.62	12,662
1.60–1.80	3.4	51.8	1.18	1.47	5,980	89.8	9.4	.20	.65	12,409
Sink –1.80	10.2	75.0	2.71	2.92	1,850	100.0	16.1	.45	.88	11,332
Minus– 100	2.1	24.5	.56	1.00	10,020	100.0	16.3	.45	.89	11,305

TABLE 39. WASHING CHARACTERISTICS OF COAL OBTAINED FROM CORE HOLE 16, STANDING ROCK AREA, ⅜ INCH BY 0

SPECIFIC GRAVITY FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
Float –1.30	61.6	4.5	0.10	0.88	12,860	61.6	4.5	0.10	0.88	12,860
1.30–1.40	22.2	9.9	.47	.81	12,130	83.8	5.9	.20	.86	12,667
1.40–1.50	5.8	24.0	.54	.92	10,020	89.6	7.1	.22	.86	12,495
1.50–1.60	3.9	34.1	.45	.81	8,450	93.5	8.2	.23	.86	12,326
1.60–1.80	3.2	43.0	.30	.65	6,920	96.7	9.4	.23	.86	12,148
Sink –1.80	3.3	74.1	1.18	1.19	2,160	100.0	11.5	.26	.87	11,818
Minus– 100	3.5	23.0	.20	1.20	10,360	100.0	11.9	.26	.88	11,769

TABLE 40. SCREEN ANALYSIS OF COAL OBTAINED FROM CORE HOLE 12, SAMPLE A, BISTI AREA, ⅜ INCH BY 0

SIZE FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
⅜ by 7	63.7	21.9	0.08	0.39	9,030	63.7	21.9	0.08	0.39	9,030
7 by 14	14.2	20.7	.08	.41	9,150	77.9	21.7	.08	.39	9,052
14 by 28	9.3	19.9	.16	.39	9,210	87.2	21.5	.09	.39	9,069
28 by 100	9.6	22.5	.04	.45	10,257	96.8	21.6	.08	.40	9,186
100 by 200	1.3	26.3	.04	.47	9,770	98.1	21.6	.08	.40	9,194
Minus– 200	1.9	30.9	.04	.49	9,060	100.0	21.8	.08	.40	9,192

TABLE 41. SCREEN ANALYSIS OF COAL OBTAINED FROM CORE HOLE 12, SAMPLE B, BISTI AREA, ⅜ INCH BY 0

SIZE FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
⅜ by 7	61.7	20.4	0.04	0.40	10,820	61.7	20.4	0.04	0.40	10,820
7 by 14	15.8	15.0	.07	.44	11,620	77.5	19.3	.05	.41	10,983
14 by 28	10.6	15.7	.06	.51	11,500	88.1	18.9	.05	.42	11,045
28 by 100	8.9	17.5	.15	.52	11,187	97.0	18.7	.06	.43	11,058
100 by 200	1.4	19.5	.10	.53	10,810	98.4	18.8	.06	.43	11,054
Minus– 200	1.6	22.0	.91	1.38	10,580	100.0	18.8	.07	.45	11,047

TABLE 42. SCREEN ANALYSIS OF COAL OBTAINED FROM CORE HOLE 13, SAMPLE A, BISTI AREA, ⅜ INCH BY 0

SIZE FRACTION	DIRECT					CUMULATIVE				
	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
⅜ by 7	50.6	23.4	0.08	0.52	9,440	50.6	23.4	0.08	0.52	9,440
7 by 14	20.5	22.4	.03	.59	9,450	71.1	23.1	.06	.54	9,442
14 by 28	10.4	23.1	.06	.60	9,140	81.5	23.1	.06	.55	9,404
28 by 100	12.8	24.6	.05	.72	8,915	94.3	23.3	.06	.57	9,338
100 by 200	2.4	29.0	.06	.82	8,270	96.7	23.4	.06	.58	9,311
Minus– 200	3.3	32.3	.16	.96	7,720	100.0	23.7	.06	.59	9,259

TABLE 43. SCREEN ANALYSIS OF COAL OBTAINED FROM CORE HOLE 13, SAMPLE B, BISTI AREA, ⅜ INCH BY 0

	DIRECT					CUMULATIVE				
SIZE FRACTION	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
⅜ by 7	63.2	21.6	0.04	0.36	10,250	63.2	21.6	0.04	0.36	10,250
7 by 14	15.1	19.2	.03	.50	10,560	78.3	21.1	.04	.39	10,310
14 by 28	10.8	19.1	.12	.48	10,570	89.1	20.9	.05	.40	10,341
28 by 100	8.1	19.3	.12	.51	10,552	97.2	20.8	.05	.41	10,359
100 by 200	1.3	22.1	.21	.56	10,240	98.5	20.8	.06	.41	10,357
Minus–200	1.5	25.8	.49	.80	9,810	100.0	20.8	.06	.42	10,349

TABLE 44. SCREEN ANALYSIS OF COAL OBTAINED FROM CORE HOLE 11, SAMPLE A, STAR LAKE AREA, ⅜ INCH BY 0

	DIRECT					CUMULATIVE				
SIZE FRACTION	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
⅜ by 7	60.2	21.7	0.18	0.70	10, 430	60.2	21.7	0.18	0.70	10,430
7 by 14	15.6	18.4	.18	.76	10,860	75.8	21.0	.18	.71	10,518
14 by 28	11.0	19.2	.16	.67	10,680	86.8	20.8	.18	.71	10,539
28 by 100	9.7	19.8	.18	.88	10,547	96.5	20.7	.18	.72	10,540
100 by 200	1.5	23.2	.21	1.05	9,990	98.0	20.7	.18	.73	10,531
Minus–200	2.0	27.5	.45	1.31	9,290	100.0	20.9	.18	.74	10,506

TABLE 45. SCREEN ANALYSIS OF COAL OBTAINED FROM CORE HOLE 11, SAMPLE B, STAR LAKE AREA, ⅜ INCH BY 0

	DIRECT					CUMULATIVE				
SIZE FRACTION	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS	WEIGHT, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT	BRITISH THERMAL UNITS
⅜ by 7	62.8	34.0	0.20	0.64	8,660	62.8	34.0	0.20	0.64	8,660
7 by 14	14.2	32.9	.12	.58	8,820	77.0	33.8	.18	.63	8,690
14 by 28	10.3	36.2	.14	.52	8,280	87.3	34.0	.18	.62	8,641
28 by 100	8.9	38.1	.17	.58	8,043	96.2	34.4	.18	.61	8,586
100 by 200	1.6	41.5	.21	.65	7,530	97.8	34.6	.18	.61	8,568
Minus–200	2.2	43.4	.53	.93	7,140	100.0	34.8	.19	.62	8,537

TABLE 46. ULTIMATE ANALYSES OF CORE SAMPLES COLLECTED IN SAN JUAN BASIN

NMBM & MR			AS RECEIVED						MOISTURE-FREE						MOISTURE- AND ASH-FREE				
HOLE NUMBER	SAMPLE DESIGNATION	COAL AREA	HYDROGEN	CARBON	NITROGEN	OXYGEN	SULFUR	ASH	HYDROGEN	CARBON	NITROGEN	OXYGEN	SULFUR	ASH	HYDROGEN	CARBON	NITROGEN	OXYGEN	SULFUR
8	—	Cortez	3.1	40.2	0.5	9.5	0.3	46.4	2.8	41.6	0.5	6.7	0.3	48.1	5.4	80.2	1.0	12.7	0.7
5	—	Newcomb	5.5	43.9	.9	26.5	.5	22.7	4.3	53.9	1.0	12.3	.7	27.8	5.9	74.7	1.4	17.1	.9
5A	A	Newcomb	5.8	55.6	1.1	23.3	1.2	13.0	4.8	66.0	1.3	11.1	1.4	15.4	5.7	78.0	1.5	13.2	1.6
5A	B	Newcomb	6.0	55.6	1.1	25.2	1.4	10.7	4.9	67.3	1.3	11.8	1.7	13.0	5.6	77.4	1.5	13.5	2.0
12	A	Bisti	5.3	49.5	.9	22.9	.3	21.1	4.6	56.7	1.1	13.0	.4	24.2	6.1	74.8	1.4	17.2	.5
12	B	Bisti	5.7	54.4	1.1	22.5	.3	16.0	4.7	63.6	1.2	11.4	.4	18.7	5.8	78.3	1.5	13.9	.5
13	A	Bisti	5.3	44.1	.9	29.9	.5	19.3	3.9	54.7	1.1	15.7	.6	24.0	5.2	72.0	1.5	20.5	.8
13	B	Bisti	5.5	50.8	1.0	24.7	.4	17.6	4.4	60.9	1.2	11.9	.5	21.1	5.5	77.1	1.5	15.2	.7
15A	—	Bisti	5.6	54.7	1.0	22.1	.5	16.1	4.8	62.4	1.1	12.7	.6	18.4	5.9	76.4	1.3	15.7	.7
7A	—	Chaco Canyon	2.8	22.6	.5	11.5	1.3	61.3	2.1	24.3	.5	5.6	1.4	66.1	—	—	—	—	—
11	A	Star Lake	5.5	52.5	1.0	22.9	.5	17.6	4.6	60.8	1.1	12.5	.6	20.4	5.7	76.4	1.4	15.7	.8
11	B	Star Lake	4.8	43.0	.8	20.4	.5	30.5	3.9	49.2	.9	10.6	.6	34.8	6.0	75.5	1.4	16.2	.9
3A	A	Standing Rock	6.4	60.9	1.0	24.1	.5	7.1	5.5	71.9	1.2	12.5	.5	8.4	6.0	78.5	1.3	13.6	.6
3A	B	Standing Rock	5.9	61.5	1.0	26.2	.5	4.9	4.8	74.3	1.2	13.2	.6	5.9	5.1	79.0	1.3	13.9	.7
3A	C	Standing Rock	5.8	54.7	.9	23.5	1.0	14.1	4.7	65.4	1.1	10.7	1.2	16.9	5.7	78.7	1.3	12.9	1.4
3B	A	Standing Rock	5.4	50.4	.8	24.5	.5	18.4	4.2	60.0	1.0	12.3	.6	21.9	5.4	76.8	1.3	15.8	.7
3B	C	Standing Rock	5.8	54.3	.9	24.3	.8	13.9	4.8	64.1	1.1	12.6	1.0	16.4	5.8	76.7	1.3	15.0	1.2
16	—	Standing Rock	6.0	57.4	.9	25.4	.6	9.7	5.0	68.8	1.1	12.7	.7	11.7	5.7	77.8	1.2	14.5	.8

TABLE 47. PROXIMATE ANALYSIS OF CORE SAMPLES COLLECTED IN SAN JUAN BASIN

NMBM & MR			AS RECEIVED							MOISTURE- AND ASH-FREE	
			PERCENT				MOISTURE-FREE				
HOLE NUMBER	SAMPLE DESIGNA-TION	COAL AREA	MOISTURE	VOLATILE	CARBON	ASH	VOLATILE	CARBON	ASH	VOLATILE	CARBON
8	—	Cortez	3.5 (3.8[1])	19.1	31.0	46.4	19.8	32.1	48.1	38.2	61.8
5	—	Newcomb	18.5 (16.0)	27.7	31.1	22.7	34.0	38.2	27.8	47.2	52.8
5A	A	Newcomb	15.8 (16.4)	31.6	39.6	13.0	37.5	47.1	15.4	44.3	55.7
5A	B	Newcomb	17.4 (16.9)	31.5	40.4	10.7	38.1	48.9	13.0	43.8	56.2
12	A	Bisti	12.7 (14.0)	31.9	34.3	21.1	36.5	39.3	24.2	48.2	51.8
12	B	Bisti	14.6 (15.3)	30.8	38.6	16.0	36.1	45.2	18.7	44.4	55.6
13	A	Bisti	19.4 (19.9)	29.4	31.9	19.3	36.5	39.5	24.0	48.0	52.0
13	B	Bisti	16.6 (17.0)	29.3	36.5	17.6	35.2	43.7	21.1	44.6	55.4
15A	—	Bisti	12.4 (13.5)	33.9	37.6	16.1	38.7	42.9	18.4	47.5	52.5
7A	—	Chaco Canyon	7.2 (10.4)	16.8	14.7	61.3	18.1	15.8	66.1	—	—
11	A	Star Lake	13.6 (13.8)	33.4	35.4	17.6	38.6	41.0	20.4	48.5	51.5
11	B	Star Lake	12.6 (13.4)	28.7	28.2	30.5	32.8	32.4	34.8	50.3	49.7
3A	A	Standing Rock	15.3 (15.8)	36.9	40.7	7.1	43.6	48.0	8.4	47.6	52.4
3A	B	Standing Rock	17.3 (17.2)	34.5	43.3	4.9	41.7	52.4	5.9	44.3	55.7
3A	C	Standing Rock	16.4 (16.0)	31.8	37.7	14.9	38.1	45.0	16.9	45.8	54.2
3B	A	Standing Rock	16.0 (15.4)	31.1	34.5	18.4	37.1	41.0	21.9	47.5	52.5
3B	C	Standing Rock	15.4 (15.7)	33.2	37.5	13.9	39.2	44.4	16.4	46.9	53.1
16	—	Standing Rock	16.5 (16.4)	33.4	40.4	9.7	40.0	48.3	11.7	45.3	54.7

[1] Equilibrium moisture.

TABLE 48. ANALYSIS OF ASHES OF CORE SAMPLES COLLECTED IN SAN JUAN BASIN

NMBM & MR												
HOLE NUMBER	SAMPLE DESIGNA-TION	COAL AREA	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO_2	Na_2O	SO_4	SiO_2	TiO_2
8	—	Cortez	31.1	0.5	2.4	1.6	0.3	0.03	1.3	0.9	60.9	1.7
5	—	Newcomb	27.4	0.3	1.8	.7	.3	.03	2.4	1.1	63.0	1.2
5A	A	Newcomb	19.4	2.8	6.7	.6	1.2	.03	1.7	2.3	64.5	1.6
5A	B	Newcomb	25.1	2.7	9.7	.6	1.0	.03	2.4	1.9	56.7	1.2
12	A	Bisti	27.4	2.9	2.5	.5	.2	.03	2.2	3.7	58.1	1.5
12	B	Bisti	26.0	2.1	5.1	.3	.6	.02	5.4	2.0	58.3	1.4
13	A	Bisti	26.9	1.7	3.8	.9	.6	.06	2.0	1.9	60.5	1.4
13	B	Bisti	27.0	2.2	3.7	.5	.3	.03	3.0	1.8	61.0	1.4
15A	—	Bisti	38.7	4.0	3.0	.4	.2	.05	3.2	5.2	50.8	1.9
7A	—	Chaco Canyon	9.2	.5	3.5	1.4	.6	.02	.9	.7	83.4	.6
11	A	Star Lake	28.3	5.2	3.0	.3	.4	.02	2.8	5.4	52.7	1.6
11	B	Star Lake	29.2	1.5	2.3	.6	.6	.03	2.6	1.6	60.6	1.2
3A	A	Standing Rock	26.2	5.5	5.9	.3	.9	.05	4.3	6.6	50.3	1.1
3A	B	Standing Rock	15.7	7.3	7.9	.3	1.2	.11	4.8	12.3	48.0	1.6
3A	C	Standing Rock	17.5	2.5	7.4	.7	1.0	.05	1.6	3.1	67.8	1.2
3B	A	Standing Rock	25.5	2.9	5.9	.7	1.0	.14	2.0	3.8	56.2	1.3
3B	C	Standing Rock	18.9	7.3	4.9	1.2	1.0	.14	1.4	8.0	55.8	1.2
16	—	Standing Rock	28.6	3.7	5.4	.4	.6	.06	3.6	5.5	50.3	1.4

TABLE 49. ADDITIONAL ANALYSES OF CORE SAMPLES COLLECTED IN SAN JUAN BASIN

NMBM & MR Hole number	NMBM & MR Sample designation	Coal area	British thermal units: As received	British thermal units: Moisture free	British thermal units: Moisture and ash free	Ash fusibility °F: Initial deformation temp.	Ash fusibility °F: Softening temp.	Ash fusibility °F: Fluid temp.	Hardgrove grindability index	Pyritic sulfur moisture free
8	—	Cortez	6,810	7,060	13,590	2,910+	—	—	59	0.13
5	—	Newcomb	7,660	9,410	13,030	2,910+	—	—	64	.11
5A	A	Newcomb	9,700	11,510	13,610	2,570	2,620	2,690	55	.71
5A	B	Newcomb	9,730	11,780	13,540	2,730	2,780	2,830	58	1.10
12	A	Bisti	8,680	9,940	13,120	2,910+	—	—	51	.09
12	B	Bisti	9,440	11,050	13,600	2,910+	—	—	50	.10
13	A	Bisti	7,420	9,210	12,110	2,910+	—	—	71	.04
13	B	Bisti	8,880	10,640	13,480	2,910+	—	—	56	.08
15A	—	Bisti	9,630	10,990	13,470	2,910+	—	—	53	.18
7A	—	Chaco Canyon	3,980	4,290	—	2,870	2,910+	—	71	1.03
11	A	Star Lake	9,110	10,540	13,240	2,910+	—	—	55	.10
11	B	Star Lake	7,510	8,590	13,180	2,910+	—	—	51	.12
3A	A	Standing Rock	10,620	12,540	13,690	2,570	2,620	2,670	56	.01
3A	B	Standing Rock	10,810	13,070	13,900	2,090	2,140	2,250	62	.03
3A	C	Standing Rock	9,520	11,390	13,710	2,260	2,460	2,710	57	.75
3B	A	Standing Rock	8,870	10,570	13,530	2,790	2,840	2,890	62	.03
3B	C	Standing Rock	9,480	11,200	13,390	2,410	2,470	2,520	56	.41
16	—	Standing Rock	10,070	12,060	13,650	2,830	2,900	2,910+	62	.17

ELECTRICAL LOGGING

Figure 59 shows a typical suite of electrical logs for one of the coal tests (hole No. 8). In this case, gamma, spontaneous potential, resistivity, neutron, and gamma-gamma (density) logs were run. The geologist's description of the cuttings samples and of the core taken are included, along with a graphic plot of the formations penetrated, for comparison with electrical logs.

The resistivity log proved to be a reliable indicator of coal in sections with little sandstone, but did not always distinguish adequately between coal and sandstone beds of similar thickness. In most cases the distinction could be made by use of the neutron log, but a more definitive indication of coal (or extremely carbonaceous shale) was provided by the density log because of the almost unique low density 0f the organic material. In most cases, the best approach proved to be use of the density log to locate coal beds and the resistivity log for more precise determination of thickness once the coal was identified. The spontaneous potential log could often be adjusted to give strong response to coal, but the response was not reliable. In some instances, coals of approximately equal thickness and resistivity were recorded very differently by the spontaneous potential trace.

Gamma (natural radioactivity) logs were run principally for correlation purposes; in general, coals had very low radioactivity and could be distinguished readily from the more radioactive shale beds but not from "clean" sandstones. Some coals, however, were radioactive enough to be confused with shale.

Position and thickness of partings as thin as 1.0 foot could generally be determined from the resistivity log at the 20feet-per-inch scale used in this project, and tops and bottoms of coal beds could be determined with like precision. A subjective determination of ash content (i.e., whether "clean" or "dirty") could often be made.

The resistivity and spontaneous potential logs were strongly affected by the chemical character of the fluid in the hole. An effort was made to use the purest available fresh water for drilling so that the resistivity of the water would be low and allow small differences in formation resistivity to be discernible. A highly conductive water would have "short circuited" the measuring current and masked such differences. The density log, relying as it does on measurement of absorption of radiation, is independent of fluid conductivity and can be used to advantage where the formation water is highly conductive.

A caliper log, which traces a continuous record of hole diameter, was run in some holes. An indication of relative hardness of a bed can be obtained from the degree to which it "washed out" as the hole was drilled.

NEW RESERVES INDICATED BY DRILLING

Before the drilling program was begun, several areas were recognized as having some potential for strippable coal, and it was planned to drill one or two carefully placed holes in each of several of the most promising areas. The areas chosen for this sort of preliminary exploration were: the western part of the San Mateo area, the southeastern end of the Standing Rock area and the immediate vicinity of Standing Rock, the extreme eastern part of the Gallup field, the northern end of the Newcomb area, the western end of the Chaco Canyon area, and the southeastern part of the Cortez area. Substantial new reserves were indicated by the drilling in the Standing Rock area (test holes Nos. 3A, 3B, and 6), the Newcomb area (test holes Nos. 5 and 5A), and the Cortez area (test holes Nos. 8, 9, and 10), and a small but significant reserve was further delineated in the western Chaco Canyon area. Speculative estimates of the benefits of the program in terms of new coal found are shown in Table 50.

TABLE 50. SUMMARY OF NEW STRIPPABLE RESERVES ESTIMATED AS A RESULT OF DRILLING PROGRAM, IN CONJUNCTION WITH SURFACE MAPPING AND USE OF OIL AND GAS TEST DATA

Field or area	Indicated reserve, millions of tons	Remarks
Standing Rock	75.0	Eastern end. Some extension likely
Standing Rock	63.5	Standing Rock Trading Post area. Some extension likely
Newcomb	77.8	North end of area
Cortez	135.4	East of Cortez
Cortez	10.0	West of Cortez
	361.7	

Economic Factors in the Utilization of San Juan Basin Coal

by William R. *Speer*

The purpose of this chapter is to evaluate the economic factors which govern the uses to which the San Juan Basin coal will be put in the future. In order to fit the San Juan Basin coal of New Mexico and Colorado into the national and regional energy pattern, it is necessary first to discuss national energy requirements, and the partial interchangeability of fuels and the geographic distribution of supplies.

NATIONAL DEMAND FOR ENERGY

The National Research Council (1969) estimated that the United States by the year 2000 will support a projected population of between 300 and 340 million people, compared to the present 204.7 million. The world population at that time will have grown from the current 3.5 billion to between 6 and 7 billion people. According to Glenn Seaborg (1969), Chairman of the U.S. Atomic Energy Commission:

> "The first city with a population as great as 100,000 came into existence about 25 centuries ago. It took another 2,300 years for the first city to reach the million mark—and this was as you know London about 1830. In 1900, 70 years later, 10 cities had a population of a million; today another 70 years, there are more than 130 such cities, and seven of these contain more than 10 million people.
>
> In the first century A.D., the world's population was about 250 million people. It took a full 16 centuries for that figure to double. The population of the world today is more than 3 billion, and its doubling time has decreased to a mere 35 years.
>
> Let us see what may lie ahead for the world's census. Our more than 3 billion people will become by the year 2000—just around the corner, actually—more than 6 billion people. Unless we become successful in our programs of population control, today's infant could expect to see in old age a world containing 15 billion people. His grandchildren might live to see a nightmarish world population of 60 billion—a full 20 times the number we have on earth today.
>
> Closer to home, in the United States today, there are 50 million more Americans than there were in 1950, and 20 million more than there were in 1960. It has been estimated that by 1975 there will be still 30 million more. One population expert has said that at current rates of increase the population of our metropolitan areas would multiply 40 times within the next 100 years."

Man lives in a world of finite resources upon which he is entirely dependent for his existence, thus the intelligent management of available resources is a necessity in order to sustain, and perhaps improve, human life on earth. The increasing number of pe0ple on earth and the rate of this increase add a note of urgency to all resource management decisions. Even if the projected 50-percent increase in United States population by the year 2000 is reduced by a leveling off of the birth rate, intensive management of all nonrenewable resources is essential.

Besides food supplies, an integrated management includes mineral fuels, metallic and nonmetallic minerals, and industrial rocks. The nonfuel minerals and industrial rocks are unevenly distributed and in short supply in many categories essential to an industrialized society. Known reserves of metallic minerals, even in low-grade ores, will be exhausted by the end of this century. Potential reserves and those yet to be found will require improvements and innovations in exploration, extraction, and utilization methods. Resources which might be expected from exploitation of the seas are a largely unknown, but perhaps overrated source of probable supplementary reserves.

In considering fuel resources, the rapid rate of consumption is startling. M. King Hubbert observed (National Research Council, 1969):

> "When consideration is given to the factual data pertaining to both the world and the U.S. rates of production of coal and oil . . . two results of outstanding significance become obvious. The first of these is the extreme brevity of the time during which most of these developments have occurred. For example, although coal has been mined for about 800 years, one-half of the coal produced during that period has been mined during the last 31 years. Half of the world's cumulative production of petroleum has occurred during the 12-year period since 1956. Similarly, for the United States, half of the cumulative coal production has occurred during the 38-year period since 1930, and half of the oil production during the 16-year period since 1952. In brief, most of the world's consumption of energy from the fossil fuels during its entire history has occurred during the last 25 years.
>
> The second obvious conclusion from these data is that the steady rates of growth sustained during a period of several decades in each instance cannot be maintained for much longer periods of time."

Hubbert's calculations indicate that the earth's coal supplies are sufficient to serve as a major source of industrial energy for only two to three centuries. Petroleum resources, both oil and natural gas, have a capacity of only 70 to 80 years at present consumption rates. Other sources of energy, excluding nuclear energy, do not appear promising for more than a fractional portion of the requirements. These sources include solar energy (technologically unpromising), geothermal and tidal energy (limited to favorable occurrences), and hydropower (most sites developed in the industrial regions, but having potentialities in undeveloped areas).

Nuclear energy alone is of sufficient magnitude to meet the world's future demands, but it has some technological limitations which will have to be overcome. The primary problem is that power reactors as presently designed are extremely wasteful of their uranium fuel, and uranium deposits are limited. It is technically feasible, however, to construct a breeder reactor which will effectively utilize uranium fuel to the extent that proven and potential uranium reserves represent an energy source many times larger than that of all fossil fuels. The use of this type of energy for all power generation, with the consequent saving of the fossil fuels, is considered by the National Academy of Sciences to be of such importance to the future that the following recommendations for suggested national policy were made:

"That the development of high-neutron-economy reactors be accelerated, including an efficient and safe type or types of breeder reactor(s). The development of nuclear energy is an urgent national and global goal because of the approaching depletion of fossil fuels and the need to conserve them for other purposes. But without greater utilization of uranium-238 and thorium-232 through breeding or other efficient conversion, the economics of nuclearower is such that the supply of uranium-235 from high-gradep ores at current prices could become severely restricted within a few decades. The achievement of nuclear fusion, of course, would greatly extend nuclear reserves in the very long term, and fundamental research in this field should be continued.

"That the fossil fuels be conserved for uses which cannot be met by other sources. The fossil fuels (petroleum, natural gas, coal) are needed for petrochemicals, synthetic polymers, and essential liquid fuels, for which suitable substitutes are as yet unknown. They might also play a part in synthetic or bacterial food production (although such a use is also limited). They should not be spent in the generation of electricity, for heating, and for industrial purposes where substitutes can qualify. The Department of the Interior should be authorized and directed to develop and institute a practicable and effective hydrocarbon conservation program."

Not only has the demand for energy increased correspondingly with the population increase, but the per capita use of energy has also increased. Overall energy consumption has grown at the rate of 5 percent per year since 1965, as compared to a 2.8 percent average annual increase during the period 1947 to 1956 (Broderick, 1969). A U.S. Bureau of Mines study of the nation's supply and demand for energy (Zaffarano et al., 1969) indicated that for the year 1965, oil was the leading primary energy source, supplying 42 percent of the nation's gross energy demands. Natural gas was second with 31 percent, coal was third with 23 percent, and hydropower was fourth with 4 percent. Nuclear sources were insignificant. These comparisons were made on equivalent values of British thermal units (see table 51).

Preliminary statistics for the year 1969 give the following corresponding figures: oil 39.5 percent, natural gas 35.6 percent, coal 20.6 percent, hydropower 3.1 percent, and nuclear energy 1.2 percent (U.S. Bureau of Census, 1970). Utility electricity is considered as a secondary source of energy, being generated by the fossil fuels as primary sources of energy. The percentage of each primary source used in generating electricity in 1965 was 65 percent by coal, 27 percent by natural gas, and 8 percent by oil (Zaffarano et al., 1969). The nation's t0tal consumption of these energy sources in 1965, in each of the four main sectors of use, were as shown in Table 51: electrical-power generation 21 percent, industrial 29 percent, transportation 25 percent, and household and commercial 21 percent. Four percent is classified as miscellaneous. Included in the transportation category is the extensive use of motor fuels, while the industrial cate-

TABLE 51. ENERGY CONVERSION FACTORS AND PRICES

FUEL	COMBUSTION ENERGY		AVERAGE PRICE/M²BTU	
Coal	Est. Av. Btu's/lb.[a]	M²Btu's/ton[a]	Mine-Mouth Ave.—U.S.[b]	
Anthracite	12,700	25.4		
Bitum. & lignite	13,100	26.2	$0.068 to 0.285	$0.189
Coke	13,000	26.0		
Fruitland subbit.	9,000	18.0	0.14[c]	
Mesaverde subbit.	10,500	21.5	0.158[c]	
Petroleum Products		M²Btu's/bbl.[d]	Producer[e]	Consumer[e]
Gasoline		5.248	$0.84-1.18 (refiner)	$1.19-2.07
Kerosene		5.670		0.07-0.85
Distillate fuel oil		5.825		0.66-0.87
Residual fuel oil		6.287		0.40-0.70
Liquefied petr. gases (L.P.G.)		4.011	0.40-0.50[f]	
Crude oil (avg.)		5.677	0.55[f]	
Natural Gas		M²Btu's/MCF[g]		
Dry methane		1.035	$0.175[h]–U.S. producer avg. 0.135[f]–San Juan Basin producer 0.38[h] –Interstate pipeline resale 1.07[i] –U.S. residential avg.	
Uranium-235	(FISSION ENERGY)	M²Btu's/gram[j]		
		77.64	$0.20 ($U_3O_8$)[k]	
Electrical Megawatt Hr.		M²Btu's/hr.[l]		
		10.32	$1.59–U.S. residential avg.[l]	

Sources:
(a) U.S. Bur. Mines I.C.8401
(b) Keystone Coal Industry Manual, 1970
(c) Arizona Public Service Co.
(d) U.S. Bur. Mines I.C.8411
(e) Oil and Gas Journal 9-28-70
(f) San Juan Basin listings–EPNG Co., Shell Oil Co.
(g) U.S. Bur. Mines I.C.8403
(h) Fed. Pwr. Comm.
(i) Instit. of Gas Technology
(j) Resources & Man, Nat'l Acad. of Sciences
(k) U.S. Atomic Energy Comm.
(l) U.S. Bur. Mines, I.C.8402

M²Btu = 1,000,000 Btu
Megawatt = 1,000,000 watts

g0ry includes 20 percent attributable entirely to steel industry use. Corresponding percentages for 1968 (U.S. Bureau of Census, 1970) indicate energy resource consumption in the major use sectors were 22.5 percent for electrical-power generation, 31 percent for industrial, 24.2 percent for transportation, and 21.8 percent for household and commercial, with 0.5 percent as miscellaneous.

