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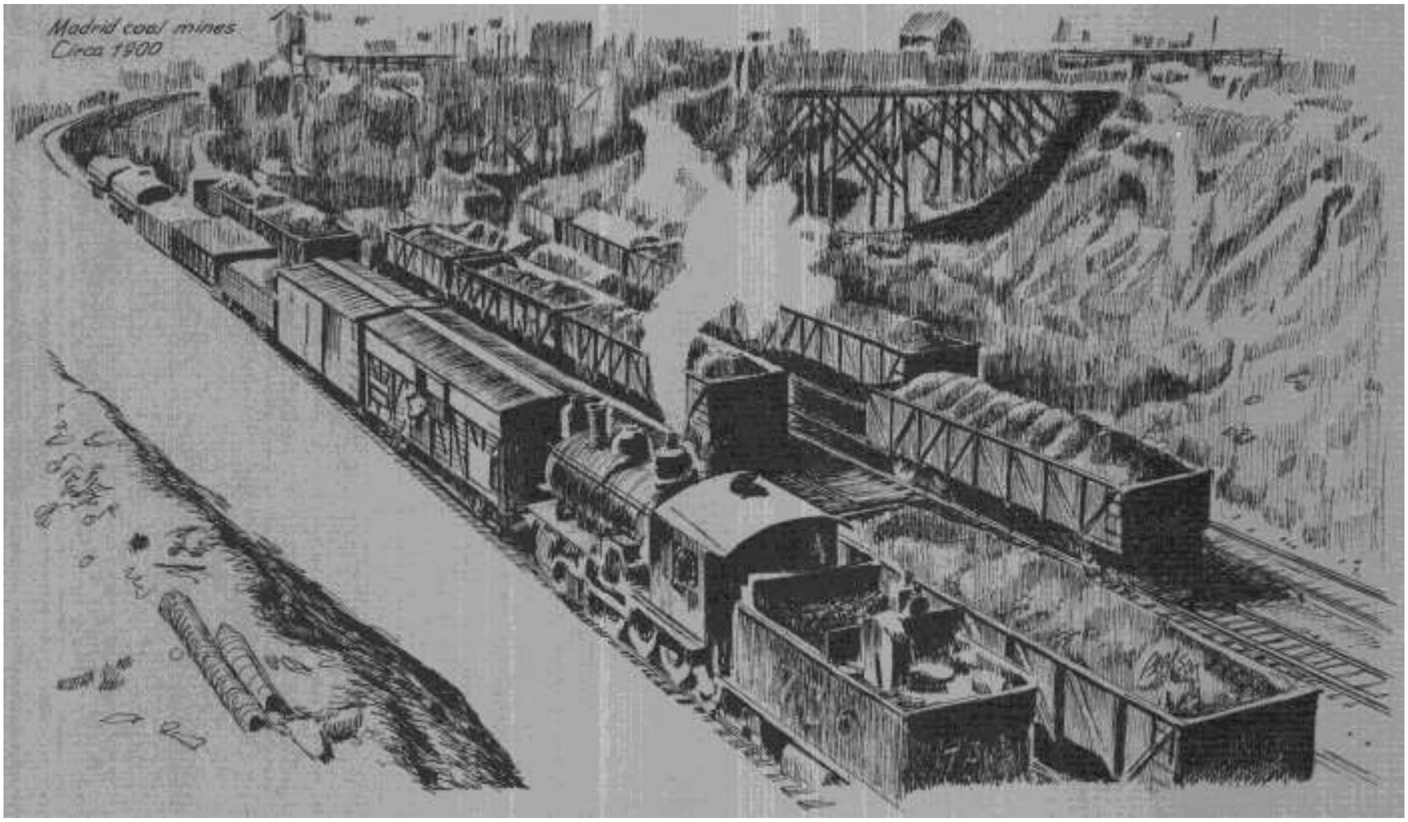
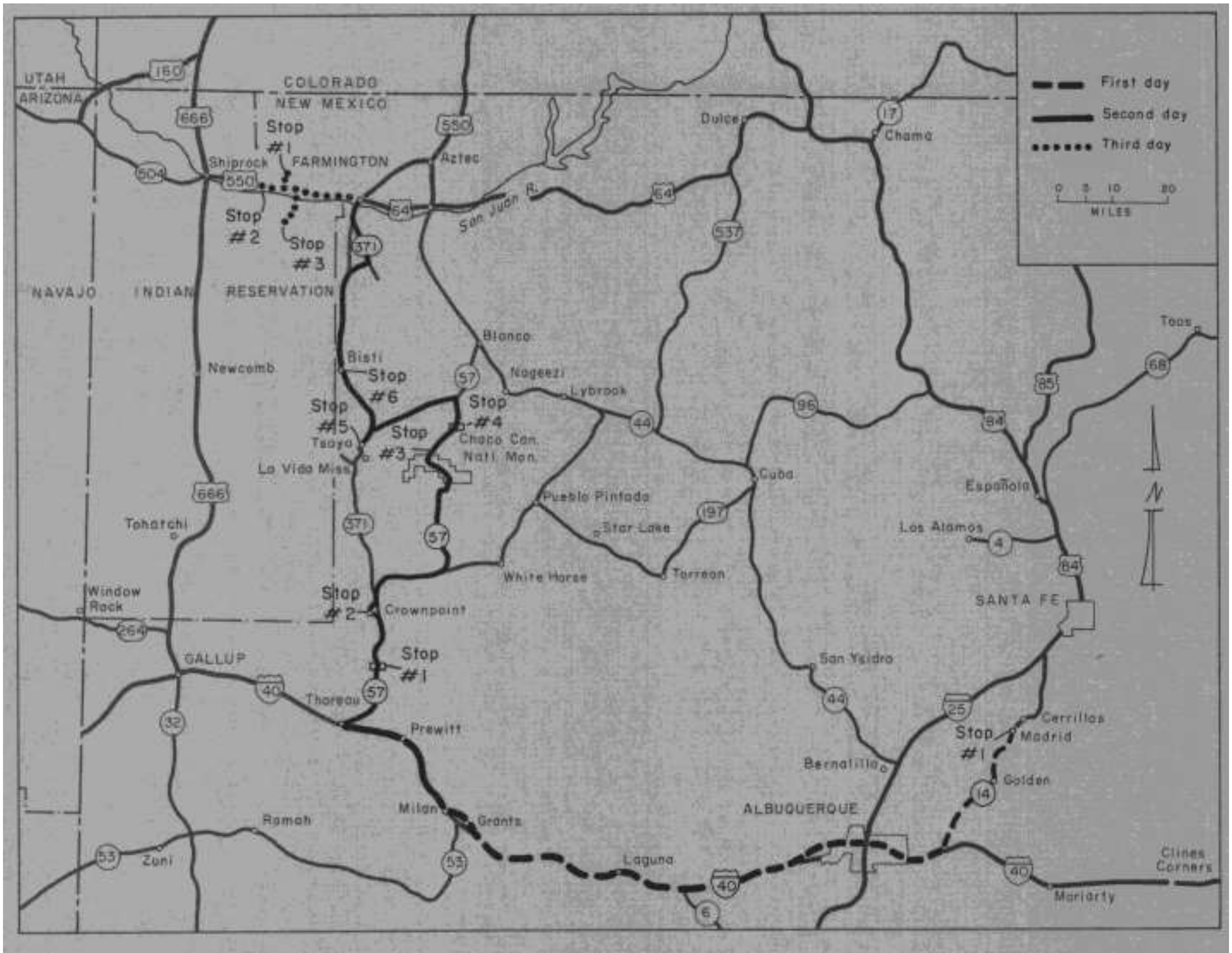