Electrical-power generation is the fastest growing consumption sector, having had a growth rate of about seven percent during the past three decades and an average of eight percent in the past three years (Boffey, 1970). This phenomenal increase in demand presently requires a doubling of electrical-generating facilities every ten years. With a current total installed generating capacity of about 313,000 megawatts, the Federal Power Commission estimated (Seaborg, 1969) that this capacity must be more than tripled by 1990 to over one million megawatts.

Regionally the western portion of the United States has experienced the greatest rate of growth in population in the nation. The consequent increase in energy demand is reflected in the fact that estimates of electrical-power requirements in the load centers of the Pacific Coast and Rocky Mountain States will quadruple between 1970 and 1990 (NAPCA, 1970).

All segments of energy use require a critical study of future production rates, recoverable reserves, competitive economics, and effective use of each of the primary sources of energy. Added to these considerations is an important new force which has made a notable entry on the national consciousness in recent years, the effect 0n the environment. This has been and will be receiving increasing attention by the public and by state and federal agencies.

The environmental movement seeks to save mankind from smothering itself in the waste products of its own industrial society. The insatiable need for energy to run factories, residences, and transportation systems, while accelerating the output of the energy industries, has simultaneously escalated related pollution problems. The production and use of fuels are primary contributors to a deteriorating environment; protective legislation has been enacted to correct obvious imbalances. While many pollution pr0blems are common to the use of all fuels, they vary in magnitude and method of amelioration. The demand for each energy source will require consideration of each fuel's unique pollution problems.

NATIONAL ENERGY SUPPLIES

Future supplies of primary energy in the United States are due both short- and long-run shortages and consequent market dislocations, according to most predictions in recent years. The dominati0n of energy growth markets by natural gas, amounting to 58 percent of the total growth in the last decade, is due a substantial drop. The production rate of natural gas in the last three years has exceeded the rate of discovery of additional reserves for the first time since 1946, heralding a shortage of this fuel. This occurs at a time when this clean fuel is in demand to meet new air-quality regulations. The shortage will pose no immediate problem for the residential and commercial customers 0r industrial users with firm contracts, but will affect new and interruptible contract industrial customers and those planning conversions to meet clean-air regulations (Oil and Gas Jour., 1970).

The large growth field of electrical-power generation is experiencing some slowdowns, partially from the failure of nuclear-reactor construction to meet demands, and partially from a drop in coal production and in residual oil supply in the big Northeastern United States market. Nuclear energy is projected to capture 60.4 percent of the power-generation market by 1995, with coal supplying 22.5 percent, natural gas 9 percent, and hydropower 5.5 percent (Bennett, 1970). The decreases in coal and gas percentages over present requirements in this field do not mean less volume demand. The overall increase in use of electrical power will result in increases in total volume requirements of both fossil fuels.

Engineers and economists of the public-utilities industry disagree at present as to what constitutes the ideal "fuel-mix" for powering the future electrical plants. Fuel-mix describes the possible combinations of primary fuels to be used in generating the nation's electrical needs. At present, the national fuel-mix, as dictated by economics, is 58 parts coal, 30 parts natural gas, 9 parts oil, and 3 parts nuclear.

From a pollution-control standpoint, an ideal fuel-mix could have the three coastal areas rely entirely on atomic power because of abundant seawater to cool reactor cores, allow the heavier industrial and populated areas of the Midwest to use clean-burning natural gas and low-sulfur oil, and restrict coal burning to sparsely populated areas of the Plains and Mountain States. One problem is that this suggestion is incompatible with the geological and geographic distribution of the fuels. The Gulf Coast and West Coast are oil rich, most of the nation's coal is presently mined in the industrial Midwest and Eastern States, uranium is concentrated in the Rocky Mountain States, and most of the gas reserves are in Texas, Oklahoma, Louisiana, and New Mexico. To shift the current fuel-mix of the several regions to conform to this ideal pollution-control "model" would, with the exception of uranium, place expensive transportation costs on the fuels.

Oil is not a big factor in power generation, except on the Eastern seaboard, but it is still the largest supplier of energy in the United States. Consumption in 1969 was 5.16 billion barrels, 46.2 percent more than that consumed in 1960. The production-to-reserve ratio als0 is falling in this fuel, with only 9.6 times as many barrels of unproduced, discovered reserves as the number of barrels produced in 1969. The drop in both oil and gas reserves is attributable in large part to the decline of exploration and drilling activity in the United States over the past decade (20.6 percent since 1960), reaching a new 27-year l0w in 1969 (Am. Assoc. Oil-well Drill. Contr., 1970). The decline in drilling activity has resulted from higher exploration costs, lower discovery rati0s, removal of tax incentives, and low product price.

Despite the oil-import control program, United States imports of foreign oil have been steadily climbing. In 1969 the 1.15 billion barrels imported represented 22.1 percent of all oil consumed by the nation. The United States has been a net importer of foreign petroleum and petroleum products since 1948.

A Chase-Manhattan Bank study (Oil and Gas Jour., 1970) indicated that by 1980 the United States will consume energy equivalent to almost 52 million barrels of oil per day. If there were no supply limitations, 16.5 million bbl./day equivalent would be supplied by natural gas, 23.5 million by oil, and the balance of **12** million by coal, nuclear, and hydropower. Impending gas shortages, however, indicate no more than 11 million barrels per day of gas equivalent will be available at that time so that the 5 million barrels per day deficit will have to be met by other fuels. Chase-Manhattan suggested that 3.5 million barrels will come from oil and two million barrels equivalent from coal. Oil requirements in 1980 were estimated to be 25 million barrels per day (compared to 15 million barrels per day in 1970) and will be supplied from the following sources: conterminous 48 States, 10 M^2b/d (million barrels per day); Alaska, 2.5 M^2b/d; and foreign imports the balance (Middle East and Africa, 7.1 M^2b/d; Canada, **2** M^2b/d; and other Free World nations, 3.2 M^2b/d). Thus, one-half of the required oil will be imported.

Another recent study (Oil and Gas Jour., 1970) stated that previous projections for an annual growth of 3.5 percent each year for the next five years for oil, 6 percent for natural gas, and 4 percent for coal should be revised to show oil gaining 5.2 percent each year and natural gas and coal having a 5-percent and **2.5-percent** gain respectively. The gains in oil use are to be in residual fuels and distillates. Residual fuel oil is used by many electrical-power utilities in the industrial Northeast in lieu of coal. The stronger mining-safety standards and higher startup, labor, and transportation costs of coal will lessen its use. Use of distillate in residential heating and as a replacement for turbine fuel in electrical power "peak-shaving" (short-term, high-load) plants, is seen as cutting into use of natural gas. Gas is in demand to meet antipollution requirements, but the impending shortage of gas makes switching feasible.

It is difficult to envision increases of domestic residual fuel oil sales, in view of the late 1970 residual fuel oil shortage crises, and the resultant power outages on the Eastern seaboard. A study of this problem by the U.S. Department of Interior's Office of Oil and Gas (Petroleum Info., 1970) revealed that 93.7 percent of the needs of consumers on the East coast are supplied by foreign imports, principally from Western European refineries processing low-sulfur crudes from Africa. United States refiners ceased refining the heavy residual oils, changing to the more marketable lighter ends, when importation of cheaper foreign residual was essentially decontrolled in 1966 in the face of increased demand. This demand resulted from the fact that residual oil is the largest source of energy consumption in Eastern United States, accounting for 45 percent of total consumption in 1969. Foreign residual deliveries to East coast ports in 1969 accounted for 40 percent of the nation's total imports during the year.

An acute shortage has recently developed as a result of the Middle East political crises. This has driven the price per barrel of residual oil to over $4 in some instances. The immediate Middle East problem in oil supply disruptions results from the cutting of the Trans-Arabian pipeline in Syria, Libyan government cutbacks in production to exact higher royalty rates, a shortage of tankers which are now being used on longer European runs, and a marked escalation in tanker rates. This situation has forced United States refiners to reassess the residual market, but the conversion has resulted in a lag time and a dislocation of the gasoline and distillate markets. Coal may be the main benefactor, as it may win back some of the electric-utility market lost to oil in past years. However, the rigid pollution-control measures enacted on the East coast (sulfur content limits of **2.2** percent, to be dropped to 1 percent in 1971) affects the use of coal.

The percentage of contributi0n coal made to the total United States energy consumption has steadily declined from a high of 90 percent in 1900, but there has not been a comparable decrease in production. This results, of course, from the marked total increase in the use of energy. The lowest annual coal production in this century was 360 million tons in 1932; the highest was 688 million tons in 1947 (Averitt, 1969).

Coal as a primary energy source fell steadily in United States consumption during the 15 years following World War II, due primarily to the increased availability of petroleum and natural gas and the demise of the steam locomotive. Beginning in 1960, a rapid increase in use of coal by electric utilities was somewhat offset by a continued decline in use by the second biggest consumer of coal, the steel industry. This decline was a result of technical advances in steel making. However, even in 1969 the steel industry used the substantial amount of 95 million tons of coal to produce a record 141 million tons of steel (Phillips, 1970).

Technological advances in the use of coal in electrical-generating plants have also improved, and this is the field in which coal will have its most extensive use for the balance of this century. Phillips (1970) predicted that generating power plants alone in 1980 will require coal supplies equal to all of the nation's present annual production of 560.5 million tons. As the predicted increasing use of nuclear energy for power generation proceeds, even with the expected decline in economically obtainable petroleum and natural gas reserves, it is expected that the extensive remaining reserves of coal in the United States will serve as the source material for synthetic gas and liquid fuels, lubricants, and hydrocarbon chemicals for manufacturing.

Nuclear energy, offered as the main power source of the future, has not been considered to be a serious contender to fossil fuels for another decade. Furthermore, in the last two years, nuclear power has lost competitive position with coal and oil as a result of higher costs of nuclear components, turbines, and construction. With the additional effects of inflation and higher interest rates on the large capital costs of a nuclear reactor, orders for nuclear plants have declined and fossil-fuel plants have been interposed ahead of previously scheduled atomic units (Sporn, 1969).

The seriousness of the fuel shortages has led to consideration of the formation of a national government commission on fuels and energy, designed to coordinate government policies. These policies are now set by various governmental agencies such as the Atomic Energy Commission and Federal Power Commission. This proposed commission has the endorsement of the coal and petroleum industries and the Atomic Energy Commission; it would also establish policy on "end-use" controls or the responsibility for allocating different resources for future demands (Oil and Gas Jour., 1970).

NATIONAL AND REGIONAL FUEL RESOURCES COAL

The U.S. Geological Survey estimated (Averitt, 1969) that the nation's coal resources total 3,210 billion tons, of which half may be considered recoverable. Of this reserve, 1,560 billion tons are in a depth range from the surface down to 3,000 feet and have been determined from mapping and exploration. In the same depth range, probable resources in unmapped and unexplored areas total 1,313 billion tons. An additional 337 billion tons, unmapped and unexplored, are estimated to be in the 3,000- to 6,000-foot depth category.

The estimate of 1,605 billion tons of recoverable coal applies to that considered to be physically recoverable, but does not imply economical recoverability. Considering present mining practices only the coal resources down to a depth of 1,000 feet might be considered as economically recoverable at no more than 150 percent of current costs. Averitt (1969) noted that 89 percent of the reserves are less than 1,000 feet below the surface, and, further, that an average of 50 percent of underground coals and 80 percent of the strippable coals are physically recoverable with present-day mining methods. In 1968, 34.3 percent of all coal mined in the United States was surface mined. Utilizing these figures, an economically recoverable reserve of some 923 billion tons is available as mapped and explored and an additional 777 billion tons might be available in the unmapped or unexplored areas. The 923 billion tons might be considered as "proved" and comparable to the American Petroleum Institute's "proved" domestic petroleum reserve of 31.4 billion barrels. The combination of "proved" and "possible" would total 1,700 billion tons of coal which might be recovered at the assumed 150 percent of today's costs.

Of the nation's total coal resources, 441/2 percent is of bituminous grade and 29 percent is in beds more than 3 feet in thickness for anthracite and bituminous grades and more than 10 feet in thickness in subbituminous and lignite grades. More than half of the potential reserves lie in the Rocky Mountain States with North Dakota included.

The United States contains about 17 percent of the world's coal that has been mapped and explored and about 20 percent of the world's estimated total reserves. A comparison of all the nation's fuel resources on a uniform basis of Btu values shows coal constituting 73 percent of the total reserves estimated as recoverable. Petroleum and natural gas together make up 9 percent and oil shale 17 percent (Averitt, 1969).

New Mexico Resources

New Mexico has been credited by Averitt (1969) with the following remaining coal resources: bituminous, 10,760 million tons in the Raton, Cerrillos, Uña del Gato, Tijeras, Jornada del Muerto, Carthage, and Sierra Blanca fields; subbituminous, 50,715 million tons in the San Juan Basin coal fields and Datil Mountains, Rio Puerco, and Engle fields; anthracite and semianthracite, 4 million tons in the Cerrillos field, and with no lignite fields or production. The amounts of coal having been produced or lost in the mining process in each category are: bituminous, 188 million tons; subbituminous, 86 million tons; and anthracite, 2 million tons.

According to tonnage and heating value comparisons, New Mexico ranked tenth in a 50-state ranking in reserves determined by mapping and exploration. The State's production of coal in 1969-5,130,653 tons—was utilized 80 percent for power generation and 20 percent for steel production. This production represented an increase of more than 17 times the production in 1960 (Hays, 1970). The steel-industry use was supplied entirely from mines in the Raton Basin coal fields of northeastern New Mexico which contain most of the coking coal in the State. "Steam" coals or those used in the thermal generation of electricity come almost exclusively from the San Juan Basin of northwestern New Mexico.

In the San Juan Basin, coals occur in the Fruitland Formation, the Mesaverde Group, and the Dakota Sandstone of Late Cretaceous Age. The configuration of the Basin, with gently inward dipping strata dominating, makes many of the coal beds amenable to strip mining. Underground coal mining has taken place in the past in the Gallup Sandstone, the Dilco Coal Member and Gibson Coal Member of the Crevasse Canyon Formation, and the Allison Member and Cleary Coal Member of the Menefee Formation (all formations of the Mesaverde Group), as well as in the Fruitland Formati0n. These subsurface mines, most of which are in areas of more steeply dipping beds, are inactive or commercially unimportant at present. Two major strip-mining operations are producing today in the San Juan Basin, with a third imminent.

The McKinley mine of the Pittsburg and Midway Coal Co. produces high-volatile C bituminous coal from five separate and irregular coal lenses in the Gibson Coal Member and Cleary Coal Member. It is in the extreme southwestern corner of the Basin 14 miles west-northwest of Gallup. P & M's leases include 8,155 acres of public land with a strippable reserve of probably more than z00 million tons of coal averaging 10,500 Btu per pound.

The largest coal-stripping mine is the Utah Construction and Mining Co.'s Navajo mine just south of Fruitland. This mine has an average production of 22,000 tons per day of Fruitland Formation subbituminous coal which is utilized by the Arizona Public Service Co.'s electric generating plant near the mine. Utah Construction and Mining Co.'s lease of more than 31,000 acres on the Navajo Indian Reservation contains more than 1.1 billion tons of strippable coal (Nathan, 1965). With a projected annual production for 1970 of 5.9 million tons, it is the largest coal mine in the United States. Only about half of the estimated reserves to a maximum stripping depth of 180 feet are dedicated to the 42-year contract with Arizona Public Service Co. and other WEST Associates (Utah C0nst. & Min. Co., 1968).

A third strip mine is to become active in 1972 immediately north of the Navajo mine on properties of the Public Service Co. of New Mexico, which include federal and state leases on 7,700 acres with an estimated strippable Fruitland Formation coal reserve of over 50 million tons (Nathan, 1965). This coal will be used to supply a 1,035-megawatt electric-generating plant whose first 345-megawatt unit is scheduled for completion in the fall of 1973 (Montgomery, 1970).

Another coal lease on the Navajo Reservation, immediately south of the Utah Construction and Mining Co.'s properties, contains over 40,000 acres and an estimated Fruitland Formation coal reserve of more than 483 million tons of strippable coal. This ten-year lease is owned jointly by El Paso Natural Gas Co. and Consolidation Coal Co. These coal reserves were obtained primarily for use as feed stock for gasification processes. Extensive mining of these coals depends on current coal-gasification research, but the annual rental and development cost provisions of the lease call for expenditures of $200,000 per year. This indicates some development will be pursued.

An additional 25,800 acres of federal land are under coal leases and more than 160,000 acres are under prospecting permits in the San Juan Basin.

PETROLEUM AND NATURAL GAS

The Independent Petroleum Association of America reported that the 1969 production of crude oil in the United States was 3,364 million barrels and that of natural gas liquids was 580 million barrels. Natural gas consumption was 20.3 trillion cubic feet. Proven reserves of liquid hydrocarbons were reported (Am. Assoc. Oilwell Drill. Contr., 1970) as 29,632 million barrels of crude and 8,143 million barrels of L.N.G. The Potential Gas Committee (1969) reported proven natural gas reserves of 287 trillion cubic feet as of December 31, 1968.

New Mexico Production and Proven Reserves

New Mexico's share in the 1969 production of oil and gas was estimated by the American Petroleum Institute and the American Gas Association (Albuq. Jour., Apr. 12, 1970) as 120.5 million barrels of crude oil, 48.3 million barrels of L.P.G., and 1.08 trillion cubic feet of natural gas. During the year, an additional reserve of 91.8 million barrels of crude oil was credited to New Mexico through the discovery of new pools, new fields, extensions of known pools, and the revision of existing reserves based on new data. Additions to the liquid petroleum gases and natural gas reserves by the same methods were 33.1 million barrels and 0.23 trillion cubic feet respectively. This decline in the ratio of discovery to the amount of production in each commodity followed the national trend. The additions gave New Mexico the following remaining recoverable reserves: crude oil, 840 million barrels; natural gas liquids, 400 million barrels; and natural gas, 14.3 trillion cubic feet.

In the San Juan Basin, the natural gas reserves of 9.1 trillion cubic feet represent over three percent of the nation's total remaining recoverable reserves by A.G.A. estimates as of January 1, 1970. The State's largest interstate gas pipeline transporter credits the Basin with slightly under 23 trillion cubic feet original proven reserves of which six trillion cubic feet had already been produced as of January r, 1970. The remaining recoverable reserve of about 17 trillion cubic feet is almost double the A.G.A. estimate. The San Juan Basin field, producing roughly two billion cubic feet of gas per day from more than 10,500 wells in Upper Cretaceous sandstones, represents the nation's second largest single source of gas. The Hugoton field in Kansas ranks first. Over 92 percent of the producible gas from the Basin lies within the State of New Mexico. Natural gas products plants in the New Mexico part of the Basin process an average of 1.46 billion cubic feet of gas per day for the recovery of 58,800 barrels per day of propane, iso- and normal butanes and natural gasoline (Oil and Gas Jour., 1970).

Future Requirements and Potential Supplies

The A.P.I. and A.G.A. also reported (Oil and Gas Jour., 1970) a decline in the productive capacity of the United States (excluding Alaska) on a daily basis. Crude oil productive capacities in 1969 were down 428,000 barrels per day or 3.5 percent from the previous year. Liquefied natural gases were down 98,000 barrels per day or 3 percent and natural gas capacity was down 5.091 billion cubic feet per day or 4.8 percent. New Mexico was one of a few states having an excess capacity which was 23,000 barrels per day of crude oil and 20,000 barrels per day of L.N.G. The State, however, experienced a decline in natural gas capacity of 362 million cubic feet per day.

The National Petroleum Council's study (Indep. Petrol. Mon., 1970) for the Interior Department on future petroleum provinces of the United States, a panel of 135 petroleum geologists from all regions, was more optimistic and estimated that 55 percent of the discoverable oil and 66 percent of the discoverable gas remains to be found. If found and recovered at the present average rate of 32 percent of the total oil in place and 50 percent of the gas in the ground, the potential discoverable reserves could amount to 141 billion barrels of oil and 1,227 trillion cubic feet of gas. The report suggested that increased recovery factors of 60 percent are not unreasonable, given new well-completion techniques, in which case the potential reserves would be vastly increased.

Since liquid petroleum is utilized primarily in the transportation and industrial sectors of the nation's consumption and is competitive with coal in only a limited manner under current market demands, an examination of the economic resources of the natural gas industry is more pertinent to this study.

Undiscovered supplies of natural gas, which were projected by the authoritative Potential Gas Committee of the Mineral Resources Institute of the Colorado School of Mines, were broken down into categories of probable, possible, and speculative. These categories are based, respectively, on growth of existing fields (probable), new field discoveries in areas of established production (possible), and new field discoveries in areas of sufficient sediment thickness and type, but with no previous production (speculative). Their report (1969), as of December 31, 1968, placed the total ultimate discoverable volume of gas in the United States, including Alaska, at 1,859 trillion cubic feet. Of this total, 345 trillion cubic feet have already been produced, 287 trillion cubic feet are in the category of proven reserves (both drilled and undrilled, as estimated by the A.G.A. Gas Reserves Comm.), and 1,227 trillion cubic feet are in the undiscovered, potential category. The latter status is broken down as 260 trillion cubic feet of gas as probable, 335 trillion cubic feet possible, and 632 trillion cubic feet speculative.

This study divided the United States into eleven separate regions. New Mexico and Arizona were combined into one region having potential supplies of 12 trillion cubic feet of natural gas in the probable category, 3 trillion cubic feet in the possible, and 13 trillion cubic feet in the speculative category.

A parallel committee, the Future Gas Requirements Committee under the auspices of the gas industry in association with the Denver Research Institute, also predicted the nation's future need for natural gas. Their predictions have been compared with similar estimates made by the Institute of Gas Technology by H. R. Linden, Director of the I.G.T. Linden noted (1970) that the Committee estimates of 1.1 trillion cubic feet per year increase in requirements projected until the year 2000, do not take into account a drop in requirements after 1970 as the gas supply becomes unavailable. The I.G.T. projection showed requirements dropping to 0.8 to 0.9 trillion cubic feet per year in the 1970-80 period and a further decline to 0.6 to 0.7 trillion cubic feet from 1990 to 2000. This decline represents a growth rate of 2.5 percent per year compared to a conservative total United States primary energy growth rate of 3.1 percent per year over the same period. I.G.T.'s forecasts show natural gas' share of the total primary energy growth to be 31 percent in 1969, 33 percent in 1975, 32 percent in 1980, 29 percent in 1990, and 26 percent in 2000.

The impending shortage of natural gas is especially difficult for that industry to accept in the face of the marked annual increases in sales enjoyed during the last three years. Gas sales to utilities increased 5.4 percent in 1967, 8.3 percent in 1968, and 9.5 percent in 1969 according to A.G.A. figures. Sales to central power generation plants by Federal Power Commission statistics increased 5.3 percent in 1967, 14.5 percent in 1968, and 10.8 percent in 1969. Active pursuit of new potential markets has been a large part of the gas industry's recent programs.

The magnitude of the gas supply problem is indicated by the discrepancy between the current deliverability and the projected demands. The reserve to production ratio is the best indicator of deliverability. A ratio of ten years reserve is generally considered to be an absolute minimal at which deliverability can be economically maintained. The present ratio is only 13.8 years reserve.

On the basis of the 1969 projection by the Future Gas Requirements Committee, the net requirements for natural gas in the period of 1970 to 1990 would total 660 trillion cubic feet or an average of 31.4 cubic feet per year. If a reserve to production ratio of ten years is maintained, an increase of 400 trillion cubic feet is required by 1990 or 128.5 trillion cubic feet more than the total proven reserves at the end of 1969. This increase would require an addition of 38 trillion cubic feet per year from now until 1990, as compared with the current reserve addition of 21 trillion cubic feet in 1969 (Linden, 1970).

The available and potential supply of recoverable gas is not the immediate problem. The Potential Gas Commission projects economically recoverable reserves at 1,858 trillion cubic feet, the I.G.T. estimates 1,305 trillion cubic feet, and the U.S. Geological Survey estimates 2,740 trillion cubic feet. These estimates all indicate an adequate reserve to meet future demands. The problem is a technological and economical one of making the supplies available in the conterminous 48 States.

One need, as cited by gas producers to the Federal Power Commission, is to increase the incentive for additional domestic exploration and drilling by increasing the price of gas paid at the wellhead to the producer. The F.P.C. controls these prices and has regulated them in areas of major production on a complex cost-based, rate-of-return method in each area. Presently, the nationwide average price being received by domestic producers is $0.181/MCF (thousand cubic feet) or $0.175/M²Btu (million Btu) (Petrol. Info., 1970).

The F.P.C. has been studying recommendations by their staff that wellhead prices be increased for "new" gas (contractually uncommitted for purchase, as compared with "old" gas or gas contracted prior to 1960) from $0.035 to $0.115/MCF, depending on the area. They have also recommended that present rate-making procedures be overhauled to give more consideration to market realities. The staff's recommendations (Oil and Gas Jour., 1970) in the case of New Mexico's San Juan Basin was for a new gas price of $0.245/MCF as compared to the current $0.12 to 0.14/ MCF. This increase, however, would have little effect on most San Juan gas reserves as the majority of the remaining reserves and prospective acreage is committed under previous contracts and would be classified as "old" gas.

Even if a wellhead price increase were made effective immediately, serious deficiencies in natural-gas supply would begin in 1972-74 and reach an 18 to 24 trillion cubic feet/ year deficit by 1990, assuming the maintenance of a ten-year reserve to production ratio and using the Future Requirements Committee report's demand and import projections. Using the more conservative I.G.T. requirement forecast, a deficiency will begin in 1974 to 1977, would reach 12 to 18 trillion cubic feet in 1990, and 19 to 25 trillion cubic feet in the year 2000 (Linden, 1970).

As supplies from conventional sources decrease, a combination of additional sources will be required to maintain this ten-year ratio. Sources presently being considered are: additional, economically marginal, proven reserves; pipeline imports from Canada and Mexico; imports of liquefied natural gas by cryogenic tanker; and synthetic pipeline gas manufactured from coal.

Production from marginal reserves because of a wellhead price increase is expected to supplement the rapid drawdown of existing reserves in the immediate future. During the next decade, the import of gas from Canada will increase rapidly and L.N.G. import programs will be initiated and developed. From 1975 to 1985, the projection is for major United States pr0ducer price incentives in the conterminous States, importation of Alaskan gas, and then increases in Canadian and L.N.G. imports. The regular addition of synthetic pipeline gas from coal is expected to supplement an increasing dependence on pipeline and L.N.G. imports for the period of 1980 to 2000 (Linden, 1970).

A net of only 678.6 billion cubic feet or 3.2 percent of the total domestic consumption is now being imported. The average cost is 24¢ per MCF ($0.23/M²Btu) (Petrol. Info., 1970). Imports from Mexico are negligible and are projected to remain at a steady rate of about 0.04 trillion cubic feet per year. Canadian imports totaled about 680 billion cubic feet or almost 94 percent of gross imports int0 the United States during 1969. The U.S. Government has attempted to establish a common energy policy with Canada's regulatory body, their National Energy Board. The N.E.B. recently authorized (Smith, 1970) the exp0rt of 6.3 trillion cubic feet of natural gas into the United States over a 15- to 20-year period, in addition to 12 trillion cubic feet previously approved. Recently negotiated contracts indicate a purchase price at the border of about $0.32 to $0.40 per MCF. For comparison, the cost of transporting Alaskan natural gas from Prudhoe Bay to the Chicago area, based on current prices, has been estimated to be at least $0.60 per MCF (Smith, 1970).

The importation of liquefied petroleum gas, while offering a large supply potential, is fraught with the difficulties of obtaining governmental and regulatory approval as well as costly financing for plant and tanker construction. Columbia Gas System of New York has (Oil and Gas Jour., 1970) a contract to take 300 million cubic feet per day of Algerian L.N.G. from El Paso Natural Gas Co. starting in late 1974 at an initial dockside cost of $0.58/M^{2}Btu ($0.56/ MCF). El Paso Natural Gas Co. has contracted with the Algerian government for an additional 1.2 million cfpd which will be available for sale at that time. Columbia Gas System will also purchase another 425 million cfpd of Venezuelan L.N.G. from a Standard of New Jersey affiliate at $0.535/M^{2}Btu ($0.517/MCF). These 25- and 20-year contracts are subject to price adjustments for labor costs, capital costs of facilities when installed, costs of foreign purchase, taxes and duties, and freight costs.

The technique of using nuclear explosives underground to stimulate increased recoveries of gas reserves locked in low-permeability sandstones is due accelerated development (Oil and Gas Jour., 1970). These sandstone reservoirs contain substantial amounts of gas reserves, principally in the Rocky Mountain area, which are largely unrecoverable by present conventional well-stimulation methods. The possibility of increasing the yield from these types of subsurface reservoirs has been the subject of combined gas industry and federal government research efforts in the past few years.

The first experiment, Project Gasbuggy, a joint venture of the U.S. Atomic Energy Commission, the U.S. Bureau of Mines, and the El Paso Natural Gas Co., was conducted in 1967 in the northeastern part of the San Juan Basin. It culminated in the detonation of a 26-kiloton nuclear explosive in the Pictured Cliffs Sandstone at a well-bore depth of about 4,250 feet. An evaluation (Atkinson et al., 1970) of the extended postshot production tests of the test well indicated that gas recovery over a 20-year period should be 900 million cubic feet of gas, an increase of at least five times that which would be recovered from a conventional field well in the same area.

A second, similar experiment, Project Rulison, was conducted by the U.S. Government and Austral Oil Co., Inc., in northwestern Colorado during late 1969. The test well, drilled to Cretaceous gas sands, was stimulated by a 40-kiloton nuclear device and is currently undergoing a series of production tests after reentry. Preliminary tests (Oil and Gas Jour., 1970) have shown gas-flow rates of up to 21 million cubic feet per day, a substantial increase over normal field well rates. Initial studies (Jacobs et al., 1970) of the Gasbuggy test indicated that radioactive concentrations in the gas produced from the well are relatively low and are well within acceptable radiation limits established by the government. The Rulison test has similar findings (Oil and Gas Jour., 1970). Both of these tests were designed to help evaluate the physical possibilities of this technique of well stimulation, and were not intended to provide economic feasibility data. Additional projects have been proposed to help evaluate the economic considerations of the use of nuclear explosives.

NUCLEAR ENERGY

Until about 1960, the use of nuclear energy was limited almost entirely to military requirements. The raw materials were tightly controlled by U.S. Atomic Energy Commission regulation. The shifting emphasis to civilian use, the buildup of government stocks, and the backlog of nuclear power requirements have resulted in general decrease in demand for uranium, the principal source of fissionable nuclear energy. The government uranium purchase program was revised in 1958 by a stretchout of delivery contracts and a reduction in the purchase price of uranium ore. The peak production of ore occurred in 1960 with 18,842 tons of uranium oxide being shipped to mills. The average price paid by the federal government for this ore was $8.75 per pound. During 1969, 12,595 tons of ore was produced at an average price of just under $7.00 per pound (A.E.C., 1970).

The use of nuclear energy as a fuel is limited at present to processes in which the heat produced by the controlled fission of the nucleus of a uranium-235 atom can be used indirectly. Nonmilitary use is almost exclusively for electricity generation. Here the heat is used to produce steam that is utilized in the same manner as in power plants using the combustion heat of fossil fuels. The physical assembly in which the controlled chain reaction of fission occurs is a nuclear reactor.

Burners, converters, and breeders are the three types of reactors. The burner consumes the naturally occurring fissile isotope, which is entirely uranium-235. Since U235 is a rare chemical element representing only 1 / 141 th of natural uranium, itself rare, there is a severe limitation on its use. The converter reactor converts the nonfissionable uranium-238 isotope, which comprises 99.28 percent of all natural uranium, into a fissionable isotope which does not occur in nature. The heat of fission from this previously nonexistent isotope is utilized for more efficient use of the reactor fuel. The basic difference between the converter reactor and the breeder reactor is that in the former only a fraction of the fertile material U238 can be converted before the supply is completely exhausted. In the breeder reactor, more fissile material is produced than is consumed, and it is possible in theory to utilize all of the fertile material (Nat. Acad. Sci., 1969).

In late 1970 there were sixteen operating nuclear-powered generators producing 5,100 MW (megawatts) of power. Fifty-five plants, designed for 44,500 MW, were under construction, thirty-seven plants to generate 35,900 MW were on order, and nine plants to generate 8,000 MW had been announced. The total was 117 plants geared to generate 93,500 MW of power (Assoc. Press, 1970). According to the

U.S. Atomic Energy Commission's annual report for 1967, all central-station nuclear power plants ordered from 1958 to 1967, with the exception of two gas-cooled reactors, were light-water reactors. Light-water reactors are essentially burner reactors. Thus there is much concern about the heavy drain that these burner reactors will have on the reserves of lower cost U_{235} ores.

The light-water reactors are of two basic designs: the boiling-water reactor (BWR), and the pressurized-water reactor (PWR). The BWR generates steam by circulating water through the fuel rods in the completely contained core of the reactor, heating it to boiling, then extracting steam from the confinement to operate the turbine. The fuel elements are pelletized fuel material, stacked end to end within cladding metal tubes of zirconium or stainless steel alloys. The fuel elements, therefore, do not transmit radioactivity directly to the water. In the PWR, the water never leaves containment as steam but is recirculated in the reactor core while the heat is transferred by a heat exchanger to a secondary water system in a separate steam generator.

Both reactors are limited to an efficiency of about 33 percent as a result of the high-temperature steam (550° to 600°F typically) and the waste heat elimination temperature (80° to 90°F). A generating plant burning coal or oil has equivalent thermal efficiency values of 38 to 40 percent (Seaborg, 1969).

Nuclear-power plants now being built are in most instances licensed by the Atomic Energy Commission for 40 years of operation. By the end of this period, the plants probably will have become obsolete because of improvements in technology. A similar obsolescence age is used by industry when considering fossil-fueled plants.

The Liquid Metal Fast Breeder Reactor (LMFBR) being developed in the Atomic Energy Commission's research program for use in the 1980's not only utilizes all of the fuel-element material with a fuel-consumption efficiency 50 to 80 times better than the LWR, but will be 40 percent more efficient in the exclusion of waste heat, therefore increasing the thermal efficiency to the level of fossil-fuel plants. The molten-salt breeder reactor (MSBR) also being developed has these same advantages (Seaborg, 1969).

The fuel contained in a nuclear reactor is leased by the Atomic Energy Commission to industrial users after having been enriched from uranium oxide (U_30_8) concentrates. During 1969, the domestic nuclear power industry leased enriched uranium equivalent to 1,640 tons of U_30_8 from the Atomic Energy Commission. At the end of 1969, the total amount leased was equivalent to 4,600 tons of U_30_8 (A.E.C., 1970). The concentrates are provided by domestic mills after the processing of mined ores. The percentage of U_30_8 in ore is exceedingly small, averaging 0.24 percent in all ores produced in the United States through 1969.

An Atomic Energy Commission fuel-supply survey as of February 1, 3970 (A.E.C., 1970) showed that domestic uranium producers have contracted to supply 85,000 tons of U_30_8 to be delivered from 1970 to 1984 to domestic utilities and reactor manufacturers. In addition, 3,400 tons will be shipped to foreign users from 1970 to 1982. An additional 19,600 tons of unfulfilled requirements by all consumers was reported which may come either from excess stocks or direct purchase from uranium producers.

Fuel-procurement timing is determined by lead times for the various steps ranging from receipt of U_30_8 by the government to commercial operation of a reactor. For a reactor's first core, the lead time averages 22.6 months for: (1) receipt of U_30_8 from the uranium producer to receipt of enriched UF_6 from the Atomic Energy Commission, (2) from receipt of enriched UF_6 to receipt of fabricated fuel elements at the reactor site, and (3) delivery of fabricated fuel elements to initial commercial operation. For reloads, or replacement of spent fuel rods, which occurs about once a year, the lead time is 18.9 months.

In 1969, 12,281 tons of U_30_8 in domestic ore was shipped to domestic processing mills. The nation's ore reserves recoverable at $8 per pound were estimated (A.E.C., 1970) as 204,080 tons U_30_8. Commissioner Jas. T. Ramey of the Atomic Energy Commission stated (A.E.C., 1969) that by 1980, the nation's nuclear-powered generating capacity is expected to reach 350,000 MW, requiring a capital investment of $25 billion, and producing 25 to 30 percent of the nation's total power. Should the growth of nuclear-powered electrical generation reach this projected 150,000 MW, the 3980 domestic requirement for concentrate would jump to 34,200 tons U_30_8 and result in a cumulative need of 244,-700 tons. This exceeds the known reserve estimates, and would necessitate the mining of lower grade, more expensive ore. However, more efficient fuel use in the LMFBR and the MSBR reactors probably will obviate a resort to the lower grade deposits.

The nation's uranium ore resources are concentrated in the Rocky Mountain region. Almost 64 percent of the total tonnage produced in 3969 came from the Colorado Plateau area alone, with an additional 28 percent produced from the Wyoming Basins. Reserve estimates as of January 1, 1970, credit these two regions with 50 and 40 percent, respectively, of the known potential resources (A.E.C., 1970).

New Mexico led the nation in 1969 production of uranium ore with 6,210 tons U_30_8 equivalency or 49.3 percent of the total United States production. The State's cumulative production through 1969 was slightly more than 36.4 million tons of ore with a weighted average grade of 0.22 percent. This total of 79,430 tons of U_30_8 was produced almost exclusively from the southern part of the San Juan Basin derived from sandstone and limestone beds of Jurassic age. More than 92 percent of the ore is from peneconcordant deposits in sandstones of the Morrison Formation, and more than two-thirds came from underground mines in the Ambrosia Lake district northwest of Grants. The balance is produced principally from the Paguate-Jackpile open-pit mine near Laguna (Hilpert, 1969). Three new shifts were sunk in 1969, one at Churchrock, and two in the Ambrosia Lake area. Three concentrating mills with a collective capacity of 13,500 tons of ore per day are presently operating in the Grants mining area. The value of uranium ore produced in New Mexico in 1969 amounted to $77.5 million (Hays, 1970).

OIL SHALE

Oil shale, while containing an estimated reserve of over two trillion barrels of liquid fuel (Averitt, 1970), generally has been considered only as a supplementary source of energy. Economic problems of mining and of converting the extensive deposits to a usable, competitive product remain. Oil shale represents 17 percent of the nation's energy reserve on a Btu-equivalent basis, but the costs of mining, retorting, refining, and waste disposition require extensive capital outlays. Ample deposits of oil shales and appropriate methods of mining have been established. The technological expertise for recovering oil has been developed to as advanced a state as possible without a full-scale, commercial operation. The advent of a commercially competitive industry awaits solution of primarily political and legal considerations.

From 80 to 90 percent of the nation's richest oil-shale deposits underlie public domain land in adjoining parts of Colorado, Utah, and Wyoming. This land was withdrawn from commercial exploitation by the federal government in 1930, pending a policy decision on regulations for leasing of these lands to private industry. The establishment of a policy to insure proper use, orderly development, and adequate reclamation of this natural resource still awaits, after 40 years, a decision. As recently as May, 1970, a program for oil-shale development, formulated by a joint committee of the U.S. Department of the Interior, and approved by the Office of Science and Technology, Council on Environmental Quality, and Bureau of the Budget, was presented to the Secretary of the Interior. The plan was rejected by former Secretary Hickel based on economic considerations of the cost of production. He concluded that federal-lease offerings were premature at that time.

In addition to policy decisions, the development of oil shale awaits resolution of legal conflicts on the status of various unpatented oil-shale placer claims. These claims, which number over 100,000, were staked prior to the Mineral Leasing Act of 1920 and before the 1930 government withdrawal. The unpatented claims have been the source of title problems on much federal acreage and their validity generally has been attacked by the federal government. Many similar claims were patented, are valid, and many of these have been consolidated into significant holdings by several oil companies. These blocks have been the basis, along with government experiments and anticipated government leasing, for the research and development of oil-shale mining and retorting techniques that have been developed to date.

Oil shale is a marlstone or shale containing a high percentage of organic matter called kerogen, intimately associated with a mixture of minerals. Kerogen can be converted to a form of oil by pyrolysis or heating in the 800° to 000°F range. This oil is a mixture of hydrocarbons and hydrocarbon derivatives containing oxygen, nitrogen, and sulfur. Secondary products of the pyrolysis are low-Btu gases and a carbonaceous residue which remains in the inorganic rock.

The liquid shale oil is refined to products similar to those obtained from crude petroleum; however, the refining is complicated by the presence of substantial amounts of nitrogen and sulfur, which are deleterious to catalysts used in refining processes. Because the properties of oil shales vary considerably, technology of ore treatment is variable. A number of pyrolysis methods or retorting techniques have been designed for the richer Colorado, Wyoming, and Utah deposits (Carver, 1964). All methods have yet to be tested for use in the large-scale operations contemplated.

The known resources of oil shale in the United States with yields of at least ten gallons per ton are estimated (U.S. Bur. Mines, 1965) as equal to 2.2 trillion barrels or more than 25 times the amount of crude oil produced in the United States to date. One tenth of this reserve occurs in the Central and Eastern States, principally in the Cincinnati Arch area of Kentucky, Indiana, Ohio, and Tennessee. These deposits are in Devonian-age black shales which are more deficient in hydrogen content than the Western oil shales.

When Western oil shales yielding more than 25 gallons per ton are considered, there are about 400 billion barrels of reserve (Donnell, 1970). This reserve is in the three richest zones of the Green River Formation. The largest reserve is the Mahogany zone which covers an area of about 1,132 square miles and contains 154 billion barrels of reserve.

The amount of oil recoverable economically from these oil shales will depend on the mining extraction ratios and retorting efficiency. Initial studies indicated (Ertel, 1965) that because the deposits are uniform, room-and-pillar underground mining is practical and efficient. The strength of the roof rocks would allow a 75-percent extraction. With modern underground mining techniques, a yield of 80,000 tons per day is feasible. The oil-shale deposit thickens toward the center of its area and attains continuous thicknesses of as much as 1,900 feet, which could average 25 gallons per ton yield. Because this area of maximum oil-shale thickness is beneath an overburden of about I,000 feet, strip mining was not considered initially. As the technology of large-scale strip mining progresses, it is believed possible (Ertel, 1965) that this method would offer the best possibility of maximum resource use and, in the long run, would achieve lower mining costs than underground methods. Other than technical considerations, the main deterrents are the massive initial stripping and mining costs, and the overburden-disposal problem.

Even if the deposits are mined underground, waste disposal is a primary problem. The retorting of oil shale results in an extensive tonnage of spent shale which must be disposed of and yet meet environmental-quality requirements. The Western oil-shale deposits are fortuitously located in a sparsely populated and infrequently cultivated plateau country of deeply incised canyons. Initial proposals envision disposing of the waste in the canyons with proper attention given to land-reclamation requirements. Later disposal in mined-out areas is a secondary possibility.

Another problem is the availability of the substantial amounts of water required for the mining and extraction processes. These requirements could amount to as much as 50 to 100 gallons of water per barrel of oil produced. Studies indicate that, while a considerable volume of water is available, advanced planning for storage facilities and development of adequate reserve capacity is an important requirement.

Most of the apparent problems and high costs are centered on mining and material-handling phases. It was apparent in early planning stages, that in-situ treatment of the oil shale would eliminate many of these considerations. A prerequisite to treatment of the shale in place is the creation of permeability in a rock which possesses no natural permeability or porosity. Experiments have been conducted by several companies indicating that communication could be established between wells by artificially induced fractures. Further, in-situ retorting could be conducted by the injection of gas in the fractured deposit, maintenance of combustion by pressurized air injection, and extraction of retorted oil by producing from surrounding wells. A study of the feasibility of using a subsurface nuclear explosion to shatter the oil shale for retorting in place has been made, as well as recommendations for a controlled nuclear explosion experiment by a joint government-industry group.

Oil shale's place in the nation's energy picture will be considerable in the future, but it is far in the future. With the history of the federal government's policy indecision and the temporary relief from cheaper energy supplies, including imported and Alaskan oil, a five- to ten-year delay in the commercial production of shale oil is not unrealistic. Many of the potentials of oil shale are shared by coal, but coal has the advantages of: a greater economically recoverable reserve; a wider geographic distribution and abundance; a higher Btu content; and a considerably lesser ash or residue content (Averitt, 1970). These factors will also bear on the future of shale oil.

OTHER ENERGY RESOURCES

Hydroelectric

Hydropower is a long-used, familiar, partially developed power source. In 1968 the use of falling water to turn turbines for the generation of electricity accounted for 225 million kilowatt hours (U.S. Bur. Census, 1970). This represented 17 percent of the total electricity produced in the United States. Most of the dam sites storing water for hydropower are in the Western half of the nation, including Alaska. The potential sites of sufficient storage size and water availability are principally on the river systems of the same region. Proposals for the development of a number of these sites, notably Bridge Canyon and Marble Canyon on the Colorado River, have been successfully opposed by environmentalists on the grounds of possible ecological damage. Economic considerations also have played a part in the postponement of further development.

A survey (Young, 1955) of undeveloped hydropower sites in the country showed an estimated capacity of 129,709 megawatts. Even if fully developed, the total hydropower capabilities would be able to supply only 17 percent of the nation's projected electrical requirements for 1990. New Mexico's water-power resources are relatively small, being one-tenth of one percent of the nation's total, considering both developed and undeveloped sites. The former prominence of hydropower as an energy source will continue to decline to an even more supplementary role.

Tidal

Similar to hydropower as an energy source is the harnessing of the ebb and flow of tides to generate power. This use of tidal water has not been developed in the United States although studies of potential sites and techniques have been made. There are only a few possible locations of sites and the requirements of complex engineering techniques are deterrents.

Geothermal

Natural heat emanating from both the earth and the sun also represents a potential source of energy. Geothermal potentialities occur in those areas of the earth which have a higher than normal heat flow to the surface, which are typically in volcanic and tectonically active regions. The transfer of heat from magmatic zones in the earth's crust is effected by fluids circulating through high-permeability zones, such as faults and fractures, to the surface or near surface. The heat is stored in near-surface rocks principally by conduction and may be tapped by drilling holes near high-temperature zones, typically in areas of hot springs.

Steam and superheated water produced from drill holes may be utilized for the generation of electricity and less extensively for space heating. The effective recovery of steam for extended periods of time is dependent primarily on the extent of the permeability conduit. The quantity of heat stored in the rocks is dependent on many geological variables which can be only reasonably predicted. Preliminary estimates (White, 1965) of the country's geothermally stored heat to a 10,000-foot depth were on the order of 12×10^{15} Btu. This is the heat equivalent of slightly over 461 million tons of bituminous coal. The large majority of the nation's geothermal areas are in the western half of the country including Hawaii and Alaska.

Solar

All life on earth depends on solar energy for survival, but its use as a power source has received little attention. The problem in utilizing solar energy is the attenuation of its strength by the earth's atmospheric blanket. To collect and concentrate such diffused energy presents difficult technological problems. The few experiments developed in the last century have used a direct conversion of the sun's radiation and have required impractically large collector surface areas for a relatively minor amount of power.

The advent of the nation's space program offered direct collection of solar energy unhampered by atmospheric diffusion. The practicality of the storage of this energy in solar cells was demonstrated by use in space-exploration devices. Subsequently collection and conversion of large energy supplies by orbiting satellites and their transmission back to earth by beams of concentrated power to receiving stations on earth has been studied. These stations would have to be capable of accepting the required power stepup and be able to convert it to normal electrical power for regular transmission networks. This would require technological advances and expenditures far beyond present capabilities, but the nature of this energy source is of a magnitude comparable to or exceeding that of nuclear energy. Glaser (1968) and others believe that the expanding demand for energy, and the environmental deterioration that may accompany fossil-fueled and nuclear-energized power generation, warrants further research into the development of solar energy.

FACTORS IN THE UTILIZATION OF COAL

GENERAL

Mining

The cost of mining coal varies widely throughout the United States, dependent mainly upon the method of mining, either underground or surface stripping. A third technique, auger mining, is the most effective, but in 1968 it provided only three percent of the total production. Of the nation's total production of 545.2 million tons in 1968, 63 percent was mined underground and 34 percent by strip mining (Keystone, 1970).

Strip-mining equipment requires substantial capital investment. Typical requirements include: (1) large-capacity (up to 250-cubic-yard) draglines for overburden removal, costing about $20 to 25 million; (2) power shovels of equivalent cost, but much less capacity, for digging and loading the coal, assisted by: (3) front-end loaders, which have grown in size to as much as a 24-cubic-yard capacity; (4) truck-mounted drilling units for the drilling of blast holes; and (5) specialized bottom-dump, coal-hauling trucks of as much as 24o-ton capacity. Capital costs for large-scale stripping operations could approximate $3.6o per ton of the annual capacity of the mine (Stanford Res. Inst., 1970). Additional capital costs may include processing facilities, including those for crushing, washing, blending, stacking, and loading.

Investment costs for underground mining equipment vary widely depending upon the mining method employed. Mining may be by room-and-pillar methods using either conventional cutting, drilling, and loading machinery or continuous mining machinery which digs and loads steadily. An increasing number of underground mines are employing the long-wall method developed in Europe, in which as much as 600foot-long panels of coal are removed, allowing the roof to collapse behind the removal face as mining progresses.

Mining techniques are constantly improving the percentage of coal recovered with averages of 6o percent in underground mines and 90 percent in stripping mines now possible. The productivity per-man-day is also improving, although this has shown a tendency to stabilize in recent years. In 1968 an average of 15.4 tons per-man-day came from underground bituminous mines and 34.2 tons from stripping operations (Keystone, 1970).

The variance in production per-man-day is reflected in the price-per-ton cost of coal produced from the two types of mining methods. A hypothetical comparison might show a typical Midwestern underground bituminous mine of 15,000 tons daily production having a mining cost in the range of $3.40 per ton, while a Rocky Mountain strip mine of 20,000 tons daily production might approximate $1.8o per ton. The addition of profit and taxes would result in an f.o.b. mine price of around $4.3o and $2.50, respectively. In 1968 the national average value was $5.22 per ton for underground mines and $3.75 per ton for strip mines, regardless of market (U.S. Bur. Mines, 1968).

Labor costs, with attendant fringe benefit costs, are the main factors influencing production costs. In 1969 employment costs averaged about $6.25 per hour including wages, benefits, and payments to the United Mine Workers Welfare fund and governmental agencies (Phillips, 1970). Continued inflationary trends will tend to increase labor costs. The price of materials has also escalated more than 3o percent in the last ten years.

The effect of these factors on underground mining is shown by considering the percentage each factor represents in the total selling price of today's underground coal. Estimated (Hauser, 1970) percentages are as follows: total labor 4o percent, materials and supplies 73 percent, managed costs 8 percent, U.M.W. Welfare Fund 8 percent, depletion or royalty 10 percent, depreciation 9 percent, and profit and taxes 12 percent.

Also affecting costs of underground coal mining are the stringent regulations of the Mine Health and Safety Act of 1969. Included in the requirements are: (1) maximum levels for respirable coal dust and methane gas; (2) safety standards for roof control, ventilation, electrical equipment, and explosives use; and (3) authority for U.S. Bureau of Mines inspectors to enforce the regulations by fine or shutdown for violations.

The supply of coal has been interrupted by voluntary closing of some mines for economic reasons. Mandatory closings will undoubtedly have a future effect. A price increase of about $0.75 per ton is predicted as a direct result of compliance with the new regulations. This increase, together with the leveling off of effective productivity owing to increased labor and supplies cost increases, is expected to raise the mine price of underground coal to as high as $9.55 per ton or $0.40 per million Btu by 1980 (Hale, 1969). The Federal Council of Economic Advisors reported that bituminous coal prices are up at an annual rate of 56 percent during the first half of 1970 (Petrol. Info., 1970). Enactment of new reclamation requirements for stripping mines, and increasing labor and supply costs also will affect the price of stripping coals.

Beneficiation

Noncombustible constituents of coal include thin partings of sandstone, siltstone, and shale, as well as discrete grains of the same materials within the coal. Sulfur occurs in coal as elemental sulfur combined in the molecular structure of the coal, as discrete "pyrites" (iron sulfides), and as sulfates. The sulfates are only a small percentage of the total sulfur, whereas the organic sulfur cannot be removed by physical means. Thus, precombustion sulfur removal is directed entirely at pyritic sulfur.

Conventional sizing and washing methods to meet normal Btu quality specifications utilize the removal of coarser parts of mineral matter (plus 35-mesh) by the use of jigs, shaking tables, heavy-medium processes, or hydrocyclones. The finer, more disseminated mineral matter is reduced with greater difficulty by hydrocyclones and froth flotation, with the former generally being more successful. Using these methods to remove the objectionable material results in a substantial loss of the bulk product, in some instances as much as one-third of the coal.

Any practical preparation process of pyrite removal requires grinding of the coal to a finer mesh than the 3/8- to 1/4-inch top size to which utility-feed coals are normally crushed. Finer grinding results in greater product loss, but makes the process compatible for use between the pulverizers and the boilers at power plants.

A beneficiation plant crushing the coal to minus 3/8-inch, with cleaning of the fine sizes, is estimated (Leonard and Cockrell, 1970) to have a capital cost of $5.6 million and results in preparation costs of $o.487 per ton (or $0.019 per M²Btu for a 12,000-Btu coal). In the case of sizing the coal to a minus 14-mesh product suitable for pipeline slurry, the preparation costs would be $0.416 per ton (or $0.016 per M²Btu).

A study to estimate costs of sulfur removal at the power plant after pulverization, but prior to burning, resulted in capital costs of $6.3 million with preparation costs of $o.532 per ton ($0.021 per M²Btu). Normal pulverization costs are about $0.32 per ton at the power plant. Other experimental methods of pyrite removal include: (a) magnetic separation by induced electrostatic charges; (b) thermal methods of producing a desulfurized char fuel; (c) chemical leaching; and (d) bacterial oxidation (Leonard and Cockrell, 1970).

Transportation

Nationally the cost of coal production is usually the major part of total cost, but the cost of transportation is critical and at times exceeds the production costs. Now, as in the past, railroads are the main mode of transportation of coal. They currently handle more than 7o percent of the nation's coal (McCullough, 1970). Railroad freight rates have had a large part in keeping coal competitive in markets of certain areas by reduction of coal-hauling rates through unit-train haulage. During the period from 1958 to 1968, freight charges per ton of coal went down about 13 percent (Saalback, 197o). Since 1968 railroads have increased their freight rates and it is unlikely that the rates will go down in the future, despite the widespread use of the unit train.

The unit train is a transportation development in which locomotives and specialized cars are used exclusively for set runs between a mine and its customer on fixed schedules and with specialized loading and unloading facilities. The method, which has come into practice widely in the past decade, has helped limit costly uncertainties of coal shipment and has allowed outside financial support for new rolling stock. During 1968 over one-fourth of bituminous coal shipments by railroads was by unit trains.

Another method of transportation receiving increased attention recently is that of slurry pipelining. This is the process of pumping solid coal, ground to an appropriate size, in a fluid medium to its destination through a large-diameter pipeline. This technique has application for other materials such as sulfur, phosphate, limestone, gold, and iron and copper tailings. The fluid most often is water, but it may be petroleum. Studies also are being made on pneumatic pipeline transport by air or natural gas. This has an appeal in the arid Southwest, but, although technically feasible, this method presents many problems of compressor wear, low system capacity, and density control (Hays, 1970).

Two major coal-slurry pipelines have been constructed in the United States and others are in the planning stages for Canada and Australia (Hughes et al., 1970). A 10-inch diameter, 108-mile line capable of pumping 1.3 million tons per year was operated in Ohio in the 1950's by Consolidation Coal Co. until a reduction in railroad freight rates allowed its abandonment (McCullough, 1970). The other project, currently in the testing stages, is the 273-mile, 18-inch slurry pipeline designed to move 4.8 million tons of coal per year from Peabody Coal Co.'s Black Mesa mine in northern Arizona to the Southern California-Edison power plant at Bullhead City, Nevada.

This project is a prime example of the economics of pipelining versus unit-train railroading. The solids pipelines can be competitive, provided sufficient volumes and distances are involved and provided existing rail facilities are not already available from origin to destination. For the Arizona pipeline, although unit trains could have used 23o miles of existing track, it would have required the installation of 140 miles of new track. This requirement of additional capital investment, plus the discovery of sufficient water resources near the mine, made the pipelining method economically more attractive.

Although no costs per-ton-mile have been divulged on this project a theoretical chart of coal transportation costs (Hughes et al., 197o) has been developed which includes coal preparation and separation charges for various pipe diameters and distances. Using the Black Mesa parameters, the chart indicates a cost of about $0.0095 per ton mile. This equals $2.59 per ton or $0.23 per million Btu and thus could closely approach or exceed the actual mining costs.

A comparison of typical United States transportation rates shows railroad rates ranging from o.9 to 1.40 per-tonmile with no loading or unloading charges and rates of 0.4 to 0.90 per-ton-mile for a unit train with no loading or unloading charges. These figures assume a minimal two million tons-per-year volume over a distance of 30o to 500 miles. Comparable slurry-pipeline rates are o.3 to 0.50 per-ton-mile with no preparation or separation charges and 0.7 to 1.1¢ per-ton-mile with these charges included.

Power Generation

Coal, along with the other energy resources, appears assured of a large future growth. A recent projection (Saalback, 1970) estimated that for the year 1985 the nation's population of 265 million people will require 110 x 10^{15} Btu's of power or 415 M² Btu's per person. The generation of this power will require 32.6 percent of all the nation's primary energy resources. Of these resources, 39.3 percent, or 55o million tons, will come from coal. This prediction is for a total coal production of 800 million tons for both domestic use and foreign export, but it does not include additional requirements for the production of synthetic fuels—which may become commercial realities by 1985.

In the Western states, coal production increased by more than 6o percent during the 1960's. In contrast, the average cost of coal declined 22 percent from 1960 to 1967 (Link and Keenan, 1968). The decrease in prices was attributable to increased mechanization, particularly in strip mining, allowing greater productivity per man hour. This mechanization and increased productivity has allowed producers to guarantee stable, long-term pricing contracts; these appeal to the power industry and have a definite effect on the selection of energy sources.

Most of the Western coal mines are large and supply only one or two customers. Customers are primarily electrical power utilities and in the West, most of them have constructed minemouth generating stations, or ones near the coal supply. This requires consideration of the cost of transporting the electricity by power-line systems. The development of extra-high-voltage transmission lines has facilitated efficient long-distance transmission of electricity.

Another ameliorating effect, especially in the West, has been the recent tendency of electric utilities to combine into regional grids for power interchange. These associations, such as the WEST group (Western Energy Supply and Transmission Associates; see table 52), allow cost sharing in the construction of large minemouth plants and the ability to "wheel" (transfer or trade) blocks of electrical power from one region to another. Thus, the location of the mine is of less economic importance to the individual utility. These combinations also will allow the use of the smaller or older plants to supply only "peaking" (greater-than-average, seasonal electrical loads) power requirements.

Availability of water for steam and for cooling purposes is a necessity for power generation, and is particularly critical in the more arid states of the Southwest. About fifteen acre-feet per year is required for each megawatt of plant capacity. A sufficient water supply has been assured in the Western states near most coal resources in storage reservoirs and rivers of the Upper and Lower Colorado River Projects. The construction of man-made lakes to impound water obtained by allocations from these systems represents an appreciable cost item. Development of more efficient air-cooling towers may help solve this problem.

Another economic factor is the effect of the new air-and-water pollution-control legislation. Equipment designed to control power-plant emissions to required limits represents a substantial part of capital costs for plant construction.

TABLE 52. MEMBERS OF WESTERN ENERGY SUPPLY AND TRANSMISSION ASSOCIATES (WEST)

1. Arizona Power Authority—state agency marketing U.S. Bureau of Reclamation power.
2. Arizona Public Service Company
3. Arizona Electric Power Cooperative, Inc.
4. City of Burbank, California
5. City of Colorado Springs, Colorado
6. Colorado-Ute Electrical Association, Montrose, Colorado
7. El Paso Electric Company
8. City of Glendale, California
9. Imperial Irrigation District, California
10. City of Los Angeles, Department of Water and Power
11. Nevada Power Company
12. Pacific Power and Light Company
13. City of Pasadena, California
14. Plains Generation & Transmission Cooperative, Inc., New Mexico
15. Public Service Company of Colorado
16. Public Service Company of New Mexico
17. Salt River Project of Arizona
18. San Diego Gas and Electric Company
19. Sierra Pacific Power Company
20. Southern Colorado Power Division of Central Telephone and Utilities Corporation
21. Tucson Gas and Electric Company
22. Utah Power and Light Company

COAL GASIFICATION

Much of the current budget of the U.S. Bureau of Mines' Office of Coal Research is allotted to coal-gasification processes. These are designed to develop 900 to 1,000 Btu per-cubic-foot pipeline gas in commercial quantities from coal. The funds are supporting several pilot projects by private industry to perfect technical details and to attempt to reduce costs of each process to a level competitive with natural gas.

A common problem to each gasification process is that to manufacture methane, which has a 1:4 ratio of carbon to hydrogen, from a typical bituminous coal, having a ratio of 15:1, requires the addition of large quantities of hydrogen in proper chemical combination. A substantial amount of impurities must also be removed.