Guidebook to Coal Geology of Northwest New Mexico

by E. C. Beaumont, J. W Shomaker, W. J. Stone, and others

New Mexico Bureau of Mines & Mineral Resources

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY



LOCATION MAP SHOWING FIELD TRIP ROUTE THROUGH NORTHWEST NEW MEXICO.

Circular 154

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Guidebook to Coal Geology of Northwest New Mexico

compiled and edited by
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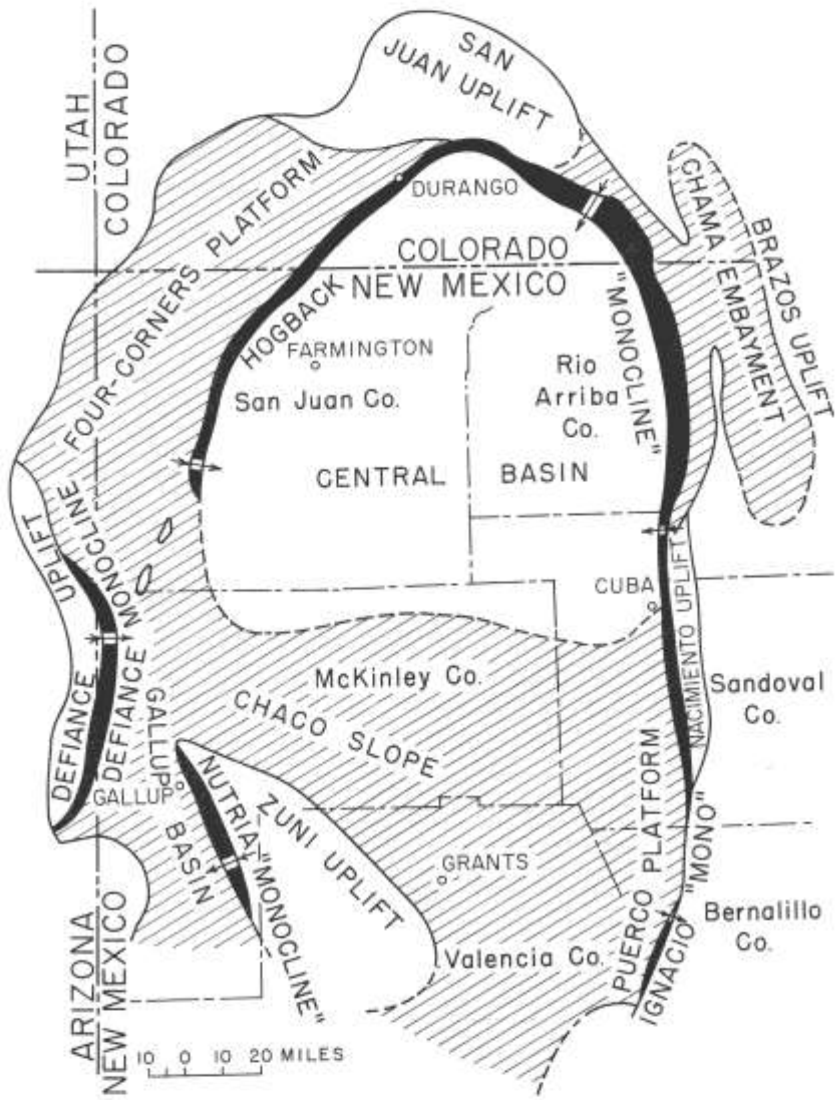


FIGURE 1—STRUCTURAL ELEMENTS OF SAN JUAN BASIN (Kelley, 1951, p. 125).

ABSTRACT

This guidebook contains geologic road logs for a three-day field trip on the coal resources of northwestern New Mexico. The first day focuses on the Madrid coal field, northeast of Albuquerque. The second and third days are devoted to the coals of the San Juan Basin. The guidebook also contains three technical papers covering the Cretaceous stratigraphy of the Madrid coal field, the palynology of the Crevasse Canyon and Menefee Formations, and the availability of ground water for coal development in the San Juan Basin.

Introduction

The San Juan Basin is a structural depression at the eastern edge of the Colorado Plateau. The Basin has about 6,000 ft of structural relief and covers about 10,000 sq mi of northwestern New Mexico and south-eastern Colorado (fig. 1). Monoclines are the most distinct structures in the Colorado Plateau; excellent examples occur in the San Juan Basin, the most prominent being the north-south-trending Hogback Mountain, near the west edge of the Basin. Over 14,000 ft of sedimentary rocks occur in the deepest part of the Basin, as indicated in a well drilled to basement near Gobernador in northwestern Rio Arriba County.

For the geologic map of the San Juan Basin see fig. 15, p. 19. Jurassic and older rocks mark the perimeter of the Basin. Within the Basin broad bands of Cretaceous and younger rock units crop out. The Cretaceous-Tertiary boundary occurs within the Ojo Alamo Sandstone. The central and eastern areas are covered by rocks of Tertiary age. Quaternary deposits occur in stream valleys, in terraces, along mountain fronts, and atop all other rock units.

The general stratigraphic succession in the San Juan Basin is shown in the chart presented inside the back cover. The uranium-bearing Jurassic rocks are believed to record nonmarine or continental deposition extending northward from highlands in the south. The Cretaceous portion of the sedimentary record of the Basin is summarized in the cross section (fig. 16, p. 20). The coal-bearing strata are believed to represent deposition in, and at the margins of, the vast Cretaceous seaway that extended across the continent from the Arctic Ocean to the Gulf of Mexico about 135 million years ago. As this sea lapped on and off the land, a unique record of alternating carbonaceous shales and coals of coastal plain origin, marine shoreline sandstones, and marine offshore shales was produced (fig. 2). Nonmarine conditions were restored after the sea retreated at the end of Cretaceous time resulting in the Tertiary continental deposits in the central Basin.