Office of Coal Research contracts are supporting the following projects: (1) Bituminous Coal Research Co.'s study of a two-staged entrained gasification process, (2) the Institute of Gas Technology's hydrogasifier process, (3) Consolidation Coal Co.'s CO_2 acceptor process, and (4) M. W. Kellogg's molten-salt process.

Two basic approaches are used. The first is a two-step procedure in which the reaction of steam and oxygen with coal produces a synthesis gas (a mixture of the carbon oxides and hydrogen), which is then purified and methanated with a catalyst. The U.S. Bureau of Mines has developed a two-stage gasification method preceding methanation which it plans to test by building a prototype plant to yield 250 million cubic feet per day of high-Btu gas. A preliminary study (Forney et al., 1970) indicated that the gas can be produced at a selling price of $0.54 per MCF based on the natural gas industry's financial structure and its average return on investment. The plant will cost an estimated $165 million. It will use fluid-bed gasification, followed by a gas-purification procedure to reduce the carbon dioxide and remove most of the sulfur compounds. The advantages of the process are the ability to use caking coals directly and to make more than half of the ultimate methane in the gasifier prior to methanation.

The second basic approach is hydrogasification. In this process, a mixture of steam and hydrogen reacts with the coal at temperatures of 1,200° to 1,800°F under a pressure of 500 to 2,000 pounds per square inch. The resulting gas, containing methane, hydrogen, and carbon oxides, is purified and the carbon monoxide and hydrogen are catalytically methanated. This method maintains a better heat balance and reduces the amount of hydrogen needed to be introduced from outside the gasifier, as only about half of the coal fed into the hydrogasifier is converted. The less reactive char is used in the production of the needed hydrogen by an electrothermal gasifier (Risser, 1970).

The IGT Hygas process (Scora, 1970), using the hydrogasification process, produces 960-Btu gas at a ratio of 700 Btu of gas for each 1,000 Btu of coal. A plant producing 250 million cubic feet per day would consume 15,000 tons of coal daily. The IGT pilot plant at Chicago is in final stages of construction and is scheduled to be producing synthetic gas by 1971. This plant is designed to convert 80 tons of Illinois coal to 1.5 million cubic feet of synthetic gas daily (Coal Age, 1970).

The CO_2 acceptor process uses northern Rocky Mountain lignite. The moisture is removed by flash drying. Devolatilization occurs prior to the lignite's introduction into the gasifier unit. Steam and hot, calcined dolomite are fed into the unit where the steam reacts with the lignite to form hydrogen, carbon monoxide, and carbon dioxide. The carbon dioxide combines with the calcined dolomite to form carbonates, while the other gases pass through a devolatilizer into a purifier, then into a methanator. The char and spent dolomite are regenerated for reuse.

In the molten-salt process, steam reacts with coal to form synthetic gas while molten salt, heated by the combustion of the coal with air in a heating section of the gasifier unit, is circulated through the synthetic gas section to supply the heat for gasification. The resultant raw synthetic gas is then cleaned and methanated.

The various processes were evaluated (Stanford Res. Inst., 1970) on the basis of competitiveness from a cost per million Btu standpoint. Besides the processes discussed, a privately funded steam-iron process under development by IGT was also appraised. This process is a hydrogasification approach in which the necessary hydrogen additive is generated by steam reacting with hot reduced iron ore to form iron oxide and hydrogen, rather than by the electrothermal process.

The evaluation established as parameters: (a) pipeline gas with a heating value of 900-Btu per cubic foot at delivery pressures of 1,000 psi; (b) a plant production of 250 million cubic feet per day of pipeline-quality gas; (c) an assumption that the gas-producing plant would be a regulated public utility financed with 65 percent debt capital at an interest rate of 7 percent per year and a net income to the utility operator of 9.4 percent per year of equity capital; and (d) a plant on-stream factor of 90 percent. The object of the evaluation was to screen out processes that were noncompetitive. The standard of noncompetitiveness was set at the point where the process requires a selling price of more than *60* per million Btu above the gas produced from the lowest cost process. Four different plant-feed coals were used with the following tabulated results:

	Cents per million Btu in product gas			
	Illinois No. 6 coal	*Pittsburgh seam coal*	*No. Dakota lignite*	*Wyoming sub-bituminous*
BCR	64.3 (N)[a)]		(N)	(N)
M. W. Kellogg Co. [b)]	(N)	71.4	(N)	(N)
IGT electrothermal [c)]	62.8 (N)		(N)	(N)
IGT electrothermal [d)]	56.4		56.2	44.0
Steam-iron	58.4		58.2	45.6
CO_2 acceptor	(N)		55.7	45.2

a) (N) means the process was judged to be noncompetitive.
b) This process was evaluated using the same coal that Kellogg used in its evaluation. It was judged to be noncompetitive when processing this coal and would be even more costly when processing Illinois No. 6 coal.
c) With power for reaction heat purchased from a char-burning, conventional-power plant.
d) With power purchased from a char-burning, magnetohydrodynamic power-generating plant.

A more recent evaluation (Ertel and Sopcisak, 1970) assumed more up-to-date economic conditions in comparing the IGT and the CO_2 acceptor processes. Assuming a coal cost of \$0.14/M^{2}Btu, an interest rate of 8 percent, and a gross return on investment of 10 percent, a plant-site cost of gas of \$0.589/MCF (\$0.569/M^{2}Btu) for the IGT process and \$0.569/MCF (\$0.55/M^{2}Btu) for the Consol operation was calculated. Also noted was the fact that a conservative effort could have plants using the two different processes ready for commercial use in 1976 and 1977. Currently gasification-plant construction costs are estimated to average about one-half million dollars per million cubic feet of capacity (Smith, 1970).

The Director of the Institute of Gas Technology commented, "There is little question that the development of the technology (to make synthetic gas from coal) is progressing at the rate required to allow construction of first generation plants beginning as early as 1972. Thus large scale commercial production of synthetic pipeline gas from coal could begin around 1980" (Linden, 1970).

COAL LIQUEFACTION

Research in making liquid fuels from coal is being pursued by the Office of Coal Research. The problems and processes of obtaining liquid, petroleum-quality fuels are very similar to those encountered in coal gasification and, indeed, each field has adaptabilities for the other. The major disadvantages of coal as a source for liquid fuels are: (a) the high ash content, and (b) the relatively large quantities of hydrogen that must be added. Based on a hydrogen cost of \$0.25/MCF and consumption of 5 to 10 MCF of hydrogen per barrel of produced liquid fuel, the hydrogenation costs alone could amount to \$1.25 to \$2.50 per barrel of oil produced (Gary, 1969).

Two of the basic processes of liquefaction are similar to those of gasification. The first involves the reaction of coal with oxygen and steam to form a synthetic gas consisting primarily of carbon monoxide and hydrogen; after purification, they are combined catalytically at high pressures and temperatures to form hydrocarbons in the gasoline molecular weight range. The second process utilizes direct hydrogenation of the carbon in coal to produce hydrocarbons of gasoline molecular weight. The present Office of Coal Research funded projects include: (a) Consolidation Coal Co.'s Synthetic Fuel (CSF) process; (b) The F.M.C. Char Oil Energy Development (COED) process; (c) Project Seacoke of Atlantic-Richfield Oil Co.; and (d) the H-Coal process of Hydrocarbon Research, Inc.

The only commercial production of synthetic liquid fuels in the world is in the Republic of South Africa using the Fischer-Tropsch process. This process involves coal gasification into a synthetic gas which, after purification, is passed over an iron catalyst to promote hydrogenation of carbon monoxide and produce an end product of gasoline, diesel fuel, and waxes.

The CSF pilot plant at Cresap, West Virginia, was completed in 1967 to obtain data for design and for economic evaluation of a commercial plant. It has been inactive for the past year. In this process, the coal is dissolved in a liquid solvent produced by the process, and the ash and less reactive coal portions are filtered out of the solution. The solvent is then separated from the solution by distillation and the solute extract is catalytically hydrocracked to produce refinery feedstock.

A 50,000-barrel-per-day plant using this process to produce gasoline is estimated to have a capital cost of $245 million, exclusive of land, royalties, initial catalyst, and working capital. The capital investment includes units for coal preparation, hydroconversion, hydrotreating, hydrocracking, catalytic reforming, gas treating, hydrogen generation, and sulfur recovery. Using 20,522 tons of coal per day at $3.75 per ton, the plant is estimated to produce gasoline at a cost of $0.155 per gallon ($6.51 per barrel) when the return on investment is 6.4 percent (Parsons, 1969).

The CSF process is also being evaluated as a method for producing synthetic crude oil. The crude produced does not have properties comparable to a natural crude oil in that: (a) it is a 100-percent rectified distillate product of about 750°F end point, and (b) it contains almost 80 percent by volume of mid-distillate boiling range oil, which is of considerably lower gravity than cuts of corresponding boiling points from most natural crude oils.

Based on a scale-up of pilot-plant data, a commercial plant of almost 46,000 barrels per day of 33.4 A.P.I. crude oil capacity, using 19,086 tons per day of Eastern U.S. coal at $3.75 per ton, would require an average selling price of $5.14 per barrel at the plant for a 6.4 percent return on investment. This cost is obviously unattractive, but an extrapolation of this study applied to a very large 250,000-barrel-per-day plant using Western coal at a price of $1.25 per ton ($0.05/M^2Btu) for 103,884 tons per day would produce a plant-site price of about $3.25 per barrel. This attractive cost figure also assumes that the char produced will have no value, although there is the possibility of sale of the char as an electric-generating plant feed (Parsons, 1969).

An evaluation of the CSF pilot-plant program in its late-1969 final stage indicated that the process, plagued with a number of mechanical problems, could not be competitive with crude-oil sources. The program made improvements in the areas of ammonium sulfide separation and simplification of the hydrogen-purification and tar-acid recovery systems. It may become more competitive by improvement in the areas of low-sulfur fuel oil production, catalysts, and a higher hydrogen purity process.

The COED process is based on converting that part of coal most easily hydrogenated to a synthetic crude oil and producing a low-volatile, low-sulfur char with a gross heating value of about 12,800 Btu as fuel for an electric-power plant. The process utilizes a multistage fluidized-bed pyrolysis of the coal. The FMC Corporation's analyses indicate that the economics are definitely affected by the quality of coal used. Optimum coal types are high-volatile B and C grade bituminous coals of the Rocky Mountain and Midwest areas. One ton of these coals yields 1.3 barrels of oil, 10,000 cubic feet of hydrogen, and 950 pounds of char.

On a plant processing 25,000 tons per day of Western bituminous coal, the total investment of both fixed and working capital would be $91 million, when producing merchantable hydrogen, and $84 million when not producing hydrogen (Coal Age, 1970). Such a plant would not be economically attractive unless it was near an industrial complex that would use its products, i.e. a refinery for the oil, an ammonia plant for the hydrogen, and a power plant for the char.

A $4.5 million pilot plant utilizing the COED process was dedicated by the FMC Corporation in Princeton, New Jersey, in October, 1970. It was designed to convert 36 tons of coal per day into synthetic crude oil, pipeline gas, and fuel char. The crude will be converted into a high-grade synthetic fuel oil at the rate of 30 barrels per day. It will provide engineering data for the design of a commercial plant and information on output yields from a variety of coals (Petrol. Info., 1970).

Project Seacoke is a process in which finely crushed coal is fed into an oil refinery's fluidized coking unit along with the residual fuel oil normally used as feedstock. The coal's volatile constituents are converted to liquid fuels along with that of the resid, while the coke and char mixture remaining serve as power-plant fuel. The difficulty inherent in this system is that the products are very poisonous to the catalysts used in normal cracking and reforming operations, and they must be hydrotreated with large volumes of expensive hydrogen before being processed at a conventional refinery (Gary, 1969).

The H-Coal process is a variation of the H-Oil process used commercially by Hydrocarbon Research, Inc. to produce gasoline from residual oils. The H-Coal product is a light crude oil that can be converted to gasoline in a conventional refinery. The coal is crushed and mixed with an equal weight of recycle oil, then this slurry is preheated and fed, together with hydrogen, to reactors operating at 2,750 psi. The reactor contains an ebullated bed of active catalyst which converts about 90 percent of the moisture and ash-free coal to liquid and gaseous products. The process requires the use of natural gas as a feed to the hydrogen-manufacturing unit and will produce either gasoline and domestic furnace oil in a 2: x ratio or gasoline only. A 00,000-barrel-per-day plant for gasoline only is estimated to have a $320 to $350 million capital cost, which, with an 8.1-percent return on investment profit after taxes, would require a sale price of $4.62 per barrel. By-product sales from this plant would include number-6 fuel oil, sulfuric acid, ammonium sulfate, and a coal residue (Gary, 1969).

Improvements in the various liquefaction processes and hydrogen-production techniques will lower the costs of producing synthetic liquid fuels to the point of eventual competition with crude oil and gasoline. Progress will depend upon the economic factors of the petroleum industry's ability to provide oil reserves for the rapidly increasing demand. The oil discovery at Prudhoe Bay, Alaska, with recoverable reserves of 20 to 30 billion barrels, probably will retard the rate of synthetic oil's development. However the large reserve of Prudhoe Bay shrinks to about a three-year supply when compared to the projected electric-power requirements in the year 2000 of 9 billion barrels of oil equivalent or 2,125 million tons of bituminous coal equivalent (Sporn, 1970).

OTHER FUTURE COAL USES

Coal may also supply raw materials for a number of chemicals. It has been a mainstay of the dyestuff industry and the early plastics industry. The Office of Coal Research has contracted with Skeist Laboratories, Inc., to evaluate (Gary, 1969) the possible economic advantages of the production and sale of certain chemicals from coal. Included in the study are ethylene, propylene, benzene, toluene, exylene, naphthalene, phenol, cresol, cresylic acid, hydrogen, sulfur, and ammonia.

Another promising process is a now largely theoretical method of generating electrical power. It is termed magnetohydrodynamics or MHD and would offer the following advantages over conventional or nuclear-powered generating plants: (1) would drastically reduce both thermal and atmospheric pollution; (2) make better use of coal reserves, especially low-grade coals; (3) offer opportunities in water-scarce areas; (4) improve efficiency and reliability of electric-power systems; and (5) provide low-cost power.

The MHD process combines the normal three-step process of power generation into one single step. In conventional plants, no matter how fueled, the fuel is burned, or allowed limited fission, to supply heat. The heat makes steam which expands to turn a turbine. The turbine shaft drives a generator which delivers electrical power. The technical and economic factors in this three-step process limit the efficiency of a coal-fired plant to about 4o percent and that of a nuclear-powered plant to about 3o percent. In a MHD plant, the hot combustion products of fuel and air are made to conduct electricity by the addition of small amounts of a salt. These high-temperature, ionized gases move at a high velocity through a magnetic field where they, acting as the armature of a generator, generate electricity directly. This direct process results in efficiencies of nearly 6o percent and in much less waste heat to be absorbed environmentally. The combustion also occurs in such a way that oxides of sulfur and nitrogen can be controlled (Kantrowitz, 1970). Although the operation is fully understood, the technology (particularly for materials) is little more than embryonic.

FACTORS IN THE UTILIZATION OF URANIUM

Mining

The economics of mining uranium ore have been controlled primarily by the federal government's policies of purchase of all production. The initial program of incentive prices for uranium in the 1940's and early 1950's resulted in the establishment of a strong domestic mining industry. In 1956 a changed procurement program provided for purchase of ore concentrates at a price of $8 per pound of U_3O_8. This price fixing set limits as to what constituted an economical mine, since 90 percent of the ore production and reserves are controlled by the owners of the concentration mills (U.S. Bur. Mines, 1969). Since 1963 the government has been following a policy of gradual disengagement as the sole customer of the uranium-mining industry, but the standards set by its purchasing schedules have influenced current economic considerations. The current prices being paid independent mine operators for uranium ore are near the government purchase price discontinued in 1962. These prices ranged from $1.50 per pound on contained U_3O_8 for an ore grade of o.1 percent up to $3.50 per pound for ore grades of 0.2 or more percent.

The withdrawal of the federal-purchase program has been more than made up for by the increasing demand of the electric-power industry. The anticipated increase in requirements has sustained a minor boom in exploration. This is reflected by the setting of a new record for exploration and development drilling footage in 1969, being triple the amount drilled in 1967 (A.E.C., 197o). Of the almost 3o-million total footage drilled, 69 percent was classified as exploratory. The increased exploration in one year added 26 percent to the ore reserves that are categorized by the industry as "recoverable at $8 per pound." Even assuming a greatly reduced ratio of reserve discovery to exploratory drilling efforts, an adequate supply of uranium ore may be expected for the foreseeable future at relatively stable prices. Assuming the reserves are available, the mining costs will tend to be a function of production costs.

Processing

The first step of conversion of uranium ore to usable fuel is concentration. The mined ores are concentrated by processing mills which are operated predominantly by companies controlling the ore reserves. In 1968 thirteen mills produced 7,338 tons of U_3O_8 concentrate for Atomic Energy Commission purchase at a fixed price averaging slightly under $8 per pound. Private industry purchased about 5,000 tons. The federal government's price schedule was reduced automatically to a maximum of $6.70 per pound in 1969 and 1970. It was estimated (U.S. Bur. Mines, 1969) that this would result in an average price being between $5.50 and $6.00 per pound adjusted for specification grades. Prices to private industry were probably less, but were projected to be between $8 and $9 by the late 1970's (Hauser, 1970).

The second step in uranium fuel processing is conversion of the U_3O_8 concentrate to UF_6 by commercial chemical plants. This conversion is a relatively small part of the total fuel cost, but it will be subject to probable future labor and material cost escalations.

After conversion, the fuel is subjected to the enrichment stage. Enrichment is the only remaining part of uranium processing which is still completely under government control, but consideration is being given the releasing of this function to private industry (U.S. Bur. Mines, 1968). The enrichment of UF_6 with uranium-235 is accomplished at any one of three government-owned gas diffusion plants. Prices vary with the degree of enrichment and have been established at $4.77 per gram of 0.I percent uranium-235 enrichment, $8.48 per gram for 0.2 percent, and $9.59 per gram for 0.5 percent enrichment.

The reprocessing of spent fuel at these same plants is based on a unit of time, rather than of weight, and is called a separative work unit (SWU). A ceiling price for the separative work units has been established at $3o/SWU subject primarily to escalations for labor and power costs. Reprocessing will become more and more prominent in the future as the greater number of power reactors require refueling, thus the increased volume will tend to lower costs. In addition the possible entry of private enterprise into the field and resulting competition will tend to lower this cost.

The fabrication of enriched fuel into fuel cores for nuclear reactors is done in commercial factories. As the requirements for cores increase and as manufacturing techniques are developed, cost reductions should be experienced. These reductions should tend to more than offset increases for labor and materials.

A projection of the economic considerations of the processing steps in converting uranium ore to an effective fuel suggests relatively stable or slightly lower costs in the future.

Nuclear-Power Generation

The costs of constructing a nuclear-powered reactor have had a considerable retarding effect on the development of nuclear-power generation. Testimony to the U.S. Joint Committee on Atomic Energy (Sporn, 1969) pointed out a retrogression in the competitive position of nuclear power vis-a-vis fossil-fuel power that resulted in the cancellation of orders for atomic units in 1968 and 1969. Peak reactor ordering was for units with a capacity of 25,780 MW in 1967. This demand declined to 16,044 MW in 1968 and to 7,190 MW in 1969. The reasons for the drop in orders were: (I) higher costs of nuclear components, of turbines, and of construction; (2) inflation's effect on construction costs; (3) higher interest on money, overhead charges, and capacity charges in bonding. The fossil fuels have had similar problems, but the inherently higher capital costs of nuclear reactors resulted in cancellations.

The projection of increased competitiveness by nuclear power was based in large part on the anticipated performance of the Jersey Central Power and Light Co.'s Oyster Creek plant, under construction in 1963 and scheduled for operation in 1969. The estimated cost of this plant was slightly over $13o per kw including the fuel inventory. The cost of electrical energy was estimated at about 2.5 mills per kwh (A.E.C., 1969). For comparison, the Power Authority of the State of New York is constructing an 820-MW plant at Oswego, which will have a capital cost of $320 per kw including fuel inventory (Coal Age, 1970). Another estimate (Sporn, 1969) of current capital costs on an 1100-MW plant planned for completion in 1976 is $203 per kw, with energy production costing about 7 mills per kwh, or double the projected Oyster Creek plant's cost.

Comparative conventional coal-power generation costs, using $0.25 per M^{2}Btu coal, have increased about 48 percent (Sporn, 1969). The Atomic Energy Commission reported that a 1,000-MW nuclear-power plant can cost up to $40 million more than an equivalent fossil-fueled plant (A.E.C., 197o). Another study (Coal Age, 1970) stated that nuclear plants in the Pacific Northwest, financed by investor-owned utilities at their capital cost rates, will produce 6.4 mills/kwh power in plants of 7,500-hrs/yr use or 6.i mills/kwh at 8,000 hours use. This compares with coal-fueled plants at 4.4 mills/kwh for 7,500 hours and 4.2 mills/kwh ca 8,000 hours use.

Sporn (1969) concluded that the LWR, which two years ago in 1968 offered potentials for nuclear-power generation competitive with fossil fuel at $0.22 to $o.248 per M^{2}Btu, has lost position to where it is now competitive only at fossil fuel costs of $0.28 to $0.295 per M^{2}Btu.

POLLUTION CONTROLS

National concern over the increasing pollution of the environment and the resulting effects on the health and welfare of the nation's people led to the legislative enactment of the Federal Air Quality Act of 1967. Previously, the responsibility for establishing standards of air-pollution abatement lay with the U.S. Department of Health, Education, and Welfare, acting through the National Air Pollution Control Administration. Effective in December of 1970, these duties, along with those of several other related federal environmental control groups including the Federal Water Quality Administration, were absorbed by a new agency, the Environmental Protection Agency.

The National Air Pollution Control Administration had established air-quality control regions throughout the nation encompassing areas with common meteorology, topography, urban-industrial development, and jurisdictional boundaries. It issues air-quality criteria and publishes reports on control techniques to serve as guidelines for state regulations for air-quality control.

Although no precise method of measurement of total pollutant emissions exists, Table 53 summarizes (Olds, 1969) and enumerates the pollutants, their sources, and estimated amounts of contribution:

It is apparent that most air pollution results from the combustion of a fuel in one form or another. While the majority originates from motor vehicles, over 14 percent is attributed to fossil-fueled power plants. The amount depends principally on the type of fuel used. Table 54 (Seaborg, 1969) summarizes estimates of the chemical pollutants emitted by a 1,000-megawatt power station for each fuel.

TABLE 53. AIR POLLUTANTS AND THEIR SOURCES

			Sources—Millions tons per year				
Pollutant	Millions tons yr.	Percent of total	Power plants	Industry	Motor vehicles	Space heat	Refuse disposal
Carbon monoxide	72	50.7	1	2	66	2	1
Sulfur oxides	26	18.3	12	9	1	3	1
Nitrogen oxides	13	9.2	3	2	6	1	1
Hydrocarbons	19	13.4	1	4	12	1	1
Particulates	12	8.4	3	6	1	1	1
Total	142	100.0	20	23	86	8	5
Percent of total			14.1	16.2	60.6	5.6	3.5

TABLE 54. CHEMICAL POLLUTANTS FROM 1,000-MEGAWATT POWER STATIONS

Pollutant	Annual emissions in tons		
	Coal[1]	Oil[2]	Natural Gas[3]
Particulates	4,950	800	510
Sulfur dioxide	97,500	58,000	13.5
Nitrogen oxides	23,000	23,900	13,300
Carbon monoxide	575	19	—
Hydrocarbons	230	735	—

1 Based on use of 2.3 million tons of coal; 2.5-percent sulfur; 97.5-percent fly-ash-removal efficiency.
2 Based on use of 460 million gallons of oil; 1.6-percent sulfur; no pollution-control equipment.
3 Based on use of 6.8 billion standard cubic feet of gas; no pollution-control equipment.

Natural gas is inherently the cleanest of fuels. Its gaseous nature precludes the formation of particulate matter and promotes complete hydrocarbon combustion. Sulfur compounds have been removed by amine solutions as a requirement to qualify as pipeline-quality gas. Nitrogen-oxide generation is the only problem encountered in the use of natural gas.

The nitrogen oxides result almost entirely from combustion and are formed when nitrogen and oxygen in the air react in the high temperatures of combustion. Since the reaction does not result from chemical combinations of constituents within the fuel, these emission problems are equally applicable in the use of coal, oil, and natural gas. Research for the National Air Pollution Control Administration indicated that the emission rates and kind of nitrogen oxides for any given combustion unit cannot be predicted. They appear to be based on several variable factors including fuel composition, heat-release rate, flame-quench rate, burner configuration, flame temperature and turbulence, and furnace design. None of these factors are amenable to standardized control. Possible amelioration may be had by low excess-air availability, flue-gas recirculation, steam or water injection, pure oxygen combustion, or fluidized-bed combustion. Control of nitrogen oxides by flue-gas removal includes (Olds, 1969) catalytic reduction, or absorption by solids or liquids with the combined removal of both sulfur and nitrogen oxides.

The emission of hydrocarbon pollutants from power plants is minor and is primarily the result of incomplete fuel combustion. This emission can be greatly reduced by better ignition controls and by the recirculation of exhaust emissions.

The use of residual fuel oil in power plants has been reduced by the limitation of the sulfur content to 2.2 percent. The U.S. Department of Health, Education, and Welfare recommended a target concentration of 0.1 ppm of sulfur dioxide in 1971 for the New York City area. A Bechtel Corp. study for the American Petroleum Institute in 1967 indicated that the cost of sulfur reduction to 1 percent would be about $0.72 per barrel for a fuel of the equivalent heating value of the Caribbean crude presently being used. For further reduction to 0.5 percent, the cost would be $0.97 per barrel. Desulfurization by hydrogenation is the most successful process, but rapid contamination of the catalyst by sulfur and by the heavy metals, and the high cost of hydrogen are expensive deterrents (N.A.P.C.A., 1968).

COAL-FUELED POWER PLANTS

The coal industry has pollution-abatement problems in the control of its product from extraction to combustion. The underground mining of coal has new strict levels of coal-dust control. New laws also protect ground water in mining areas from contamination by mine-drainage discharges, black-water runoffs, and acid runoffs from refuse piles. For strip mines, the rehabilitation of spoil piles for efficient drainage and esthetic effect, as well as by revegetation, will be considerable cost factors. More effective control of spontaneous fires in spoil piles, as well as in coal-storage piles, will be required, as will dust control at handling, transportation, and storage facilities.

The use of coal as a fuel for firing power-generating plants results in large emission of pollutants to the air. The combustion of coal creates two major pollutant problems other than the formation of nitrogen oxides. Sulfur and noncombustible mineral matter are inherent constituents of coal. Both were deposited contemporaneously with the vegetal matter that subsequently formed the coal and, as such, are integral parts of the coal. The amount of each constituent varies widely with the type of coal. Characteristics of United States coals include sulfur contents ranging from 0.3 to 7.7 percent and averaging 1.9 percent. The mineral content ranges from 2.5 to 32.6 percent and averages 8.9 percent (Averitt, 1969). When burned with the host coal, the sulfur forms noxious oxides and the mineral matter forms ash and other particulate matter ranging in size from millimeters to microns.

Abatement of plant emissions by the removal of these substances prior to combustion has been by washing, crushing, and mechanical separation as the normal beneficiation methods. More exotic methods of flotation, magnetic separation, and chemical leaching are expensive processes which also result in a loss of coal.

After combustion in furnaces, the removal of sulfur in oxide compounds is effected by treatment of flue gases. Most commonly the method is to divert the exhaust stream through a dry or wet gas scrubber, which contains finely divided carbonates, usually lime or magnesium. The carbonate combines chemically with the sulfur oxides to form a precipitate of calcium or magnesium sulfate.

A dry-limestone injection system was installed recently on Kansas Light and Power Co.'s 430-megawatt Lawrence plant as the first large-scale attempt of this method of removal. On 3½-percent sulfur content the sulfur-oxide removal is about 85 percent and gives a stack discharge equivalent to ½-percent sulfur. Particulate removal is better than 99 percent and about 30 percent of the nitrogen oxides are extracted simultaneously (Olds, 1969).

In the latest wet-scrubber systems, the gas stream is injected at a high velocity into a series of thick fluid screens which not only induces precipitation of the sulfur oxides, but also removes a high proportion of particulate matter. The resultant residue is flushed to clarifier tanks for settling and is sluiced to a disposal area. The wet-gas scrubber also will remove a high percentage of nitrogen oxides as precipitates. The simpler sulfur-oxide-removal systems, without provision for sulfur-product recovery, may require a utility investment of $7 to $8 per kw and an operating cost of $0.03

to \$0.04 per M^2Btu of fuel cost (Saalback, 1970).

The removal of inorganic ash and particulate mineral matter (predominantly silicon and aluminum oxides) from post-combustion gases is generally by electrostatic precipitation. The stack gas flows upward through a series of alternating metal plates and conductor wire screens, which, when subjected to a high-voltage direct charge on the screens, induces a charge on the solid particles and causes their collection on the plates. The plates are subjected to periodic hammering, which causes the accumulating fly ash to travel down the plates, to be collected and removed at the bottom of the precipitator. The effectiveness of the electrostatic precipitator varies dependent upon the amount, composition, and size of the particulate matter, but it is generally designed for collection efficiencies on the order of 99 percent. An electrostatic precipitator to handle low-sulfur coals costs about \$10 per kilowatt of installed capacity (Squires, 1970).

The lower the sulfur content of the coal, the more difficult is the precipitation electrostatically. The particulate matter from low-sulfur coals is more resistive to an imposed electrical charge. This is attributed to the possibility that the fused ash particles may absorb or be coated by the sulfur compounds and thereby become more susceptible to induced charging. It is estimated that a ½-percent sulfur coal would require a precipitator twice as large as one required for a 2-percent sulfur coal (Averitt, 1969). In plants burning low-sulfur coals, the more efficient dry or wet gas scrubber is utilized. The scrubber's ability to remove sulfur and nitrogen oxides in the same operation is also advantageous. Other methods of dust collection employing screens, baffles, and centrifugal systems have been used, but in most situations the efficiency of removal is well below the recommended clean-air standards.

The burning of coal for fuel at Arizona Public Service Company's 2,085-megawatt Four Corners power plant near Fruitland is the San Juan Basin's present primary pollution problem. The large volumes of coal burned and the high mineral matter contained in the coal, about **22** percent by volume, result in the emission of substantial amounts of particulate matter. The low-sulfur content of the Fruitland coal, averaging o.6 percent, mitigates in part the disadvantages of the high-ash content.

The initial three units at the station, designed for 575 megawatts, were installed in 1963 and 1964 prior to State legislation calling for particulate-removal levels below o.6 lb per million Btu. These units were equipped with mechanical dust collectors which proved to be only about 8o percent effective and which allowed about 25o tons per day of fly-ash emission. These dust collectors, costing about \$1.5 million of the original capital cost of \$too million, are to be scrapped for a scheduled installation in early 1971 of wet gas scrubbers costing about \$14 million. These scrubbers have a designed capability of 99.2 percent particulate removal, which will reduce fly-ash emission to about 36 tons per day. They also have the capability of sulfur oxide removal by chemical precipitation. No State pollution-control standards have been established with respect to acceptable sulfur or nitrogen oxides levels.

The second two units installed in 1970 at the Arizona Public Service Co. plant have a rated generating capacity of 1,510 megawatts and are equipped with electrostatic precipitators with a design capability of 98.4-percent particulate removal. This allows a fly-ash emission of about 128 tons per day. The precipitators cost \$4.3 million. The total plant capital cost is \$26o million of which \$11.7 million, or 5.2 percent, was spent on effective pollution-control equipment. The total capital investment for control equipment and ash-disposal systems should closely approach the nationwide cost figures of \$7 to \$8 per kilowatt installed capacity (Saalback, 1970).

Two methods of ash disposal are being utilized. A part of the 4,500 to 5,500 tons per day is being slurried to a 752-acre settling pond near the plant site. The balance is being back-hauled to the strip mine where it is buried in the overburden dump pits. Water used for the slurrying of ash is pumped from the company-constructed, 40,000-acre-foot cooling-water lake. The drawing off of this water helps to prevent a saline buildup in the lake. After settlement, the slurry water is allowed to return to the natural drainage.

The first 345-megawatt unit of the Public Service Co. of New Mexico's power plant, scheduled for a construction start in early 1971, will cost an estimated \$55 million. Of this capital cost, \$2.7 million or 4.9 percent will be expended on electrostatic precipitators. These pollution-control devices are guaranteed as 99.5 percent effective and represent a \$7.38-per-kw expenditure (Farmington Daily Times, Oct. 25, 1970).

NUCLEAR POWER PLANTS

The use of nuclear energy for power generation presents unique pollution problems, as well as one in common with other energy sources. Radioactive contamination is perhaps the best known, but least understood. After years of study, the effect on human physiology of exposure to radiation is imperfectly known. Apparently it is dependent upon amount and length of dosage. The human body, capable of sustaining severe damage from radiation, is also capable of tolerating relatively long periods of low-level radiation without apparent ill effects. After extensive and continuing studies of all medical data, including genetic effects and the capability of tissue regeneration, the Federal Radiation Council has established acceptable radiation-exposure standards which attempt to balance the risks of exposure against the recognized benefits of nuclear energy.

The mining and processing of radioactive ore has minimal exposure standards for mining and mill personnel. Transportation of radioactive material is also regulated for minimal hazard. Currently, the handling of nuclear energy at electrical-generating plants presents the most danger of over-exposure. Strict controls are imposed on the release of radioactive waste to the environment from these plants.

Three levels of radioactive waste—low, intermediate, and high levels—are recognized as resulting from the operation of a nuclear reactor. Controls on all levels of radioactivity are included in the design and fabrication of the fuel elements and of the waste-treatment and handling systems. The first line of containment is the confining of the fuel material within steel-alloy tubes. The second is the containment of the fuel elements within a water-coolant jacket. Almost all of the radioactive fission products are contained within the fuel element, but some leakage can occur into the surrounding water jacket. Low-level liquid and gaseous effluents from the jacket are released in only minor quantities, well below minimal established levels, to the atmosphere and surrounding bodies of water. Sources of low-level contamination include gases by diffusion or through cladding defects, corrosion products and nongas fission products such as radioactive barium, iodine, or cesium. The low-level gases are shortlived, and if retained for 3o minutes to 3o days, will decay to the acceptable limits, when they are released to the air (Science, 1970).

Atomic Energy Commission regulations call for minimum stack emissions of 7.5 million curies per year in low-level gaseous emissions, while whole-body exposures from all sources are limited to 5,000 millirems for occupational workers, 50o for any one person in the surrounding population, and an average of 170 millirems for a representative sample population group. Normal background radiation from natural earth sources is on the order of 100 millirems per year, dependent upon altitude, atmospheric conditions, and underlying rock types.

Tritium gas has a half-life of longer than normal duration, so that the holdup method is inapplicable. It is converted to tritiated water and bled from the closed cooling systems into the environmental water where it is diluted to harmless quantities.

The intermediate-level corrosion and nongaseous fission products are removed by conventional treatment of filtration, precipitation, ion exchange, and evaporation, which concentrates the liquid to a slurry that is solidified and buried, together with the ion-exchange resins and filter aids, in steel containers in one of five different commercially operated burial grounds in the United States.

The high-level radioactive fission products created and retained in the fuel elements of the reactor are transported from the reactor facility to a fuel-reprocessing plant in a shipping container designed to maintain its integrity during both normal and hypothetically unusual conditions of transport. At the reprocessing plant, the fission products are separated from the reusable uranium and plutonium, and, until recently, were stored as liquids in 85-foot-diameter steel tanks buried eight feet below ground on concrete saucer pads at the processing plant site.

The Atomic Energy Commission has maintained that they are storing, rather than disposing of, radioactive waste and are developing programs and facilities for disposal. In mid-1969, the Atomic Energy Commission announced a policy requiring that the high-level liquid wastes be converted to low-volume solids by calcining. These solids can be transported in steel containers and stored indefinitely at a federal repository in underground salt mines, where water problems or diastrophic earth movements would have essentially no effect (A.E.C., 1969). Another method being investigated is the possibility of introducing the waste material into a cement slurry and pumping it underground into suitable subsurface strata.

Nuclear-powered plants do not release the combustion products typical of fossil-fueled plants to the environment. They do, however, release abundant amounts of heated water, in common with their hydrocarbon counterparts. The heat of condensation of the plant's contained water-steam system is transferred to a secondary flow-through cooling water system which normally discharges into a lake, river, or other water body in which the temperature is raised accordingly o° to 2o° F. Being thermally less efficient, nu- 1 clear-plant calefaction of the environment is greater than that of fossil-fueled plants by about 34 percent (A.E.C., 1969).

Whether this temperature increase constitutes "pollution" or merely thermal "effects" is a source of current debate. Environmentalists note that water-dwelling organisms cannot survive even moderate changes in water temperature. A study by Federal Water Quality Administration biologists of effluents from Florida Power and Light Co.'s 864-megawatt plant on Biscayne Bay suggested ecological damage to fish, shrimp, crab, and mollusk populations by slightly altering the water temperatures in their spawning areas. Other biologists responded with the fact that fish numbers and growth increased noticeably in the Savannah River below an impounded waste-heat pond of a South Carolina reactor.

Gilluly (1970) predicted that by the year 2000, some 50 percent of all the nation's surface waters will be required to cool power plants. The Chairman of the Atomic Energy Commission noted (Seaborg, 1969) that, although by ,98o thirty percent of the heat wasted by steam-generating plants will come from nuclear units, the addition of excess heat from nuclear plants, as opposed to fossil-fueled plants, will gradually be eliminated by the introduction of fast breeder reactors in the mid-1980's. Unfortunately, the heat to be dissipated is such a low-grade energy source that it cannot be economically utilized for other purposes, such as desalinization.

Solutions to thermal dissipation other than by discharge to surface waters are expensive. They include cooling ponds, spray ponds, mechanical cooling towers, natural- and mechanical-draft hyperbolic cooling towers, and dry cooling towers. Installation of a mechanical cooling tower could cost $5 to $8 per kw, of a hyperbolic tower $10 to $15 per kw, and of a dry tower $20 to $3o per kw. The 500-megawatt Vermont Yankee nuclear plant scheduled for completion in 1971 will utilize three induced-draft cooling towers at a capital cost of $6 million or $12 per kw (A.E.C., 1969).

Although New Mexico does not have a nuclear-power generating station or radioactive-waste storage area, it does have uranium-ore processing mills that must contend with radioactive effluent. The only subsurface waste-disposal well in the State is at the Anaconda Co.'s Bluewater mill just northwest of Grants. Mill effluent from this acid-leaching process contains substantial concentrations of chloride, sulfate, and sodium ions, as well as radionuclides of natural uranium, thorium-23o, and radium-226. Concentrations of uranium are minor, ranging from 4.44×10^{-6} to 1.73×10^{-5} microcuries per milliliter and averaging 7.34×10^{-6} microcuries per milliliter in the injected water. The concentrations of thorium and radium are considerably less.

The effluent is gravity-injected into the Meseta Blanca Sandstone at a subsurface depth of 95o to 1,423 feet at rates averaging between 200 to 400 gallons per minute. Constant well monitoring is employed to detect any possible escape of fluid into other water supplies. In the six-year period from January 1, 1960 to December 31, 1965, a total of 13.89 curies or 38.8 tons of uranium was injected through this disposal well (WEST, 1969).

Considering the appreciable amount of energy resources being produced, processed, and/or used in the San Juan Basin of New Mexico and Colorado, the pollution problems are relatively few. These problems can be solved by enlight-

TABLE 55. SUMMARY OF 1968 WEST REGION SURVEY OF FUELS FOR ELECTRIC GENERATION—NATIONAL POWER SURVEY

	1965		1970		1980		1990	
	QUANTITY	% OF TOTAL	QUANTITY	% OF TOTAL	QUANTITY	% OF TOTAL	QUANTITY	% OF TOTAL
1. Population (thousands)	31,006		34,650		43,400		54,241	
2. Total energy use (10^{12}Btu)	8,904	100	10,721	100	15,585	100	22,608	100
% consumed for electric generation	—	25	—	29	—	39	—	52
% consumed for thermal elec. gen.	—	11	—	14	—	28	—	43
3. Total elec. utility generation (billion kWh)	209	100	308	100	631	100	1,205	100
Thermal elec. utility generation (billion kWh)	89	43	149	48	447	71	1,007	84
4. Fuel use for thermal elec. utility generation	—	100	—	100	—	100	—	100
(a) coal (thousand short tons)	7,729	14	15,496	20	59,264	28	98,536	21
(b) natural gas (billion cubic ft.)	628	72	855	63	685	17	724	8
(c) uranium (short tons U_3O_8)	14	1	1,027	5	8,175	47	15,640	67
(d) thorium (short tons ThO_2)	—	—	—	—	3	—	100	1
(e) oil, No. 6 (thousands bbl.)	18,555	13	7,705	4	1,400	—	1,425	—
(f) oil, low-sulfur (thousands bbl.)	—	—	16,000	8	49,375	8	46,000	3
5. Average heat rate, fossil-fueled thermal elec. gen. (Btu/kWh)	10,412	—	9,865	—	9,471	—	9,718	—
6. Fuel price estimates (¢/M^2Btu), excluding transmission								
(a) coal	16	—	15	—	16	—	17	—
(b) natural gas	30	—	31	—	34	—	36	—
(c) uranium	26	—	20	—	15	—	13	—
(d) thorium	—	—	20	—	15	—	13	—
(e) oil, No. 6	32	—	32	—	28	—	32	—
(f) oil, low-sulfur	—	—	41	—	42	—	44	—
7. Fuel reserves								
(a) coal (million short tons, 1968)			263,230					
(b) natural gas (billion cu. ft., 1966)			30,464					
(c) uranium (short tons U_3O_8, 1968)			148,000					
(d) thorium (short tons ThO_2, 1968)			100,000					
(e) oil, No. 6 (million bbl., 1966) (15% of crude & shale oil res.)			101,026					
(f) low-sulfur oil (million bbl.)			—					

Source: *Energy supply and demand for the WEST region.* A report prepared by the WEST task force on fuels, Oct., 1968.

ened cooperation between the legislative representatives of an expanding population, the agencies charged with maintaining minimal environmental pollution, and the industries striving to supply the vast requirements of energy production.

ECONOMIC DESIRABILITY OF SAN JUAN BASIN COAL RESOURCES

ELECTRICAL POWER GENERATION

The most important trend in the industrial development of the Four Corners area stems from the increasing electrical power demands of the metropolitan areas of the Southwest and Pacific Coast. The past history of reliance on hydroelectric generation for this power need is changing rapidly. The WEST association, which includes most of the electrical utilities concerned with supplying the power, conducted a study of future requirements for both the electrical power and the fuel resources available for its generation (table 55). A more recent projection by WEST of the amount of thermal-generated power required and the percentage of each fuel to be used in this generation is shown as Table 56.

From these predictions it is apparent that: (a) the substantial use of natural gas for power generation will decline rapidly as shortages of this fuel occur and as it is diverted to more selective sectors of use; (b) the use of oil, never a large factor, will also decline as a result of shortages, use diversion, and more stringent air-emission controls; (c) coal use will show a marked increase in the next decade, with a slight percentage-of-use drop by 199o, as; (d) nuclear energy use becomes the dominant source of power generation by the early 1980's.

TABLE 56. THERMAL ELECTRIC UTILITY GENERATION, WEST REGION, BILLION KWH

Fuel	1970		1980		1990	
	KWH	Percent of total	KWH	Percent of total	KWH	Percent of total
Coal	30.6	20.5	123.6	27.6	207.6	20.6
Gas	92.5	62.1	76.7	17.2	75.9	7.5
Oil	16.9	11.2	34.6	7.7	30.7	3.1
Nuclear	8.1	5.4	207.7	46.5	685.2	68.1
Other (hydro)	1.0	.7	4.4	1.0	7.4	.7
Total	149.1	99.9	447.0	100.0	1,006.8	100.0

Source: *The future of power in the WEST region, 1970-1980-1990.* A report to the Federal Power Commission, by the WEST Regional Advisory Committee, June 1969.

Although the percentage-of-use figures show the fuel-mix relationships, they do not indicate the relative quantities of each fuel required to meet the rapid overall increase in demand. For example, while the prediction of percentage-ofuse for coal is within o.1 percent from 1970 to 1990, the quantity required for 1990 is 83 million tons more than that to be produced in 1970.

The estimations are predictions based on the current economic conditions; the many considerations discussed in other sections of this report could exert a substantial influence to alter these predictions. Many of the possibilities would enhance the value of stripping coals in the San Juan Basin.

Among the more important possibilities are: (I) nuclear-reactor technology may not produce the breeder reactor as soon as predicted, thereby creating a uranium shortage; (2) reactor-construction costs may continue their rapid proportional increase; (3) nuclear-radiation and calefaction problems may prevent ready public acceptance; (4) substantial increases may occur in domestic oil and gas reserves; (5) governmental support may be offered to oil-shale development; (6) rapid development of commercial coal-gasification processes may occur; (7) the rise in underground coal-mining costs may continue; (8) more stringent pollution-control requirements may force fuel changes; and (9) an unforeseen technological breakthrough might occur in any of the energy fields.

In considering nuclear energy's future role, most of the possibilities are of a negative nature. The breeder reactor is presently only a theoretical possibility requiring much additional experimentation before a commercial version can be realized. The federal government's policy of gradual withdrawal from the nuclear scene could mean that the massive financial support required for reactor research would be slowed. A delay in the development of the breeder reactor could force the exploitation of lower grade uranium ores with attendant higher fuel costs. A continuation of the nation's current inflationary economic trend would emphasize even further the present disparities in the costs of nuclear-plant construction and components, when compared to those of conventional fossil-fueled plants. Recent planning for reactor sites in heavily populated areas has run into considerable resistance from environmentalists and the general public. Stiff pollution standards could force delays and added expense.

An increase in incentives for domestic oil exploration could result in the discovery of additional large reserves of oil and gas. The history of petroleum exploration is punctuated by examples of multimillion-barrel fields found in areas of little previous regard. And although oil and gas are separated in market considerations, no distinction is made in the field of exploration. Where oil exists, gas may be found also. Gas also enjoys an advantage in the percentage of total recoverable reserves possible. If nuclear well stimulation becomes economically feasible, reserves already discovered may be made to yield additional resources. In the long run, however, it appears that even with substantial reserve additions, both of these fuels will be required for uses other than electrical generation.

Oil shale represents the nation's largest untapped domestic energy source. Its development depends almost entirely on federal government policy. Given the possibility of a more severe energy crisis, this source could be made available for either governmental or private enterprise development. A substantial lag time from availability to commercial use would exist, however, that would require massive doses of money and experimentation effort to overcome.

The gasification of coal is on the edge of being commercially competitive. It is being actively pursued now. An acute product demand is present now. Adequate reserves of raw material are available. All the factors required for its development, assuming reasonable technological advances, are currently present. It is difficult to imagine that gasification will not be advanced to commercial reality in the near future.

Costs of mining coal underground will increase. The combination of labor problems, increasing freight rates, and stringent mine-safety and antipollution measures will work against the competitive ability of this fuel. However, except in the area of transportation, strip-mined Western coals will continue to be economically competitive. The low-sulfur coals will have a definite advantage. The technology to reduce objectionable particulate emissions effectively is available and is not prohibitively expensive when compared to the total construction costs involved. Further experience in the field should tend to reduce these expenses.

And, finally, the possibility of a technological breakthrough in any energy area always exists. Three decades ago, few persons could imagine that the atom would offer the possibility of meeting all of the world's power requirements of the future. Advancements in the field of magnetohydro-dynamics may fall into this category. And breakthroughs do not have to be of a major nature to affect the course of future fuel use.

All of these factors directly affect the desirability of San Juan Basin coal resources. The immediate effect is based on considerations of its desirabilities as a fuel for electricity generation, but there are other possible future effects.

The WEST study of electrical-power needs divides the western United States into three consuming subregions: California by itself, the Northwest (including Idaho, Montana, Oregon, Washington, and Wyoming), and the Rocky Mountains (including Arizona, Colorado, Utah, Nevada, and New Mexico). Wyoming is included in the Northwest subregion as the major supplier of that area's planned coal-fired thermal plants, which are expected to supplant previous reliance upon hydroelectric generation. The stripping coal reserves from this one State are sufficient to supply all of the projected needs of the Pacific Northwest.

Although California's great future needs are planned to be relieved primarily by nuclear generation, the support of coal-fueled plants is both necessary and substantial. Since California is coal-poor, the supplies for this support will come from the reserves found in the Rocky Mountain subregion.

The Rocky Mountain subregion itself will expand its internal use of coal for electricity generation by over 125 percent to 25 million tons in 1980. The California market will be supplied by minemouth generating plants in the Four Corners area of the southern Rockies. These plants will transmit the power to the West Coast via high-voltage transmission lines. A number of plants in this area are under construction, completed, or announced for construction. A tabulation of these generating stations with their capacities, costs, and supplying mines is presented as Table 57.

The tabulation indicates that plants already constructed or committed by contract for operation by 1980, will consume some 27.4 million tons of coal annually. The Kaiparowits project, as yet uncommitted, would add another 14 to i6 million tons to the total use, thereby exceeding the WEST estimate for 198o of 39.4 million tons for California and the Rocky Mountain subregions.

The Kaiparowits project has an ample coal reserve in the Kaiparowits Plateau field, an agreement for sufficient water supply from Lake Powell, and the advantage of a nearby tie with the existing power-line network at the Glen Canyon dam, near the proposed plant site. This project appears likely for construction, although there has been mounting opposition from conservationist groups concerned about the mass rate of emissions and the thermal effects from two large, closely situated power plants (Navajo generating station and the Kaiparowits plant) located in a National Recreation Area. An additional consideration is that the coal reserves of the Kaiparowits Plateau are adaptable only to underground mining methods.

Should the Kaiparowits project be abandoned or reduced in capacity, the San Juan Basin coals offer the best prospects for further development of the balance of the future power requirements because: (a) New Mexico's San Juan Basin has a greater reserve of strippable coals than other States in the Rocky Mountain subregion, and (b) the crucial water requirements are available.

The latest estimates of strippable coal resources in the United States (Averitt, 1970) show original reserves in millions of tons, in beds generally less than 10o feet below the surface, to be as follows for States included in WEST'S Rocky Mountain subregion: New Mexico 3,000, Colorado 1,200, Arizona 400, Utah 30o million tons, and none for Nevada. Essentially all of New Mexico's reserves are in the San Juan Basin, as reflected in this report's estimate of 5.9 billion tons being found in the surface to 250-foot-depth range. Much of the Colorado total lies east of the Continental Divide where transmission costs become prohibitive.

According to the U.S. Bureau of Reclamation (197o), the only significant amount of available surface water, not already dedicated to the previously noted power plants, is in the San Juan River storage area. An uncommitted 35,00o to 40,00o acre-feet remains impounded by the Navajo Dam for possible later diversion below the lake. In addition some 6o,000 to 100,00o acre-feet which has already been contracted for, but is currently unused, might be made available for industrial use. In addition the possibility of additional substantial water resources exists in the subsurface strata of the San Juan Basin.

A number of applications for the uncommitted surface water are presently pending; issuance of contracts for this water could alter the situation. Another similar effect would occur if the present research of dry cooling tower's results in the development of an efficient and economical method of cooling boiler waters without the extensive use of secondary water.

Another advantage for the industrial use of the San Juan Basin's coals is the operating experience already available from mining, generating, and transmission operations which have been functioning for some time. The modern utilization of coal resources in the Basin has been underway actively since 1961. In 1961 the Pittsburg and Midway Coal Mining Co., a subsidiary of Gulf Oil Corp., began stripping operations at their McKinley mine in the southwestern part of the Basin. All of the product from this mine is shipped by unit train to the Arizona Public Service Co.'s 114-megawatt Cholla power plant at Joseph City, Arizona. Production has ranged from 350,000 to 450,000 tons annually and in 1969 was 441,00o tons. At startup in 1963, the average price of the coal was $2.95 per ton at the mine and $4.75 per ton at the Cholla plant, indicating a freight rate of 1.4 cents per

TABLE 57. PLANNED ELECTRIC-GENERATING PLANTS IN THE FOUR CORNERS AREA OF NEW MEXICO, ARIZONA, UTAH, AND COLORADO

POWER PLANT & OPERATOR	LOCATION	GENERAT. CAPA. (IN MEGAWATTS)	MINE & OPERATOR	LOCATION	COAL MINING (TONS/DAY)	PLANT COSTS (MILLIONS $)
Cholla Gen. Stat. Ariz. Pub. Serv. Co.	Joseph City, Arizona	114 MW Now operating	McKinley Pittsburg & Midway Coal Mining Co.	Gallup, New Mexico	3,250	
Fruitland Stat. Ariz. Pub. Serv. Co.	Fruitland, New Mexico	2,085 MW (575+1,510) Now operating	Navajo Utah Constr. & Mining Co.	Fruitland, New Mexico	28,000	$260 ($110+150)
4 Corners Gen. Stat. Pub. Serv. of N.M.	Fruitland, New Mexico	1,035 MW (345 by Fall, 1973+690 later)	Pub. Serv. Co. of N.M. Unannounced	Fruitland, New Mexico	9,300 (3,100+6,200)	$150 ($ 55+ 95)
Mohave Stat. So. Calif.-Edison	Bullhead City, Nev.	1,580 MW (Fall, 1970)	Black Mesa Peabody Coal	Kayenta, Arizona	13,680	$191
Navajo Gen. Stat. Salt River Proj.	Page, Arizona	2,310 MW (Summer, 1974, 1975, & 1976)	Black Mesa Peabody Coal	Kayenta, Arizona	27,000	$400
Huntington G.S. Utah Power & Light Co.	Huntington, Utah	1,720 MW (430 in 1973, 1,290 later)	Huntington Cyn. Peabody Coal	Price, Utah	13,200 (3,300+9,900)	$340 ($ 85+225)
Kaiparowits G.S. WEST Assoc.	Lake Powell, Utah	6,000 MW (Uncommitted yet)	Various	Kaiparowits Plateau, Utah	45,000	$900

ton-mile for the 125-mile haul (Nathan, 1965). By late 197o, freight rates had increased an additional 39 percent and minemouth coal costs were up 15 percent to an average cost of $o.158 per million Btu.

In 1962 the Navajo mine of the Utah Construction and Mining Co. began stripping operations on the western margin of the Basin to supply the nearby Arizona Public Service Co.'s Four Corners plant near Fruitland, New Mexico. The plant's first two 175-megawatt generating units were completed in 1963 and expanded to a total capacity of 575 megawatts by an additional unit in 1964. The plant installation cost over $1 oo million and required an average of two and one-half million tons of coal annually. The contract base price for a 9,000-Btu-average-blend coal was $o.1125 per million Btu, but subject to an automatic escalation for each of ten delivered blocks of energy of 95 trillion Btu, ranging up to $0.1475 per million Btu for the tenth block. The escalation in the contract price reflected adjustments for: (a) average stripping ratios; (b) average truck-haulage distance; and (c) multiple seam percentages. Later contract price adjustments are based on the Selected Wholesale Price Indices of the U.S. Department of Labor, which reflect current nationwide operational costs.

In 1967 the Southern California Edison Co. and four other WEST members joined Arizona Public Service Co. in contructing two additional generating units at the Fruitland plant, at a cost of $16o million. These units were rated at 755 megawatts each. Their completion in mid-1970 resulted in a total plant capital cost of $260 million dollars for the 2,085 megawatt of generating capacity. The plant currently operates at about 83 percent of this capacity. The $125-per-kilowatt capital cost figure compares favorably with a nationwide average (Link and Keenan, 1968) of $114/kw in 1967 and an estimated current average of $15o/kw.

With the additional units, the coal requirements from the Navajo mine increased to almost 6 million tons for 1970, a substantial increase over the 1969 production of 3.337 million tons. With the plant in full operation, the projected annual coal requirements will be about 7½ to 8 million tons. The coal reserves on the 31,000-acre property are in as many as seven major coal seams within a stratigraphic interval of 140 feet of the Fruitland Formation. Main bed thicknesses range from four to sixteen feet, with a maximum thickness of twenty-eight feet encountered in the southern part of the lease.

Stripping operations follow a normal sequence of drilling, blasting, and dragline removal of overburden. The exposed coal seam is blasted, then loaded with power shovel or front-end loader. No unusual mining problems have been experienced. The coal is hauled by a fleet of eleven 120-ton bottom-dump trucks to a crushing and blending area adjacent to the plant some two to five miles from the pits.

With a total personnel complement of about 25o people and an average daily production of 22,000 tons, the productive output of the Navajo mine is near 85 tons per-man-day shift, or almost two and one-half times better than the 1969 national average of production from strip mines. The mining costs are well below national and regional averages for stripping operations and result in a current coal price ranging up to $0.155 per million Btu or $2.79 per ton at the plant.

Utah Construction and Mining Co. considers that less than one-third of its estimated reserves is dedicated to the current 35-year contract with its optional 15-year extension. The estimated reserves of 1.1 billion tons are calculated to a stripping of 120 feet of overburden overlying the uppermost seam or 250 feet of pit depth, whichever is the lesser. With an unused water allocation of over 6o,000 acre-feet, the company is actively seeking additional customers.

GASIFICATION

The favorable mining conditions and costs prevalent at the Navajo mine can be projected reasonably to apply to a relatively large part of the strippable reserves in the San Juan Basin. The existence of a large interstate natural-gas pipeline-gathering system near the coal reserves, points up the possibility of a second major use of the extensive resources, that of coal gasification. The decline in the gas-productive capacity of the Basin and the increased demand by the West Coast market serviced by El Paso Natural Gas Company's pipeline system makes the Basin one of the most favorable areas for the early development of commercial synthetic pipeline-quality natural gas.

Again, the availability of deliverable coal reserves and adequate water supplies are critical factors which can be met by Basin resources. An American Gas Association report indicated that sufficient coal to support a commercial coal-gasification operation of 240 million CF per day of pipeline gas using the favored Hygas process would require 5,600 to 6,670 tons per day of a supporting reserve of 120 to 145 million tons of San Juan Basin rank coals, and an ultimate supply of over 30,00o gallons per minute of water. Actual process water use was assumed to amount to 10 gallons per MCF of pipeline gas.

One of the major cost items included in the calculation of gasification costs by most of the current processes is that of electric power. Comparative proposals envision the necessity of constructing plant-site power generation facilities and, in some cases, the use of the by-product char for fuel for these facilities. The San Juan Basin offers the advantage of having power plants already operating in the immediate vicinity of possible coal-gasification plant sites.

Another possible use of San Juan Basin coals would be shipment to Midwestern industrial users as a supplement to that area's local, high-sulfur, high-cost underground coal resources. This use assumes that the increased costs of mining underground coal and increasingly stringent pollution controls will continue to a point that the rail transportation costs by unit trains to move the Basin's strippable, low-sulfur coals to this market will be offset sufficiently to make them competitive.

Although the economic factors affecting the utilization of coal are many, are extremely diverse, and are subject to constant change, future predictions leave little doubt of the importance of coal as a major fuel resource. The San Juan Basin coals in particular represent a most viable, competitive source in the continued growth of the Western United States.

Sulfur in San Juan Basin Coals

by Frank *E. Kottlowski and Edward C. Beaumont*

One of the major problems envisioned at the onset of this project was the sulfur content of the San Juan Basin coals. The collecting of fresh, meaningful coal samples with unweathered sulfur was a problem. The samples were obtained mainly from coal cores resulting from exploration drilling by private companies, from our Project CLEANAIR core drilling, and from the newly cut highwalls of strip mines. Samples from outcrops may give erroneous analyses.

The accumulation of data regarding sulfur percentages from our cored samples, from the numerous chemical analyses made by private companies, from active strip mines, and the previous analyses by the U.S. Bureau of Mines, showed that the amounts are relatively uniform and for most of the coal lenses the sulfur content is less than one percent. Evaluation of sulfur content therefore was relegated to a lesser role in the priority of objectives.

The first relatively large amount of sulfur information obtained was from Utah Construction and Mining Co. One of their reports noted that the Fruitland coal in their Navajo mine leases, considering a depth of 180 feet as strippable limits, has reserves of 1,265 million tons which average 0.724 percent sulfur. A few of their exploratory coal cores contained as much as 2 percent sulfur, but the average of the samples for any township in their lease is 0.79 percent or less. Data released by Public Service Coal Co. to Beaumont from exploratory drilling in the Bisti Fruitland area on the southwestern side of the San Juan Basin and from their extensive drilling in the Fruitland Fruitland coal area north of the Navajo mine, gave similar results as to sulfur content.

Sampling from small open pits in the Menefee Formation of the Mesaverde Group, coals older than the Fruitland coals gave similar sulfur analyses, a range from o.6 to 1.0 percent, and an average of about o.8 percent. Some analyses of Mesaverde coals made by the U.S. Bureau of Mines from beds mined in underground mines in the southern part of the San Juan Basin yielded sulfur percentages of about two, thus suggesting that the older coals may have higher percentages of sulfur. However, data gained during the coring program, as well as the majority of the analyses from lower Mesaverde coals, indicate that most of these coals are also in the one percent-and-under range. Some of the oldest Mesaverde coals are in the Zuni area, and they too, contain about o.6 percent sulfur. Similar low percentages of sulfur occur in the oldest coals sampled, the Dakota coals in the Cortez coal field.

One of the reasons for higher sulfur content, in the one- to two-percent range, is shown by analyses from a thin Gallup Sandstone coal in the Zuni area. A sample analyzed of the entire 3.3-foot-thick bed, including o.3 foot of bone coal, contained x.48 percent sulfur, as well as 15.98 percent ash. A sample of the same bed that excluded the bone coal laminae contained 0.79 percent sulfur, with 8.82 percent ash. Thus about half of the ash and sulfur appears to have been contained in the ten percent of bone coal interlaminated with the coal bed.

Obtaining fresh samples of coal that contained appreciable visible amounts of sulfur minerals proved to be difficult. Two core samples were provided by Beaumont, through the courtesy of Public Service Coal Co., from the exploratory drilling in the Fruitland Fruitland coal area. These were examined microscopically by Robert H. Weber, economic geologist and mineralogist for New Mexico State Bureau of Mines and Mineral Resources.

One sample was from Fruitland coal in section 4, T. 3o N., R. 15 W. Weber reported it contained abundant marcasite in lenticular aggregates parallel with the bedding and thin films of marcasite along transverse shrinkage fractures. The euhedral marcasite crystals range from less than o.oi to 2.0 mm in diameter, with most of them in the 0.1- to 0.2-mm size. During drying of the coal sample, which began as soon as it was removed from the plastic sample bag, soluble white iron sulfates developed as efflorescent bloom on the marcasite. Weber reported that the coal was speckled with sparse small lenticular masses of yellow resin; the resin could be confused with iron pyrites by a person looking at the coal without use of a magnifying lens.

The second Fruitland coal sample was from a test hole drilled in section 28, T. 3o N., R. 15 W. Weber reported the presence of iron sulfide, mostly as marcasite, as very sparse paint-thin films, largely in transverse shrinkage cracks, and even in less abundance as flat crystals parallel with bedding parting. Much of the yellowish material in the sample is coarse-grained, ovoid to irregularly shaped red-and-yellow pockets of resin, which are conspicuous and abundant. As with the previous sample, the iron sulfides began to break down as the sample was subjected to drying conditions. Some microscopic white films in joint fractures appeared to be gypsum.

These two coal samples were recovered from cores at considerable depths, more than 100 feet, thus they should be relatively fresh, unweathered coal. It is noteworthy that the iron sulfide has the crystal form of marcasite but x-ray diffraction patterns are mostly of pyrite, that iron sulfates develop rapidly on exposure to drying, that much of the pyrites is in transverse shrinkage cracks rather than parallel to the bedding, and that resin is more abundant than the iron sulfides.

To check the sulfur in Mesaverde coals, Shomaker and Lease collected a sample from the White Rock Navajo Tribal strip mine, a small open pit in SE1/4NW1/4 section 31, T. 22 N., R. 13 W. The coal mined is in the upper part of the Menefee Formation, and the sulfur-rich sample was a thin lens in the upper 6.4 feet of the coal.

In this sample, Weber reported marcasite abundant in thin seams of parallel and en echelon fracture fillings, and thinner transverse films. Some of the wider seams include minor amounts of tiny selenite crystals, the clear crystalline form of gypsum. As this coal had been exposed to the air for considerable time before being collected, much soluble white iron sulfate had formed as efflorescent bloom on the marcasite.

An analysis of this coal that included the entire 6.4-foot thickness was made by the U.S. Bureau of Mines Pittsburgh laboratory. This gave an as-received result of 0.7 percent sulfur, divided into 0.03 percent sulfate, 0.17 percent pyritic, and 0.49 percent organic sulfur. An approximation of the numerous other chemical analyses of San Juan Basin coals suggests that nearly all of the coals contain at least o.5 percent organic sulfur. The percentage of sulfates appears to depend on some movement of ground water through the coals, but the total of both sulfate and pyritic sulfur makes up about half of the sulfur in samples having as much as one percent of total sulfur. In samples with more than one percent sulfur, the ratio of sulfate-pyritic sulfur to organic sulfur increases for most coals analyzed.

On the surface and at very shallow depths in drill holes, San Juan Basin coals commonly contain significant amounts of sulfur in the sulfate form—gypsum. The gypsum occurs in veinlets or fracture fillings and to a lesser extent parallel to the bedding. In some instances the gypsum is intimately associated with marcasite, but more often there is an abundance of the iron-oxide minerals which presumably were derived from the sulfide through weathering. It is possible that the gypsum also is a product of the sulfide weathering, but it appears more likely that the gypsum, which is commonly present in strata both above and below the coal, has been dissolved from the enclosing rocks by groundwater action and precipitated in the coal.

Beaumont observed, in connection with the detailed drilling program conducted by Public Service Coal Co. on the Fruitland coal beds immediately north of the San Juan River, that gypsum is very rare, if not absent, in the fresh coals at depth. Vein or fracture fillings by calcite are present in considerable abundance to depths of 500 feet. These veinlets were observed to range from a mere film on the cleat face to about one-half inch in thickness. The calcite is commonly interlaminated with about equal proportions of pyrite (marcasite). This intimate mixture of the two minerals suggests the possibility that they represent the reduction of gypsum to secondary calcite and marcasite. The mechanism for this conversion may be bacterially implemented through a process similar to that described for the formation of the limestone caprock in salt domes (Feely and Kulp, 1957). Regardless of the mode of formation, the presence of sulfur in the sulfate form is uncommon in fresh coal in the San Juan Basin.

Numerous studies have been made of sulfur content in coals with the most comprehensive and recent being those of Gluskoter and Simon (1968) for Illinois coals, by Walker and Hartner (1966) for coals worldwide and including most of the coal beds in the United States, and the detailed investigations of sulfur facies by Cheek and Donaldson (1969) and by Hidalgo (1969).

The coal beds in Illinois are of Pennsylvanian age and are about 290 million years old, compared to the approximate 90-million year age of the Late Cretaceous coals in New Mexico and Colorado. Also, the coals in the Illinois-Indiana-Pennsylvania-West Virginia region appear to have accumulated under much more stable conditions than the Western Cretaceous coals, and they are more closely associated with marine strata. The coals in Illinois contain only small amounts of sulfate; rarely is gypsum present. Their iron sulfide is mainly pyrite, and large vertical variations in the content of pyritic sulfur are common. Pyrite tends to be concentrated in the bottom and top benches of the Illinois coals. There is a correlation between the percentages of organic and pyritic sulfur that Gluskoter and Simon (1968, p. 9) suggest is caused by similar modes of formation of the two types of sulfur. Organic sulfur, however, is much more uniformly distributed in the Illinois coal beds than is pyritic sulfur.

Coals with low sulfur (under two percent) in Illinois appear to be directly related to the type of roof rock overlying the coal. In most areas where the sulfur content of the coal ranges from two to ten percent, the sedimentary beds above the coal are marine black "slaty" shale and/or marine limestone. In areas where the coal beds are directly overlain by more than zo feet of gray nonmarine shale, sulfur percentages drop to less than two percent (Gluskoter and Hopkins, 1970; Hopkins and Nance, 1970). Apparently, the gray nonmarine shales represent gray muds that sealed off the peat from sulfate-bearing marine waters.

Detailed studies of the Upper Freeport (Pennsylvanian-age) coal in West Virginia by Cheek and Donaldson (1969) suggest some similar relationship between the marine or nonmarine beds overlying coals and the sulfur content of the coals. The sulfur content varies inversely with coal thickness within the same seam, and it is higher in bone coal than in the coal, especially toward the bottom and top of the seam and in areas where sandstone rather than shale is the roof rock.

A survey of the sulfur in San Juan Basin coals by Walker and Hartner (1966), as part of their worldwide compilation, showed that only in the northeastern part of the San Juan Basin, chiefly in the Monero coal field, were the amounts of sulfur for most coal beds over one percent. The results of this present investigation confirm the findings of the U.S. Bureau of Mines. However, even in the Monero coal field, where as much as 3.5 percent of sulfur occurs, the sulfur content is erratic, and some of the beds are low in sulfur. This relatively high sulfur content of the northeastern coals is to be expected, as in that part of the San Juan Basin marine strata are more abundant in the Cretaceous sequence than are nonmarine rocks. The relatively low sulfur content of the San Juan Basin Cretaceous coals is probably related to their depositional history, in that these coals formed in mainly fresh-water swamps, separated for the most part by shoreline and offshore sands from marine-deposited shales and shaly limestones.

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.*Appendix*

THE IMPACT OF COAL ON NORTHWESTERN NEW MEXICO

by Edward C. *Beaumont*

Talk at State Advisory Board Meeting, U. S. Bureau of Land Management, Farmington, New Mexico, July 23, 1970

The value of coal produced in New Mexico, in the northwest region particularly, does not approach the value of the large commodity, uranium ($6.4 million versus $77.4 million in 1969), but the pattern for uranium is set. The shallow, open-pit uranium deposits appear to have been found and developed; activities are now directed to the finding of deeper, down-dip deposits which must be developed from shafts. Coal, on the other hand, is on the threshold of a major renaissance. Yet the industry carries with it, in addition to the promises, all the elements of controversy and the responsibility that accompany the mineral industry everywhere in this nation today. Coal lands have been terribly abused in the eastern part of the country; there is no denying it; there are some ugly scars, but also there are an increasing number of beautiful parks, recreation areas, and game preserves to mark the site of former strip mines.

GEOLOGIC AND GEOGRAPHIC BACKGROUND

Coal is merely a special type of sedimentary rock, a result of the accumulation of thick deposits of organic debris laid down in swamps and lagoons. These were marginal to the vast continental seas during Late Cretaceous and Early Tertiary time, 5o to loo million years ago. The coal deposits in New Mexico and elsewhere in the Rocky Mountain States are located, or perhaps more precisely, preserved in major sedimentary basins. The two important basins in New Mexico are: (1) the Raton Basin in the northeast, and (2) the larger San Juan Basin within which Farmington is located. Both the Raton and the San Juan Basins are shared with Colorado.

In the San Juan Basin, the potentially valuable coal deposits are confined to a small part of the geologic column. In the south, east, and to some extent the west parts of the basin, the coal deposits of significance belong to the Mesaverde Group. Other thick coal deposits and perhaps those with the greatest future occur in the younger Fruitland Formation. Fruitland coals are well developed on the north, west, and south sides of the basin. Although the formation is present in the east side of the basin, the coal is absent to weakly developed. Inasmuch as the Fruitland Formation is higher in the stratigraphic section, its occurrence is more restricted than the older and thus more widely spread Mesaverde rocks in the saucer-shaped San Juan Basin.

Coal in the San Juan Basin is both bituminous and subbituminous in rank. It is generally noncoking (as contrasted with coking coal in the Raton Basin). It is more or less impure from the standpoint of day and sand content, but it is low in sulfur. Generally, San Juan Basin coals contain less than one percent sulfur, a strong point in their favor.

HISTORICAL BACKGROUND

Coal became an important energy source in Territorial New Mexico with the advent of the railroad. Production, employment, and dollar-value records are available from 1882. Production rose steadily to a peak of about four million tons in 1918. Following World War I, production declined and was slightly under three million tons in 1929. It then declined sharply during the depression years to about 2.3 million tons. World War II saw a small resurgence in production, but the post-war years brought dieselization of the railroads, loss of the steel-mill market in Pueblo, and increasing use by the power companies of that easily transportable and clean fuel, natural gas. In fact, this just about finished the coal industry in New Mexico. For instance, in 1954 production in the state was only 123 thousand tons.

In 1955 Kaiser Steel came to the Raton area, and with the exception of a fire-induced minimum production of 116 thousand tons in 1958 (the all-time low), production has continued to climb since 1954. The big turning point in production, however, has come in recent years with the advent of large-scale surface mining. Although the exploratory period began earlier, the first significant production from a strip mine in New Mexico was in 1962 with the opening of the Pittsburg and Midway Coal Mining Co.'s McKinley mine, a few miles northwest of Gallup. This was followed by Utah Construction and Mining Co.'s Navajo mine in 1963. State-wide production rose to 3.6 million tons in 1968 and to 5.1 million tons in 1969. The value of the coal produced in the state reached a peak of $13.6 million in 192o and declined to a low of $728,000 in 1954. The value of the 1969 production is more than $16 million and this does not include about 65o thousand tons that were stockpiled during the year. The Utah Construction officials inform me that with all five units of the Four Corners power plant now on the line, their production alone should climb to the 6-million-ton mark.

Employment trends with coal, as with almost any other industry, have been toward greater efficiency of production. During the earlier peak production year, 1918, there were more than 4,000 employees in the coal industry. This is more meaningful when it is considered that the population of the state then was only about 400,000 people. A sharp contrast to this period when r percent of the state's population, or perhaps 4 percent of the work force was employed in the coal industry, is the 5.1 million tons produced in 1969 that was accomplished by only 391 workers. In 1918 production was strictly a hand proposition. The average production per-man-year was 982 tons. Mechanization of underground mining was quite advanced by 1961 and the man-year rate had risen to 1,831 tons. However, the significant break in this category is tied to strip mining. By 1969 the figure had risen to a phenomenal 13,000 tons per-man-year.

MINING METHODS

Since a considerable part of the controversy with coal activities surrounds the conflict between deep mining and surface mining, it is appropriate to explore some of the differences in the two methods. The figure of 13,00o tons per man-year includes all coal mined in New Mexico. Comparison of the relative efficiency of deep mining and surface mining is revealed in the figures for 1969 when both surface-and strip-mining methods were at comparable states of technical development. The tons per man-year for surface mining was 18,000 and the corresponding figure for deep mining was about 6,300. The latter figure is a big advance for deep mining but it cannot compare with the surface techniques.

If you are wondering why anyone would persist with deep mining methods, I point out that only certain ground is amenable to surface mining. The prime requisites are: (I) abundant coal with favorable ratios of overburden to coal, and (2) generally, nearly flat-lying beds. The Raton Basin deposits are largely unfavorable in this respect. The reason they are operated economically by underground methods is that they represent a high-value product, metallurgical coking coal.

It is difficult to give a direct cost comparison between subsurface and strip-mining; however, it is fairly well established that reasonably thick coal seams under favorable overburden conditions can be strip-mined for about, or under, $2 per ton. However, rising labor costs, particularly in deep-mining, versus the improved efficiency of stripping machinery tends to broaden the disparity between the two mining methods. Maximum economic depths for stripping are presently on the order of 18o to zoo feet, but the limit beyond which it is practical to mine underground continues to retreat in the face of the changing economic and technical conditions. It is possible that an entirely new system of surface mining may double the present depth limit in the next two decades. Deep mining, on the other hand, presents costs in the neighborhood of $4.50 to $5.5o per ton. The economics of the product make the big difference, thus it is not feasible to recover the so-called "steam coal" by underground mining methods until the shallow, low-cost strip-coal has been completely utilized.

One limiting factor is that the very shallowest coal, which lies beneath less than 20 to 3o feet of overburden, is usually of no value or of limited value because it has been subjected to the actions of oxygenated waters and is generally reduced in value through low-grade oxidation or general weathering.

UTILIZATION

The San Juan Basin coal is referred to as "steam coal" to distinguish it from coking coal, with the major use of this coal being for steam-electric power generation. It is thought of solely as a fuel as is borne out by the major use of the San Juan Basin coal. Pittsburg and Midway Coal Mining Co.'s McKinley mine supplies the 110-megawatt Cholla plant of Arizona Public Service Co. in Joseph City, Arizona at the rate of 350,000 to 500,000 tons per year. The Arizona Public Service-WEST Associates complex, about 15 miles west of Farmington, will be the largest electric-generating facility west of the Mississippi when all of the units are on the line, and the Navajo mine which supplies the coal, will be, in terms of production, the largest coal mine in the United States with an eventual demand of about 8.3 million tons per year. By 1973 Public Service Co. of New Mexico and Tucson Gas and Electric Co., will have the first of three 345-megawatt units comprising their San Juan plant on line and will be producing coal at the rate of about 1.2 million tons per year. As the other two units are added, production will increase to about 3.6 million tons per year.

FUTURE DEVELOPMENT

Yet there is room for more. New Mexico is not a particularly big State in terms of coal reserves in the Rocky Mountains or the United States. The U.S. Geological Survey's estimate of remaining reserves as of January 1967 is as follows:

New Mexico	61.5 billion tons
Montana	134.2 " "
Wyoming	120.7 " "
Colorado	80.7 " "
Utah	32.3 " "

Interestingly enough, even as late as 1967 Arizona is not included as a coal-producing state. Yet within a very short period of time the Peabody Coal Co. will be supplying coal to two major power-generating facilities from their Black Mesa coal field in northern Arizona—from coal deposits closely related to those found in the San Juan Basin. I hasten to add that reserves such as the 61.5 billion tons attributed to New Mexico include all the coal that lies under less than 3,00o feet of overburden. By today's economics it is inconceivable that all of this coal could be minable. Nevertheless, there is enough available coal to provide a tremendous future for New Mexico.

For the future, the power-generating potential is obvious, but there is another aspect that I consider to have an even greater potential. During the course of an investigation of oil shale, I was sidetracked into the subject of coal hydrogenation, and arrived at the conclusion that the biggest threat to a successful oil-shale industry was from the prospective use of coal for the production of synthetic hydrocarbons. As a matter of fact, the eventual salvation for our dwindling supplies of natural-petroleum products is the synthesis of both liquid and gaseous hydrocarbons from coal. I believe that the big future for coal is not for direct conversion to thermal energy but rather as a source of basic material from which a variety of hydrocarbons can be derived. Coal, like oil shale and tar sands, is classified as a hydrogen-deficient hydrocarbon. Thus with the proper technology (which is, of course, easier said than done), hydrogen can be added to produce almost any hydrocarbon compound that might be desired.

One of the most desirable products in terms of yield on investment is gasoline. Research sponsored by the Office of Coal Research in pilot-plant operations has produced gasoline from coal by utilization of the Consol process (Consolidation Coal Co.) for as little as 10.5¢ per gallon. A requisite for this low a figure is quantity. There is a tremendous economic advantage gained in the massiveness of an operation on the order of 100,000 bpd. Another major consideration is the cost of the coal. A ton of bituminous coal from the Fruitland Formation has a yield potential of 3 to 3 1/2 barrels of oil or liquid hydrocarbons per ton. Thus for a oo,000-bpd operation the quantity of coal needed ranges from 8.5 to 9.9 million tons per year. This figure is nearly double the 1969 production for the State. Another requisite is the need for a large coal reserve. A minimum consideration is 20o million tons; however a 30o million-ton dedicated reserve would not be considered excessive.

Another product is high-Btu pipeline-quality gas. This, some well-informed authorities suggest, presents a more immediate potential for achievement. The Institute of Gas Technology has developed the Hygas process into the pilot plant stage. IGT estimates an ability to manufacture gas comparable to the best natural gas for about 380 a million Btu. This gas can be marketed for about 440 a million Btu. This is, under the present economic situation, nowhere nearly competitive with natural gas at about 280 per million Btu. In view of our diminishing resources of this marvelous fuel, it may not be too many years before we are supplementing our supplies with coal-derived synthetic gas.

A major obstacle to liquid synthetics is a lack of a moderately priced hydrogen source. The only feasible source at present is natural gas and even now in the San Juan Basin there is precious little of this commodity that is not already dedicated. The gasification process utilizes steam as a hydrogen source which requires significant quantities of water.

CAPABILITY OF THE SAN JUAN BASIN

To illustrate the capacity of the San Juan Basin to sustain one or more operations of this size, we can use Utah Construction's Navajo coal leases as an example. The company admits to strippable coal reserve of ',100 million tons—and this is not even to what I consider to be maximum strippable depths. At their anticipated maximum rate of production of 8.5 million tons, this is enough for 13o years of production. Assuming that 5o years would be a maximum life for the Four Corners power plant, it is apparent that Utah, should they be interested, could cosustain a full-scale conversion facility.

Immediately south of Utah's holdings, El Paso Natural Gas Co. and Consolidation Coal Co. have joint holdings on the Navajo Reservation which are reported to contain more than 450 million tons of coal. Again, this represents more than enough coal to meet the requirements for a large-scale conversion plant. A fact that is not widely known is that the original lease between the Navajos and El Paso Natural stated that the coal would be used specifically for gasification.

Until the past couple of years it was considered that the better coal in the Fruitland Formation—or at least the most economic—was on the Navajo Reservation. Rather recent and still largely undisclosed drilling indicates that large reserves exist to the southeast of the Reservation. Two years ago I made an estimate of 1,77o million tons of strippable coal in the Fruitland Formation in New Mexico. On the basis of increased knowledge, I can safely upgrade this figure to over 2 billion tons which is equivalent to somewhere between 6 and 7 billion barrels of oil. This is indeed a resource to be reckoned with.

ENVIRONMENTAL EFFECT

Finally, I have reached a point that cannot be avoided. What happens to the landscape when we mine the coal? Is the price we pay for the use of this abundant source of energy to be desolation and waste, or is there another answer? First, let me state clearly that the land can never be returned to its original condition. It cannot be restored to even closely resemble the natural appearance, and from my own point of view this is not a disaster. The area occupied by strippable coal, principally the outcrop area of the Fruitland Formation, lies mostly south of the San Juan River. Much of the land is a relatively flat, high plateau with extensive areas of drifting and semistabilized dunes. The interdivide areas tend toward badlands topography with sharply contrasting patterns of sandstone and shale. Sandy soil exists in the divide areas but is generally absent in the drainages. Much of the land is exposed bedrock upon which little vegetation will grow. I know that there are those who consider that there is nothing ugly in nature, and well this may be, but for much of the area that would be disturbed by strip mining, it can only be described as an "austere beauty."

The coal-mining companies are concerned and motivated to rehabilitate the land to the extent that it can be further used for some purpose, probably grazing. Utah Construction has done considerable experimentation with optimum slopes on their spoil banks. About 2 1/2 years ago they leveled three test areas in order that the BIA could conduct reseeding experiments. One of these was in the shallow overburden area where the weathering extended right to the top of the coal; the other two were in deeper coal areas where there was a complete turnover with fresh bedrock having been brought to the surface. These were planted about a year ago. In the shallow plot, about five of the eight grasses tried came up sparsely the first year, and in this second season, it is reported that some of the seed which lay dormant through last year is beginning to sprout and there is a general increase of growth indicative of natural reseeding. The two deeper areas were surfaced by a swelling bentonitic shale. The poor water absorption characteristics of this material caused it to fail to support growth of more than a few Russian thistles.

Now Utah is putting about one-half the ash which they backhaul from the power plant into the "valleys" between the spoil peaks. This is in turn covered to a depth of about three feet by material shoved off the peaks. The result is an undulating topography that has greater resistance to wind and water erosion than a completely flat plain. Utah is also interested in further research concerning the optimum planting material. In return for research aid in this area, they have offered monetary aid to the NMSU Experimental Station near Fruitland but so far these overtures have been unsuccessful. They are now considering the possibility of taking their plan to a Colorado group.

Pittsburg and Midway Coal Mining Co. is conducting similar experiments with test plots at the McKinley mine. Their handling of the spoil piles is similar to Utah's except for their not having ash to backfill into the valleys. They likewise end up with a rolling topography, perhaps more so than that of Utah's. However, they report that the surface seems well stabilized. They also report considerable success with Russian olive and Chinese elm, but spruce failed to grow. Western wheat grass seems to do best in the spoil areas, but inasmuch as they do not have the area fenced, premature grazing by sheep has made it difficult to evaluate the experiment.

Public Service Co. of New Mexico plans about the same approach. They intend to work closely with the ranchers in the area in order that lands are not needlessly disturbed nor withdrawn from surface use prematurely.

The companies are concerned. Personally, I feel that the awareness of environmental problems and a genuine concern for the future are large factors, but also I am aware that outside pressures have been in some degree responsible for shifting attitudes.

SUMMARY

In summation, the coal industry in New Mexico has truly been reborn, having risen from the most slender thread 6 years ago to a significant economic factor in northern New Mexico—particularly northwestern New Mexico. And there are indications that we have only seen the beginning. However, the real future for coal is contingent on the ability of all New Mexicans, federal and state agencies, special-interest groups, and the general citizenry, to provide the prospective developers of this resource with a rational atmosphere of cooperation, one that is conducive to the investment of venture capital of a magnitude necessary to turn a tremendous potential into a reality.

RECENT COAL DEVELOPMENTS IN THE SAN JUAN BASIN, COLORADO AND NEW MEXICO

by John W . Shomaker

Abstract of talk given at Billings meeting, Rocky Mountain Section, American Association of Petroleum Geologists, May 3, 1971

The principal San Juan Basin coals occur in the Upper Cretaceous Fruitland Formation; smaller reserves of somewhat better quality are found in several formations of the Mesaverde Group. Nearly all are subbituminous A or B or high-volatile bituminous C, with sulfur content averaging about 0.7 percent.

Since 1953, when coal exploration began in earnest in the basin, five major lease blocks totaling on the order of **2³A** billion tons of potentially strippable coal have been established. Additional areas underlain by perhaps another two billion tons are now in preliminary stages of exploration. In 5971 the Navajo mine at Fruitland probably will be the largest in the United States.

Of this reserve, about 485 million tons, so percent, is committed to electric-power generation. Much of the rest, particularly a large lease held jointly by El Paso Natural Gas Co. and Conoco's Consolidation Coal subsidiary, is likely to leave the basin the form of synthetic liquid hydrocarbons or gas. Gasification and liquefaction technology is moving rapidly, and that, plus availability of major reserves of suitable coal, rising demand for fuels, and increasing availability of pipeline and marketing capacity as gas production declines, seems to indicate the future for the basin. The ultimate reserve would appear to be equivalent to some 14 1/2 billion barrels of oil.

STRATIDYNAMICS OF COAL DEPOSITION IN SOUTHERN ROCKY MOUNTAIN REGION, U.S.A.

by Edward C. Beaumont, John W. Shomaker, and Frank E. Kottlowski

Talk for VII Internationaler Kongress für Stratigraphie and Geologie des Karbons, August, 1971

ABSTRACT

The stratidynamics of coal deposition is the direct relationship between migration rate of shorelines and their attendant depositional environments that resulted in accumulation of coal-bearing and associated facies. Significant coal deposits in the Southern Rocky Mountain region are in paludal and lagoonal facies of the classic transgressive-regressive sequences. Relative abundance of coal and thickness of paludal-lagoonal facies are largely functions of rate of strandline shift and degree of interruption of major trend.

Rapid shifts in shorelines have resulted in elimination of depositional conditions favorable to accumulations of organic debris, whereas somewhat less rapid but constant changes formed persistent, but coal-poor carbonaceous sequences in the marine-marginal facies. Slowly shifting shorelines and periods of stagnation resulted in greater accumulations of peat and resultant thick coal deposits. Minor reversals in major depositional trends have the effect of increasing local organic debris accumulations but in many places the resulting coals are irregular in lateral and vertical distribution. With major changes from transgression to regression, or vice versa, shoreline movements tended to decelerate, and in some instances to oscillate, causing thick accumulations of paludal

sediments, as well as thick, associated lagoonal, shoreline, deltaic, and nearshore facies.

Upper Carboniferous coals occur in paludal facies near the Uncompahgre and Pedernal uplifts. Thick Cretaceous coals are associated with major "turnarounds" or with stagnant shorelines. For example, near Gallup, New Mexico, maximum Dilco Member coals are immediately landward from pinchouts of transgressive Dalton Sandstone, and thick Gibson Member coals occur landward from the Point Lookout Sandstone pinchout, which is the culmination and shoreline facies of the Satan Tongue transgression. Similar facies relationships may pinpoint commercial coal deposits in Black Mesa, Arizona, in northwestern San Juan Basin, New Mexico, and Book Cliffs, Utah. Carboniferous and Cretaceous coals are absent locally in facies indicative of rapidly shifting strandlines.

INTRODUCTION

Coal beds in the southern Rocky Mountain region of the United States of America occur in Pennsylvanian, lower Permian, Cretaceous, and lower Tertiary sequences. The thin lenticular Paleozoic coals are in New Mexico, Arizona, and southern Colorado, and range from Morrowan (Namurian) to Wolfcampian (Sakmarian) in age. Cretaceous coals in New Mexico, Arizona, Utah, and Colorado are mainly of Late Cretaceous (Cenomanian through Maestrichtian) age but some thin coals are present in strata of youngest Early Cretaceous (Albian) age. Tertiary coals, similar in origin and extent to the Upper Cretaceous coals, are mainly of Paleocene age.

Lagoonal and paludal (marshy) facies containing coal beds are integral parts of the classic transgressive-regressive sequences of the Cretaceous in the southern Rocky Mountain province, as well as minor features of the varied late Paleozoic facies. Coal is associated to some degree with every advance and retreat of the Cretaceous sea in the region. There are some scattered lenses of coal in the lacustrine and floodplain facies, both fluvial and deltaic, but the significant coal deposits are restricted to the lagoonal and paludal facies. The close correlation between sedimentary accumulation and rate of migration of the shoreline illustrates the principles of stratidynamics, as the relative abundance of the coal and the thickness of the lagoonal-paludal sediments is largely a function of the rate of movement and the degree of interruption of the direction of movement of the strandline.

Stratidynamics as applied to coal suggests that there is a direct relationship between the rate of migration of a shoreline and the attendant environments of deposition, the extent and thickness of the coal beds in the lagoonal-paludal environment. Rapid shifts in a shoreline can result in the elimination of the depositional conditions favorable to the accumulation of organic debris whereas a somewhat less rapid but constant change can result in a persistent but coal-poor carbonaceous sequence representing the marine-marginal zone. Slowly shifting shorelines and periods of stagnation result in greater accumulations of organic matter and resultant coal deposits. Minor reversals in major depositional trends have the effect of increasing local accumulations of debris but in many places the results are greatly irregular lateral and vertical coal distribution. The interpreted location of the strandline at the time of a major change in the relative direction of movement of the sea is potentially significant inasmuch as there is an associated period of deceleration and, in some instances, oscillation associated with these reversals.

Excellent examples of these several relationships are shown in the San Juan Basin of New Mexico and southwestern Colorado in the Cretaceous sequence. The commercial coal deposits of the Gallup coal field, in northwest New Mexico, are associated with two major shoreline "turnarounds." The maximum development of the coal in the Dilco Member of the Crevasse Canyon Formation is immediately landward from the maximum marine transgression of the Mulatto transgression as evidenced by the pinchout of the Dalton Sandstone. Similarly in the vicinity of Gallup, the Satan transgression culminates in the pinchout of the shoreline Point Lookout Sandstone, which is seaward from thick coal beds in the Gibson Member.

The opposite extreme of the stratidynamic principle is illustrated in the central part of the San Juan Basin in New Mexico as shown by relationships between the Point Lookout Sandstone and Menefee Formation. About midway in the Point Lookout regression, there is a corresponding marked absence of coal beds in the lower Menefee lagoonal-paludal facies, indicative of a rapidly shifting strandline, as well as many thin intertonguing littoral sandstones in the underlying and lateral facies of the Point Lookout Sandstone. Similar facies relationships illustrating this principle have been mapped in the Black Mesa Basin of northeastern Arizona and the Book Cliffs region of east-central Utah.

Other factors such as climate and supply of clastic materials from the distant Cretaceous highlands have had an influence on the magnitude of the organic accumulations that resulted in coal beds, but in the southern Rocky Mountain region the stratidynamic principle is a significant factor. The principle can be applied to locate areas of maximum favorability in other coal measures having a similar genesis.

COMPARISON WITH MODERN-DAY PEAT DEPOSITS

Modern-day peat deposits are in swamps and marshes of large deltas, like that of the Mississippi River and Nile River, in large coastal plain swamps such as the Dismal Swamp of North Carolina and Virginia and the Sumatra swamp in the East Indies, in the coastal mangrove swamps and marshes like the Everglades of Florida, and in relatively narrow marsh and swamp belts landward from offshore barrier bars and between beach ridges of chenier plains such as along the Gulf Coast of the United States and Mexico.

The low percentage of sulfur in the southern Rocky Mountain Cretaceous coals suggests deposition of the organic material mainly in fresh-water swamps rather than in marine marshes. Many of the coal beds are in long, narrow belts parallel to the Late Cretaceous shorelines, are landward from barrier sandstone bars or beach sandstones, and grade landward into point bar sandstones and floodbasin or floodplain shales and siltstones. Most of the coals appear to have been deposited as peats in fresh-water lagoons and swamps, landward from a sand sequence such as that described by Sabins (1963) in the Bisti oil field in the west-central part of the San Juan Basin. Closely spaced oil tests in the Bisti area show a seaward gradation from fluvial-deltaic shales, sandstones, and coals, into beach sandstones, next into back-bar or lagoonal sandy and silty shale with sandstone lenses, then into barrier bar sandstones, and then into fore-bar and offshore sandstones that grade laterally into marine shales.

The environment of deposition of the southern Rocky Mountain Cretaceous coals seems similar to that of the peats now being deposited in estuary, deltaic coastal swamps such as that part of the Gulf Coast northeast of Galveston Bay, except that in the Gulf Coast area the numerous, relatively small rivers are filled with sand and clay debris; so much of their clastic fraction is being deposited that organic accumulations are very impure. Peats on the large-scale deltas, such as the Mississippi, are, except for those on the shoreward margins, not as intimately associated with marine sediments as are the San Juan Basin coals.

LATE PALEOZOIC COALS IN THE SOUTHERN ROCKY MOUNTAIN REGION

Thin, lenticular coal beds occur in the Pennsylvanian and lower Permian rocks of New Mexico, eastern Arizona, and southwest Colorado, ranging from Morrowan to Wolfcampian in age. Where their lateral extent can be traced, they form thickening and thinning lenses that were deposited in small irregularly-shaped basins or in long, narrow basins that paralleled the shorelines of the time. The original peats appear to have accumulated in shoreline lagoons and marshes, or in small estuaries. Most are closely associated with marine strata, including much dark fossiliferous marine shale and highly fossiliferous limestone, suggesting an origin in marine or brackish marshes.

Figure 1, an average paleogeographic map of the southwest region for Pennsylvanian time, shows the relationships of marine basins and emergent debris-supplying uplifts. During Morrowan time, about 7o percent of the region was above sea level, and marine sediments were deposited only in the basinal areas. These were the Paradox basin, lying generally north of the "Four Corners" where New Mexico, Arizona, Utah, and Colorado meet; the Pedregosa basin in southwestmost New Mexico and southeastmost Arizona; the Orogrande basin in south-central New Mexico; the Estancia basin in central New Mexico; the Rowe-Mora basin in north-central New Mexico and south-central Colorado; and the Delaware basin in southeast New Mexico and adjoining parts of Texas.

The maximum Pennsylvanian-early Permian marine flooding was during Desmoinesian time when all but the higher parts of the various landmasses, arches, and archipelagos were covered. During Virgilian time, maximum elevations were attained by the uplifts, and along their edges marine limestones of middle Pennsylvanian age were stripped by erosion. The Uncompahgre Range of southwest Colorado and north-central New Mexico, as well as the Pedernal Mountains of central and south-central New Mexico, may have towered a mile above sea level. Large, although lower landmasses were the Kaibab arch in south-central Utah and north-central Arizona, the Sierra Grande arch of northeast New Mexico and south-central Colorado, the Zuni arch of northwest New Mexico and northeast Arizona, and the Florida islands of southwest New Mexico.

The arrows (fig. 1) in northeast Arizona on the Supai delta area show the directions of sediment-bearing currents, and suggest most of the detritus was derived from the north from the Kaibab arch with minor amounts from the Zuni arch. Only the lower part of the Supai is of Pennsylvanian age; the rocks are mostly red in color and range from shallow-water marine limestone to alluvial and deltaic sandstones, shale, and limestone conglomerates. These continental and shoreline sediments grade westward, southward, and southeastward into calcareous marine sediments.

Near the transition between dominant red beds to the north and dominant marine limestone and shale to the south, lenticular impure coal beds crop out or have been penetrated by oil tests. The coaly beds are of Virgilian and Wolfcampian age, and typically occur in the following ascending vertical sequence: conglomeratic red sandstone with chert, limestone, and quartz pebbles; red silty sandstone; red shale with green blotches grading upward into gray shale; thin light-gray clay; coal laminae and beds up to 1.3 feet (0.4 m) thick intercalated with gray shale; and overlying lenses of gray shale, pale-red calcareous sandstone, and limestone-pebble conglomerate.

These pods of impure coal appear to be floodbasin deposits near stream channels and in local swamps on the Supai delta, which lay north of the main Pennsylvanian and early Permian seas. They are the southwesternmost Paleozoic coals known in the United States (McGoon, 1962; Kottlowski, 1964; Averitt and O'Sullivan, 1969; Peirce, Keith, and Wilt, 1970).

In southwest Colorado, coal lenses occur amid carbonaceous shales and arkosic channel sandstones that were deposited on the southwest flank of the active Uncompahgre uplift. Westward into the Paradox basin these coaly and siliciclastic beds grade into, first, calcareous quartzose sandstones, arenaceous limestones and red to green shales; second bioclastic to cherty calcarenites interbedded with dark-gray shales; and third into the typical Paradox facies of salt, anhydrite, dolomite, and black shale. Coal in this area is found only in the lower Paradox strata of Atokan and Desmoinesian age.

Along the east and southeast flanks of the Uncompahgre uplift in south-central Colorado and north-central New Mexico, scattered coal lenses occur in beds of Morrowan, Atokan, and Desmoinesian age. In general, lenses of older coals lie westward of the younger coal beds, and thus were nearer to the east flank of the Uncompahgre uplift. However, on the east side of the Rowe-Mora basin, as shown on Figure early Pennsylvanian coals occur, but they are on the west flank of the Sierra Grande arch.

Virgilian coals crop out south of the older coal beds, chiefly in the Sandia and Manzano Mountains areas, amid interbedded red beds and marine limestones. These coals were deposited on the west side of the Estancia basin, and mark a late Pennsylvanian expansion of the Uncompahgre uplift southward into central New Mexico. Wolfcampian coal laminae and thin beds also occur within shoreline deposits, between the vast flood of red-bed detritus that covered most of northern and central Arizona and New Mexico, and north of the marine Pedregosa, Orogrande, and Delaware basins of southern New Mexico and west Texas wherein the Wolfcampian Hueco Limestone was deposited. These coals are known chiefly from oil-test cuttings, and appear to

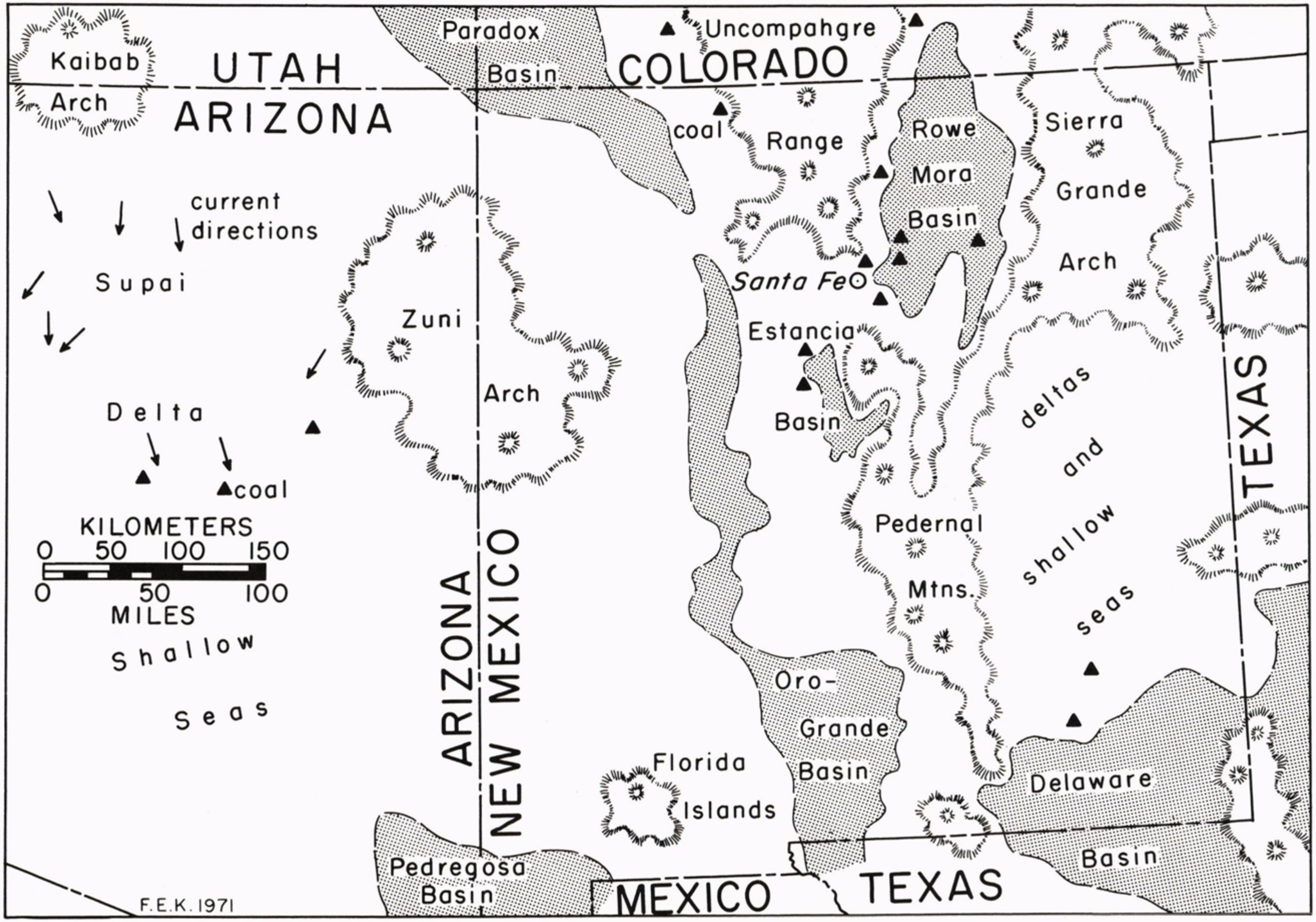

Figure 1
Upper carboniferous paleogeographic map

be concentrated on the southwest flank of the remnants of the Pedernal Mountains. Among the strata interbedded with these Wolfcampian coals are limestone conglomerates that contain large opalized logs.

The silicified logs are of upland types of trees, and suggest the Pedernal Mountains were at least a thousand meters above sea level, and the higher peaks were not far from the seashore.

Amid the deltas and irregularly bordering shallow seas on the northwest flanks of the Delaware basin, east and southeast of the Pedernal Mountains, lenses of coal have been encountered in oil-test cuttings (Kay C. Havenor, personal communication, May 1971), associated with both barrier-bar types of sandstone and point-bar stream-channel sandstone, as well as with silty and clayey floodbasin deposits. Most of these thin coals are of Morrowan (early Namurian) and Atokan (late Namurian and Westphalian A) ages and suggest that the Delaware basin may have been, during some parts of early Late Carboniferous time, almost entirely large deltas similar to those of the Illinois basin deltas in Midwestern United States.

The Pennsylvanian coal beds on the southeast side of the Uncompahgre uplift east of Santa Fe, are the best exposed, and show significant lateral and vertical relationships. Morrowan coals occur in and near the city of Santa Fe within an intertongued sequence of highly clastic, continental and marine strata. Coal occurs as pods and laminae as much as 0.5 feet (15 cm) thick amid thick (3o to 5o feet) sequences of light-gray to dark-gray shale, which are parts of irregular cycles that begin with brown lenticular micaceous calcareous sandstones, conglomeratic in part, and are terminated by interbedded light-gray to black marine shales and persistent beds of brown arenaceous fossiliferous limestone. These coaly shales appear to be floodbasin deposits laid down near the Morrowan shoreline and delta fronts.

The thicker and areally extensive lenses of coal contain many bone coal and black bituminous shale laminae, but are as much as a meter thick, and are underlain by gray underclays. Roof rocks are mainly black bituminous shale, but in many areas the coal has been eroded and the channels filled by the "grit" type of pebbly sandstone. Within the sandstones, pods of conglomerate are common, and contain angular to rounded pebbles of quartz and limestone, and of Precambrian granite and gneiss. The overall textures of the sandstones resemble stream-laid point-bar deposits.

Atokan coals, particularly those near Lamy, south of Santa Fe, similarly are pods of limited lateral extent, but with less interlaminated shale, and range from 6 to 24 inches in thickness. The coal-bearing Atokan sequence appears to be more irregular than older beds with most of the shale-sandstone-limestone sequence containing marine fossils and lateral gradations from brown calcareous micaceous sandstone into brown arenaceous bioclastic calcarenite. The coals appear to be in long narrow bodies roughly parallel to Atokan shorelines and may be lagoonal marsh fills. The fossiliferous sandstones and arenaceous limestones appear to be shoreline or nearshore marine sediments, with an intimate mixing of coarse siliciclastic material from the Uncompahgre uplift and the fossil hash that accumulates along some marine beaches.

The early Desmoinesian coals, especially near Pecos east of Santa Fe, are of considerable lateral extent, as much as two miles, and occur only in the lower part of the Desmoinesian section with the higher, younger Pennsylvanian strata in this area being entirely marine. Spectacular rocks of the overlying sequence are feldspathic limestones which contain angular fragments of red feldspar in a matrix of fossiliferous calcarenite.

The Desmoinesian coals are as much as four feet thick, with thick hard gray underclay that grades downward into brown shale, which in turn overlies brown arenaceous fossiliferous calcarenite or calcareous sandstone. Coals are overlain by black bituminous shale, massive brown crosslaminated arenaceous calcarenite (6 to 12 feet thick), or locally by thick brown calcareous sandstone. There is as much as 200 feet of black bituminous shale containing interbeds of limestone and gray to brown shale in several sequences overlying coal beds. Pebbly "grit" types of sandstone are rare in these lower Desmoinesian beds. As with the Atokan coals, the Desmoinesian coal beds appear to be in long narrow lenses parallel to and landward from beach or bar deposits. The gross lateral distribution of the coaly facies suggests landward gradation, westward or northwestward, into sandy shales, grits, and impure nonfossiliferous arkosic limestones, with seaward gradation into alternating gray fossiliferous shale and gray bioclastic limestone cut locally by channel-fill lenses of brown arkosic micaceous calcareous sandstone.

Environments of deposition appear to be marine lagoons and marshes along a shoreline dominated by marine deposition with more clay than sand being supplied from the landmass, and with prolific marine life supported in the calcareous seas.

The overall history of Pennsylvanian sedimentation in north-central New Mexico is one of progressive marine transgression onto the Uncompahgre uplift to the northwest and the Sierra Grande arch to the east. All of the Pennsylvanian rocks, however, show cyclic deposition related to cyclic transgression and regression, whether this was dependent on actual change in sea level or on surges of clastic materials from the adjoining uplands. The principles of stratidynamics apply in that the thicker coals, such as those of early Desmoinesian age, are associated with more stable transgression-regression facies, whereas the thinner and discontinuous older Pennsylvanian coals are in facies indicative of rapid, cyclic transgression and regression.

The Southwest Paleozoic coals contrast greatly with those of the Midwest and East where coal deposition is related to many complete cycles of continental to marine deposition, but they are similar to the Midwest coal measures in the close relationship with marine carbonate rocks. The Southwest Paleozoic coals contrast with the southern Rocky Mountain Cretaceous coals in the larger percentage of carbonate rocks and the larger amount of coarse-grained siliciclastic detritus in the late Paleozoic coal-bearing sequences.

LATE CRETACEOUS COALS IN THE SOUTHERN ROCKY MOUNTAIN REGION

The Late Cretaceous coals in the San Juan Basin of New Mexico and Colorado, in the Black Mesa region of northeastern Arizona, and the Book Cliffs region of Utah and Colorado have many illustrations of the stratidynamic principle. Some of the better examples are near Tsaya on the southwest-

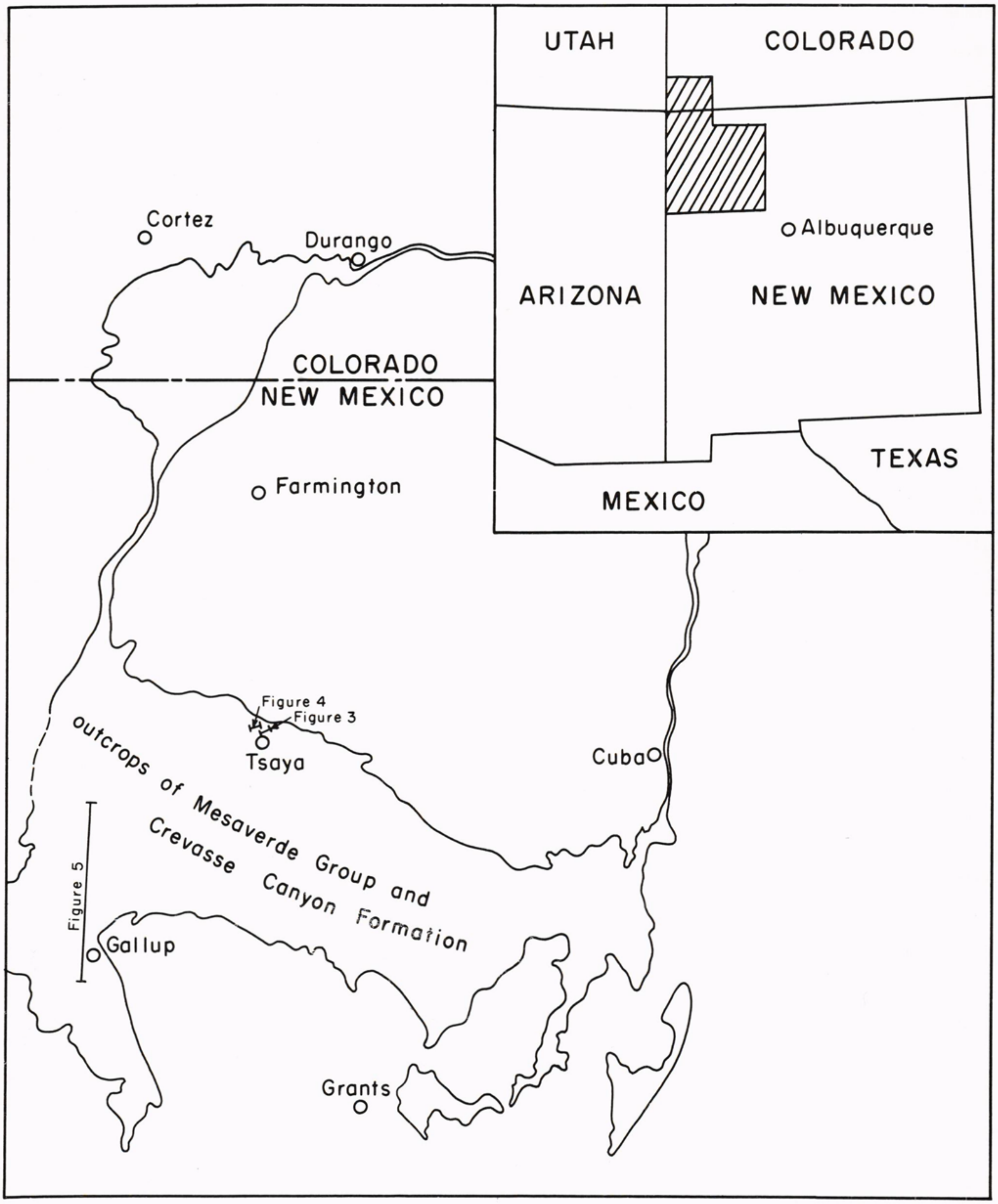

Figure 2
Index map of San Juan Basin

ern edge of the inner part of the San Juan Basin, near Gallup on the outer southwestern part of the basin, and near Monero on the northeast edge of the San Juan Basin (fig. 2).

Outcrops near Tsaya, New Mexico

Along the canyon walls bordering the Chaco River and Tsaya Wash near La Vida Mission and Tsaya, a few kilometers east of the Navajo Indian Nation lands in northwestern New Mexico, and about 8o kilometers northeast of Gallup, the Cliff House Sandstone overlies and intertongues downward with the upper coal-bearing beds of the Menefee Formation, both of Late Cretaceous age. The canyons at this location are generally cut northeast-southwest, perpendicular to the regional northwest-southeast trend of Late Cretaceous shorelines. Thus the cliffs expose cross-sections of contacts between lagoonal marsh coals (to the southwest) and the seaward sand-bar sandstones.

A typical contact between coal and marine sandstone occurs on the northwestern wall of Tsaya Canyon about 0.5 mile northeast of Tsaya (fig. 3). Bed Z is of greenish-gray silty sandstone containing numerous fragments of coal and with local top laminae of highly ferruginous sandstone. Bed

is of black, finely laminated coaly sandstone on the northeast that grades southwestward into arenaceous coal, two to three feet thick. Bed 2 is of brown sandstone containing many small ferruginous concretions, faint bedding, and has gradational contacts with Bed I. Bed 3 is of thin-bedded, crosslaminated tan sandstone, with the crosslaminae in long low-angle sets. Bed 2A is sandstone like Bed 2 and forms the podlike lens shown in Figure 3 with Beds 2 and 3, having a maximum thickness of seven feet. Bed 4 is the basal unit of the overlying thick Cliff House marine sandstone, which is more than 210 feet thick. It is grayish-orange to gray, fine-to medium-grained with angular to subangular grains, well-sorted, cliff-forming sandstone.

As shown on Figure 3, Bed 4 sandstone laps over the underlying beds from the northeast. Bed X thickens southwestward from near the crest of the lens of Beds 2-3-2A. It begins on the northeast as interlaminated brown and black coaly sandstone; southwestward the amount of coal increases until it joins with Bed I as the upper part of an arenaceous coal. And on the southwest edge of the outcrop, the combined Beds I and X thicken southwestward, mainly by increase of laminae of arenaceous coal along the intertonguing contact with Bed 4.

In that southwest direction, at a coal mine about a kilometer southwest of Tsaya, the coal bed is relatively clean coal about six feet thick, is overlain by brown carbonaceous arenaceous shale and underlain by grayish-brown underclay.

The basal beds of the Cliff House Sandstone are in some places massive sandstone, but in most areas, as on the southwest edge of Figure 3, the lower 6 to 15 feet is of interbedded fine-grained silty sandstone and arenaceous shale. The lower 3o feet of the massive Cliff House Sandstone contains many small round ferruginous concretions and scattered casts of *Ophiomorpha;* at about 3o feet above the base is a zone of abundant Ophiomorpha *(Halymenites),* some with long unbroken branches. Above are some crosslaminated sandstones, with both long-angle microtrough crosslaminae and higher angle, trough-type crosslaminae.

The upward gradation of the Cliff House Sandstone from basal irregularly interbedded silty sandstone and arenaceous shale (which downward locally grades into arenaceous coal), into structureless Ophiomorpha-bearing sandstone, and upward into partly crosslaminated sandstone suggests the typical barrier-bar sandstone upward transitions from lower shoreface, through mid shoreface, into upper shoreface-beach, and capping eolian sandstones. The thinning and thickening of the sandstone lenses in southwest-northeast directions may be due to original deposition of the sand bodies as parallel beach or bar ridges.

The brown shales and coals appear to have been deposited in fresh or brackish waters landward from the adjoining marine beach-and-bar sandstones, then buried by beach sands and forebeach sands as the sea transgressed southwestward.

To the southwest, the terrestrial sandstones southwest of Tsaya show many of the features of point-bar deposits, a discontinuous basal, poorly bedded pebbly sandstone, overlain by beds of giant-rippled festoon-crosslaminated standstone, then fine-grained horizontally laminated sandstone with laminae of silt and shale, overlain by small-scale crossbedded sandstone. Former "clay-drapes," preserved as thin shale beds disconformable on underlying sandstone, are rare. Iron-impregnated sandstone beds and laminae are conspicuous, as are the channel-filling stream-deposited pebbly beds. How-

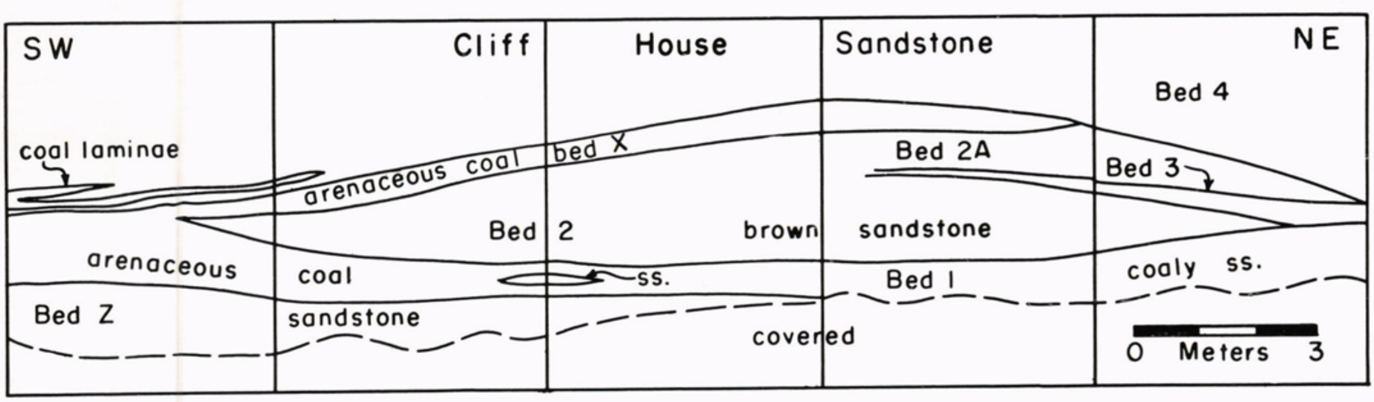

Figure 3
COAL AND SANDSTONE BAR NORTHEAST OF TSAYA, NEW MEXICO

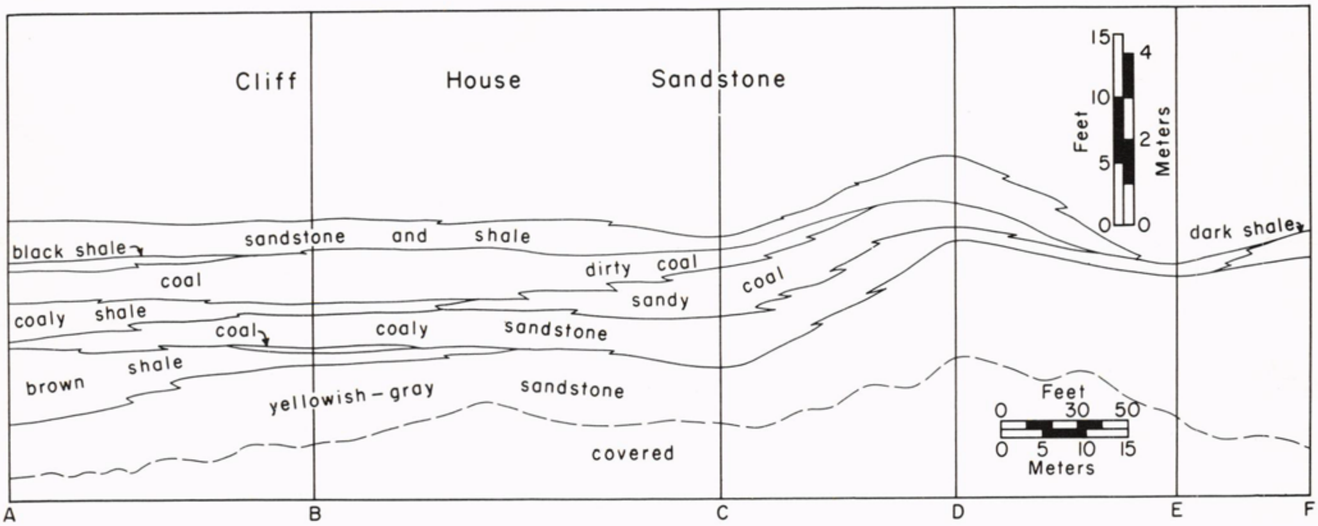

Figure 4
Coal and sandstone bar west of Tsaya, New Mexico

ever, a high percentage of both the terrestrial sediments and of the marine deposits to the northeast is of shale; gray to brown silty terrestrial shale or dark-gray calcareous fossiliferous marine shale.

A similar coal-sandstone bar contact is exposed in NW¼ NW¼ Sec. 23, T. 22 N., R 13 W., 1.2 miles west of Tsaya, but at this outcrop the coal thickens northeastward and pinches out against the sandstone bar to the southwest (fig. 4), becoming more sandy as it fingers out southwestward. At section A the coal is clean, about 2.5 feet thick, overlain by black carbonaceous shale, and underlain by brownish-gray shale and sandstone containing many coal fragments. At section B the clean coal is the bottom 12 inches, with the upper part of the coal being arenaceous and interlaminated with coaly sandstone. At section C, the coal is 5.6 feet thick, but interlaminated with siltstone and coaly sandstone; at section D the "coal" bed is more than 5o percent coaly sandstone, and in sections E and F the coaly horizon consists of arenaceous coal laminae in a thin coaly sandstone.

The Cliff House Sandstone capping the coaly sequence is similar to the Cliff House Sandstone near Tsaya. In sections A-C, the lower meter includes interbedded shale, but in sections D-F the basal beds are massive, cliff-forming, structureless, Ophioinorpha-bearing sandstones like the main mass of the Cliff House in sections A-C.

The coal bed appears to have been deposited in a marsh between marine sandstone bars, and like the coal near Tsaya, was buried and partly reworked beneath beach sands and forebeach sands.

Coal deposits near Gallup, New Mexico

Figure 5 depicts the principles of stratidynamics operative in the vicinity of Gallup, New Mexico, a coal-producing city located in the southwest corner of the San Juan Basin. Gallup came into being in the 1880s with the advent of the Atlantic and Pacific Railroad. The diagram illustrates the fortuitous location of both the railroad and the town of Gallup with respect to the maximum development of the coal deposits associated with transgressive and regressive deposition during the Cretaceous Era.

Within the scope of the diagram (fig. 5) three major reversals in the direction of strand-line movement occur. The forces responsible for these major changes in the movement of the strand line resulted in: (r) initially, a slowdown in transgressive activity that was commonly accompanied by intertonguing: (2) a near cessation of shoreline movement that resulted in near vertical facies accumulations and minor oscillations; and (3) relatively slow initial regressive movement that tended to gain momentum in the seaward direction. The slowing down of shoreline migration had the effect of providing time for relatively thick deposits of the nonmarine-marine transitional environments—the paludal and the near shore and beach zones. This resulted in relatively greater abundance of coal in the immediate vicinity of and landward from the maximum landward position of the marginal marine sand deposits.

In the example portrayed, there are two distinctive sets of coal measures having their maximum development in the vicinity of Gallup. It is interesting to note that in neither instance is the nomenclature of the units designed to correspond with type of activity in which the material was deposited.

Theoretical time-distance relationships affecting deposition in a subsiding basin

Figure 6 is intended to illustrate the effects of varying rates of shoreline movement on the accumulation of deposits in environmental zones transitional between the wholly nonmarine floodplain deposits and the wholly marine offshore muds. The smaller diagram, drawn in the form of a graph, is composed of several parallel curves representing the margins of the various transitional zones. The ordinate of the graph is scaled to represent indeterminate but constant values of time while distance is represented on the abscissa.

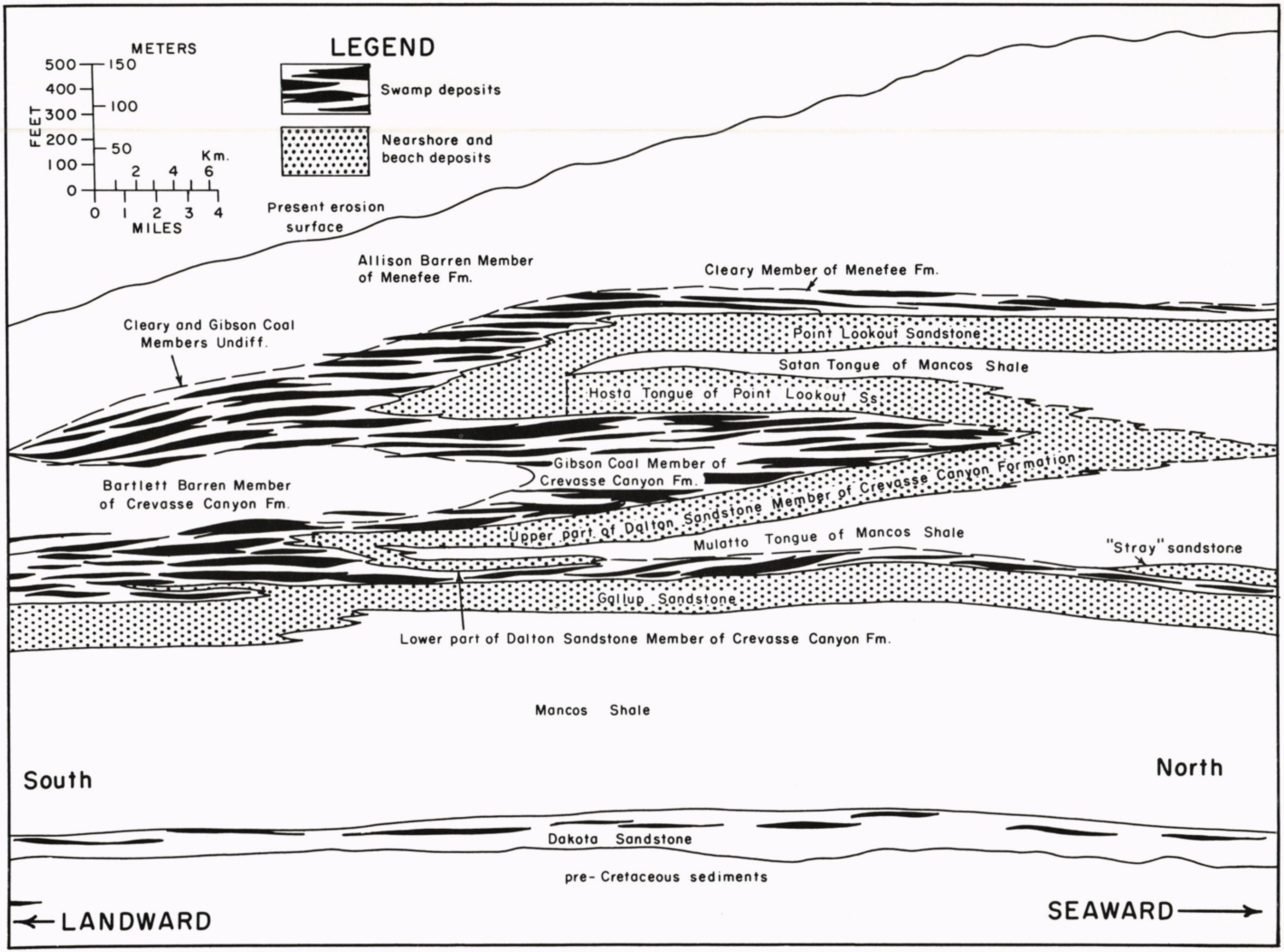

Figure 5
Cross-section of coal beds near Gallup, New Mexico

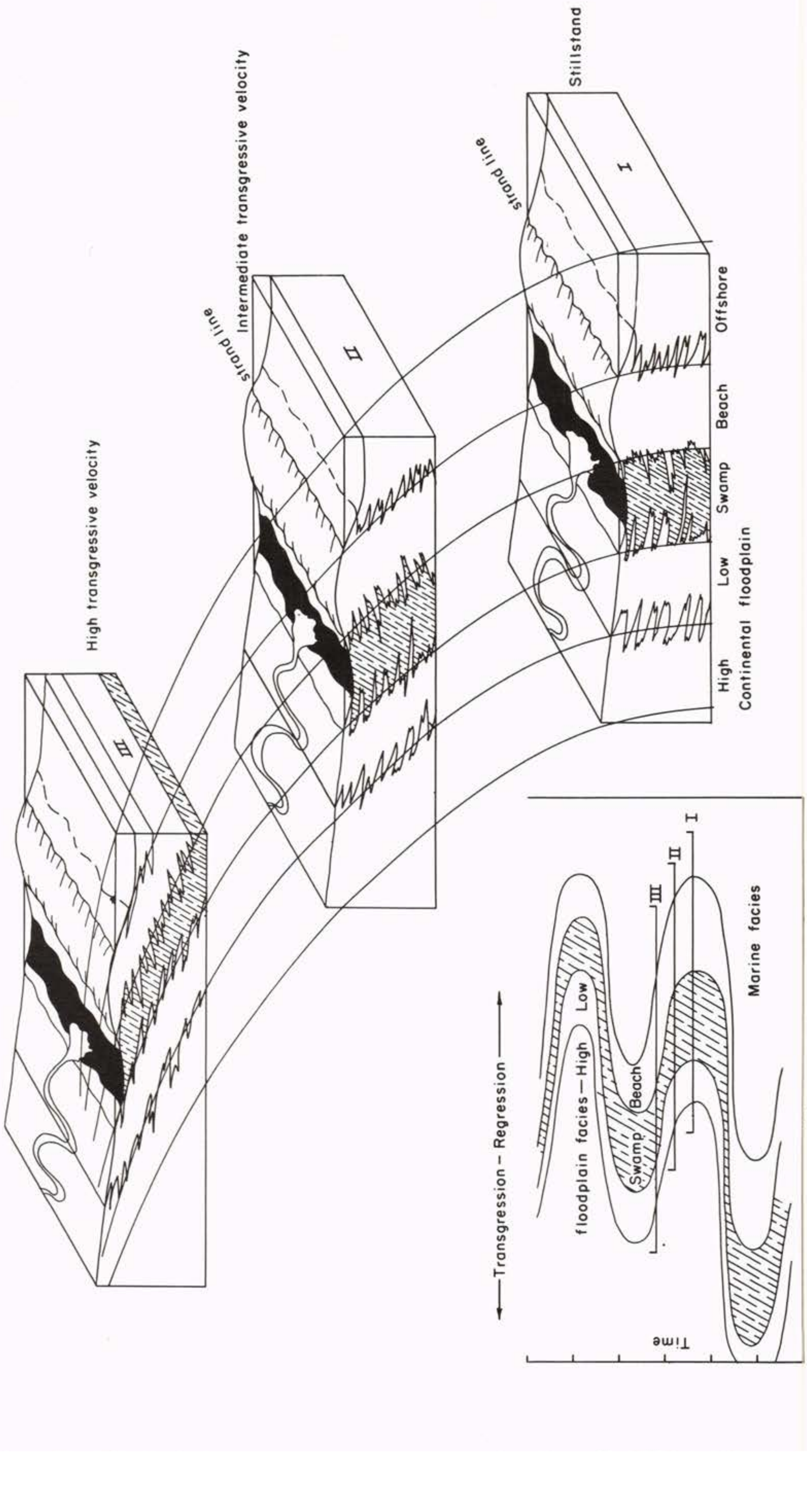

Figure 6
TIME-DISTANCE RELATIONS OF COAL DEPOSITION

As the velocity of the movement of the shoreline increases in the middle areas of either a transgressive or a regressive phase, the curves become flatter and cause a narrowing of the transitional zones. A sudden lateral shift in shoreline positions of the type that might be caused by tectonic disturbance would result in flat curves that would eliminate the transitional zones. Conversely, a slowing down in the rate of shoreline migration, as might be expected in the vicinity of a major trend reversal, results in the steepening of the various curves and the depositional bands approach their maximum width and maximum development. The maximum is reached as shoreline migration ceases and sedimentation continues in a subsiding basin and results in nearly vertical facies development.

The three block diagrams illustrate in somewhat more graphic detail the effects of changing rates of shoreline migration on the various transitional zones of sedimentation, in this case, under transgressive conditions. None of the three illustrated examples represents the extreme conditions of a complete shoreline standstill or instant lateral change, but the retardation of the development of the transitional zones is seen to be significant as the velocity of the transgression increases between block I and III.

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Numbers in **boldface** indicate main sections

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Figure 6

Stratigraphic diagram showing relationships of coal-bearing Cretaceous rocks on the west and north sides of San Juan Basin

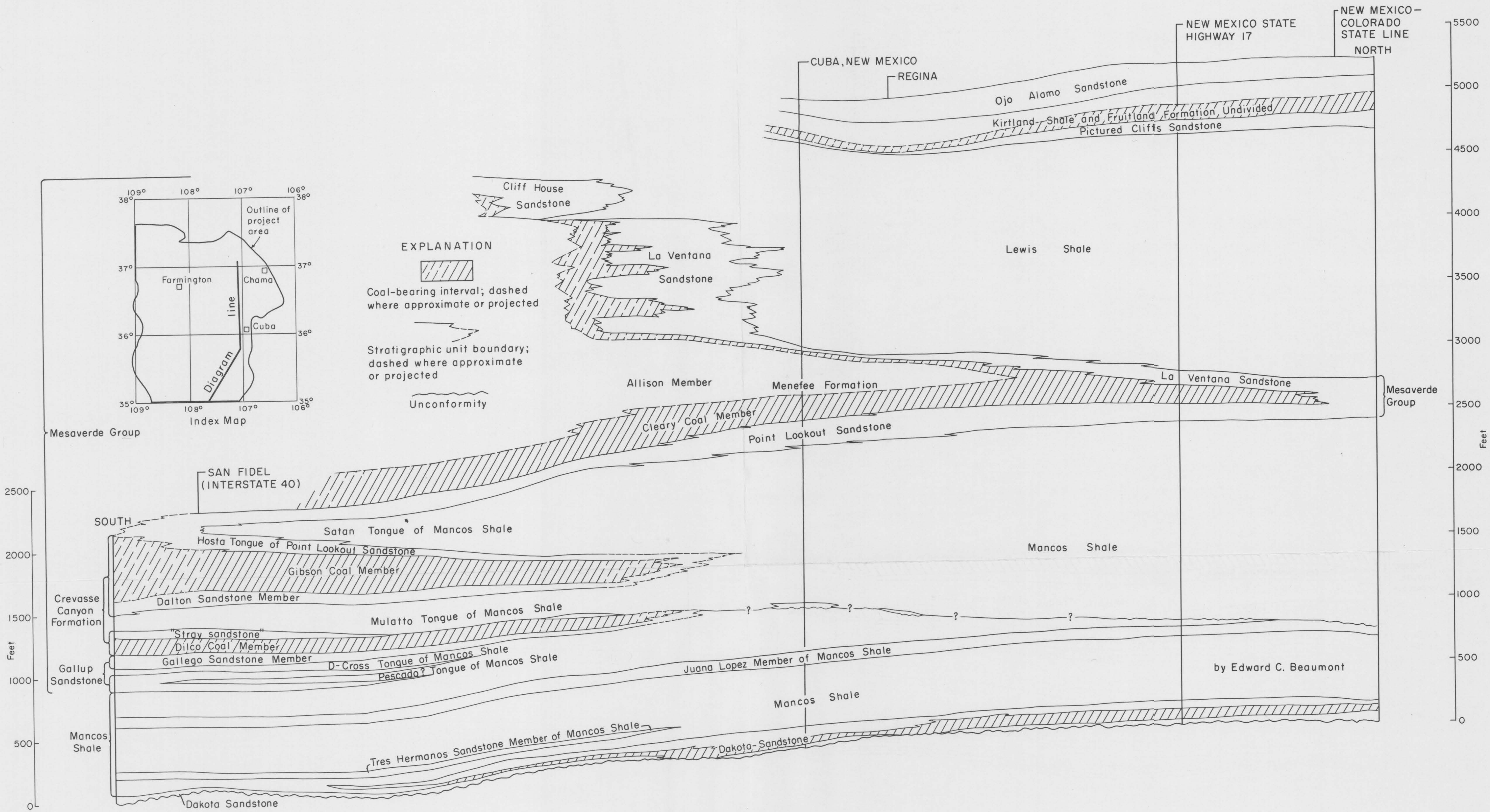


Figure 7

STRATIGRAPHIC DIAGRAM SHOWING RELATIONSHIPS OF COAL-BEARING CRETACEOUS ROCKS ON THE EAST SIDE OF SAN JUAN BASIN

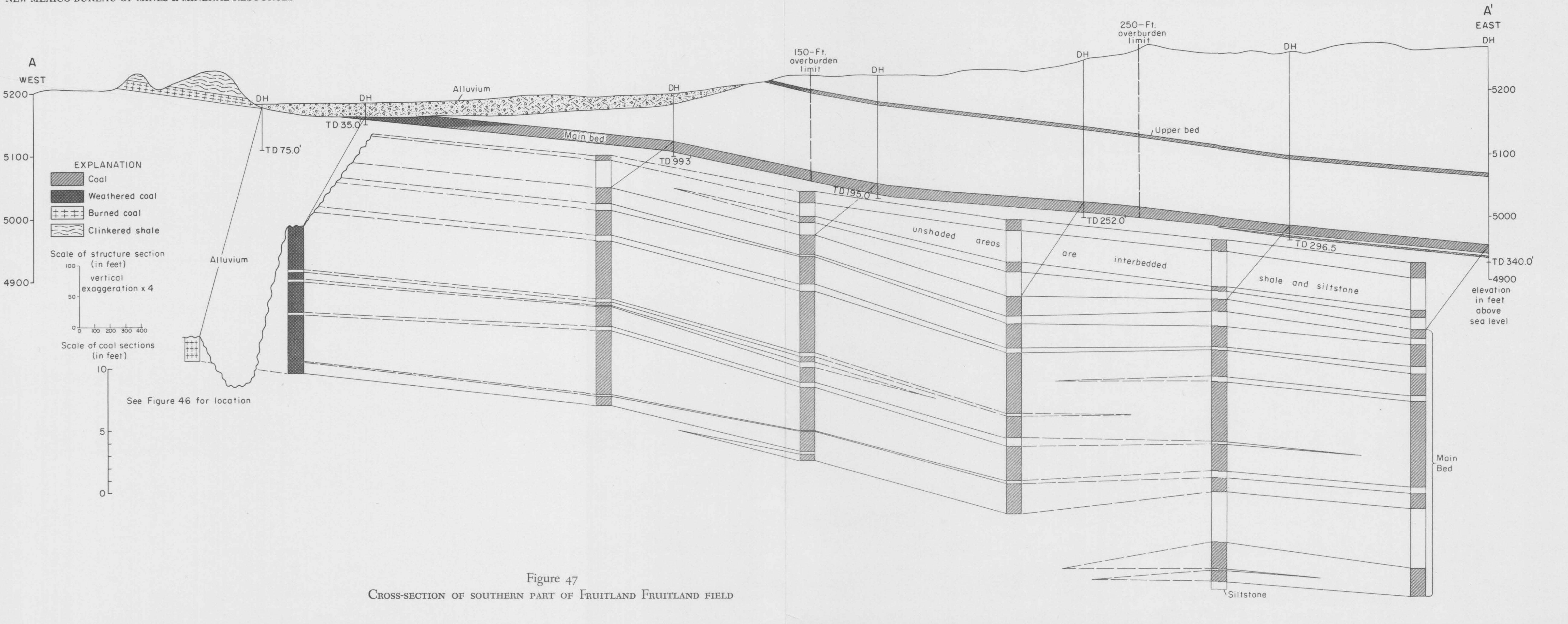
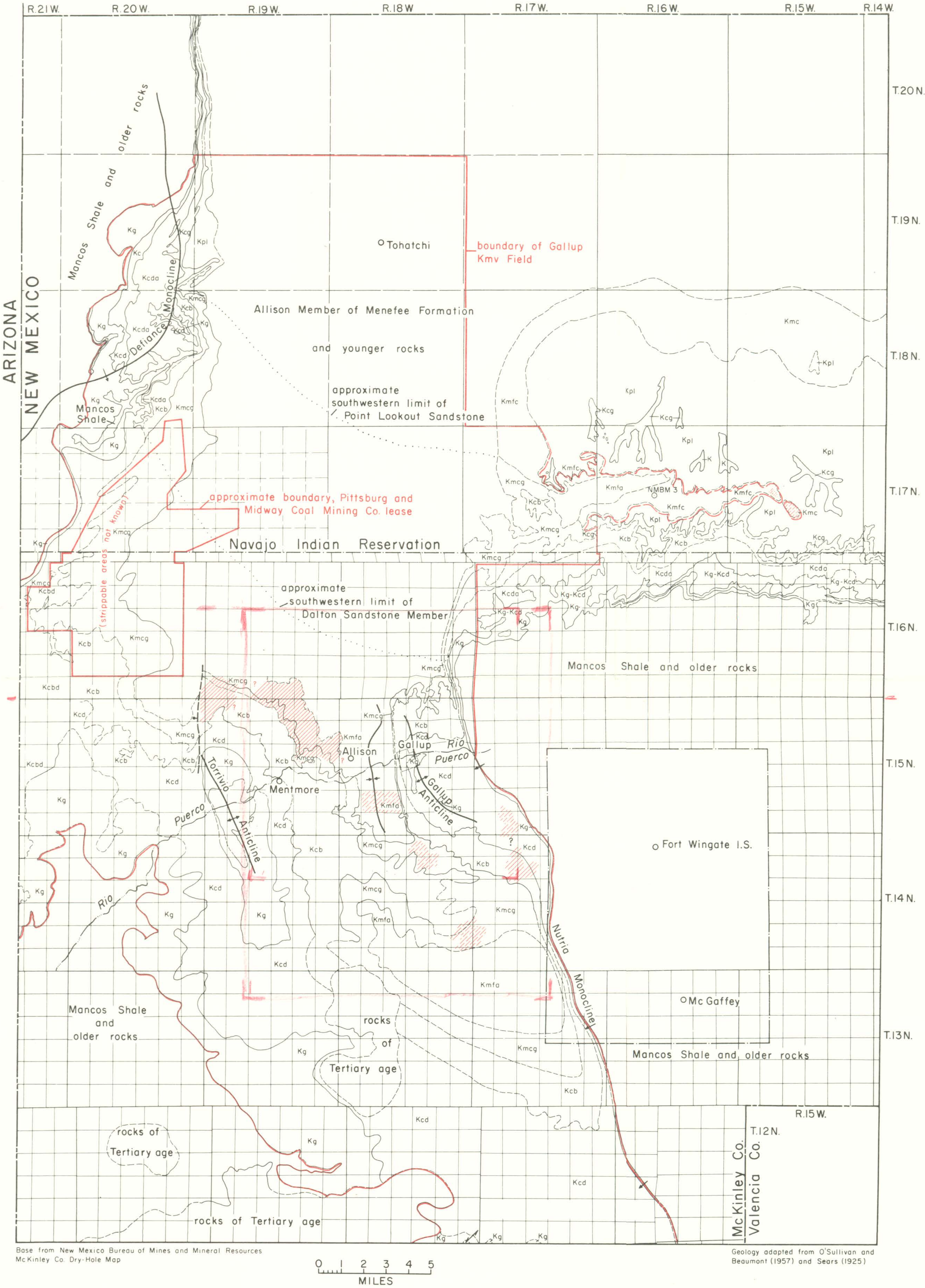


Figure 47
CROSS-SECTION OF SOUTHERN PART OF FRUITLAND FRUITLAND FIELD

Figure 59

Diagram illustrating typical electrical-log curves and comparison with sample and core description, test hole No. 8
Response to coal of resistivity and gamma-gamma (density) curves indicated by crosshatching



EXPLANATION

Kmfa / Kmfc

Menefee Formation

Tan and brown sandstone, gray and brown claystone and shale, and coal. Divided into barren Allison Member (Kmfa) and coal-bearing Cleacy Member (Kmfc)

Kpl

Point Lookout Sandstone

Tan and brown sandstone, minor gray shale

Kmcg / Kcg / Kcb / Kcbd / Kcda / Kcd

Crevasse Canyon Formation

Lenticular tan and brown sandstone, drab shale and claystone, and coal. Divided into coal-bearing Gibson Member (Kcg), barren Bartlett Member (Kcb), Dalton Sandstone Member (Kcda), and coal-bearing Dilco Member (Kcd). Combined Gibson Member and Cleary Member of Menefee Formation (Kmcg) shown where intervening Point Lookout Sandstone is absent. Bartlett and Dilco Members mapped together (Kcbd) in western part of area.

Kg

Gallup Sandstone

Tan, brown, and pinkish sandstone with minor shale

Geologic Contact

Dashed where uncertain

Fault

Dashed where inferred. Symbol indicates downthrown side

Anticlinal axis

Monoclinal axis

Synclinal axis

Areas of strippable coal outside Pittsburg and Midway Coal Mining Co. lease. Broken ruling indicates conjectural areas.

Plate 1

Map showing simplified geology and areas of strippable coal for Gallup Mesaverde field

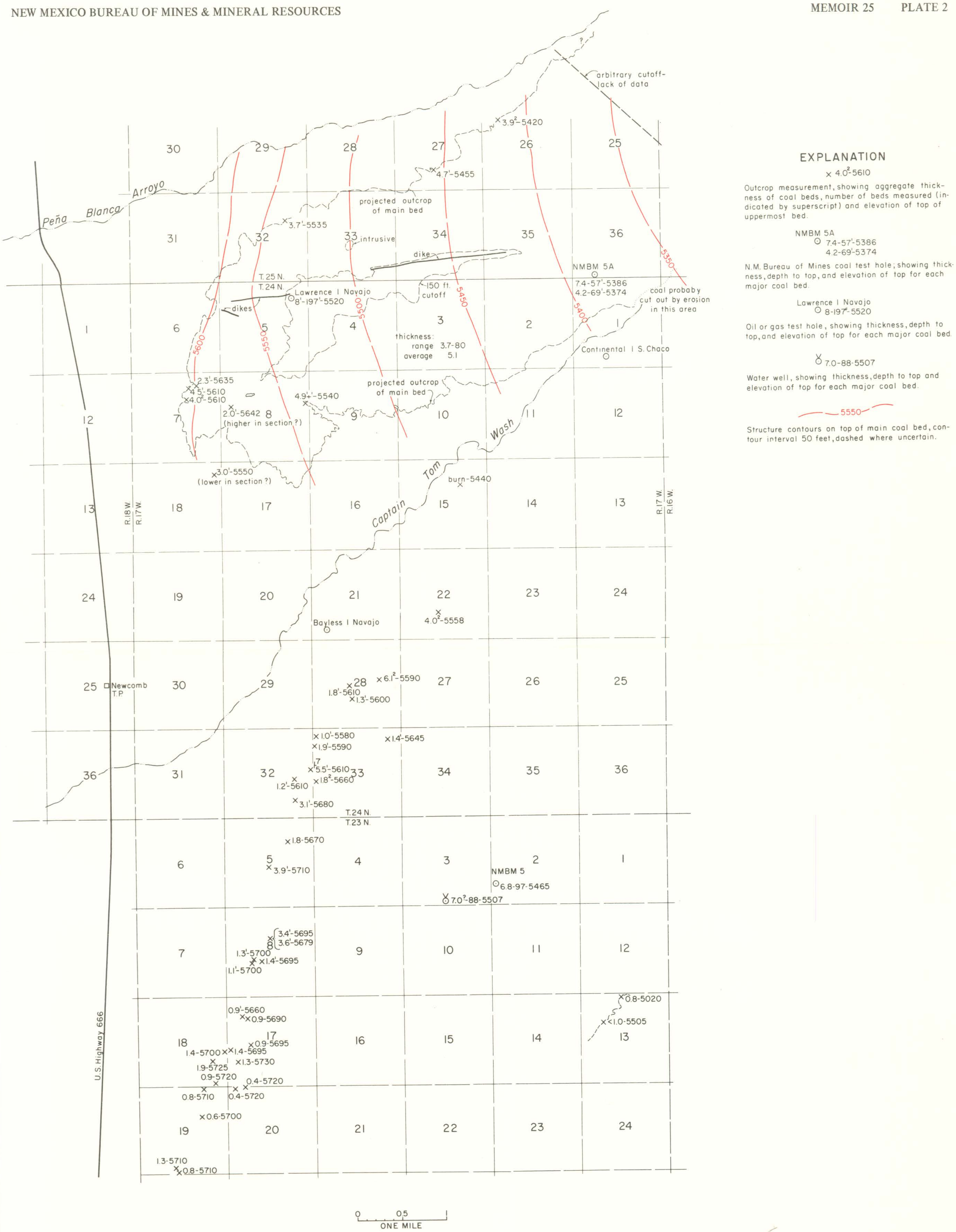


Plate 2

Map showing coal data near Captain Tom Wash, Newcomb Upper Menefee area

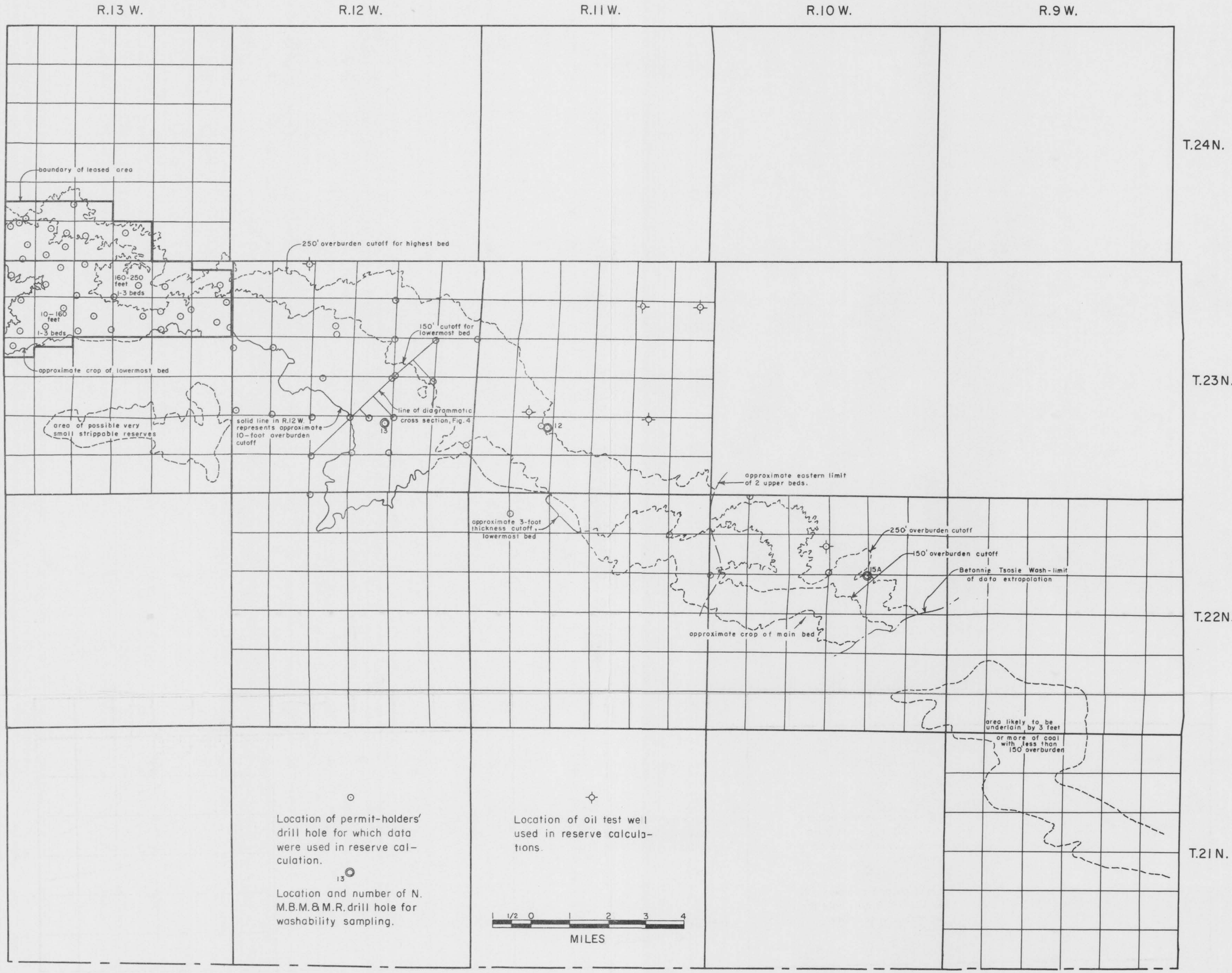


Plate 3

Map showing areas underlain by strippable reserves, Bisti Fruitland area