In physiographic terms, the San Juan Basin is situated in the Navajo Section of the Colorado Plateau and is characterized by broad open valleys, mesas, buttes, and hogbacks. Away from major valleys and canyons topographic relief is generally low. Native vegetation is sparse and shrubby. Drainage is mainly by the San Juan River, the only permanent stream in the Navajo Section of the Colorado Plateau; the San Juan River is a tributary of the Colorado River. Between the inflow point in Rio Arriba County and outflow point in San Juan County, the San Juan drops about 1,800 ft in elevation. Major tributaries include the Animas, Chaco, and La Plata Rivers. Average annual discharges reported for the period 1913-1951 are: 729,400 ac-ft (acre-feet) for the Animas at Farmington; 1,179,400 ac-ft for the San Juan near Blanco; and 2,194,800 ac-ft for the San Juan at Shiprock (Cooper and Trauger, 1967). Flow of the San Juan River across the Basin is regulated by the Navajo Dam, located about 30 mi northeast of Farmington.

The climate is arid to semiarid with an average annual precipitation of 8-10 inches. The annual pan evaporation rate, based on records for the period 1948-1962, is 67 inches. The average January temperature is 28°F; the average July temperature is 73°F.

Coal occurs throughout the Cretaceous section of the Basin. In New Mexico important deposits are largely restricted to the Mesaverde Group and the Fruitland Formation (Shomaker and others, 1971). The Mesaverde Group includes, in ascending order, the Gallup Sandstone, the Crevasse Canyon Formation, the Point Lookout Sandstone, the Menefee Formation, and the Cliff House Sandstone. Only the Crevasse Canyon and Menefee Formations are significantly coal bearing. Minor coal occurs in the Gallup and Dakota Sandstones. As shown in table 1, strippable reserves approach 6 billion tons. The largest portion of this coal is associated with Fruitland Formation. Nearly equal reserves occur in the overburden categories of 10-150 ft and 150-250 ft. Reserves of deep coal, defined as that beneath more than 250 ft of overburden, are even larger. The Fruitland alone is estimated to contain about 154 billion tons of deep coal—about 30 times the strippable reserves (Kottlowski, 1975). The Menefee Formation contains another 115 billion tons of deep coal.

At present, stripping is the major coal-mining method

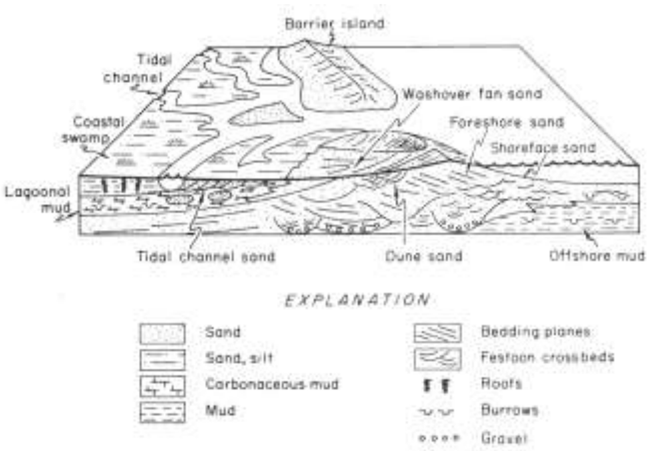


FIGURE 2—Block diagram showing some shorezone environments which may have contributed to the late Cretaceous sedimentary record of the San Juan Basin (modified from Robinson, 1976, fig. 43).

TABLE 1—Summary of Strippable Coal Reserves (Millions of Tons) for San Juan Basin, New Mexico (from Shomaker and others, 1971)

Rock units	Overburden 10-150 ft	Overburden 150-250 ft	Totals
Fruitland Fm.	2,463.0	2,628.0	5,091.0
Upper Menefee Fm.	109.5	6.3	115.8
Lower Menefee Fm. (Cleary Coal Mbr.)	nd	nd	174.7
Crevasse Canyon Fm. (Gibson & Dilco Coal Mbrs.)	295.0	201.0	496.0
Gallup Ss.	nd	nd	6.2
Totals	2,867.5	2,835.3	5,883.7

(nd = not distinguished)

TABLE 2—SUMMARY OF OPERATIONAL INFORMATION, SAN JUAN COUNTY COAL MINES
(compiled by W. J. Stone, October 1975)

Item	Navajo mine	San Juan mine
Rock unit mined	Fruitland Fm.	Fruitland Fm.
Coal seams mined	2 or 3 now, up to 7 later	1 now
Life of operation	25 more yrs	About 35 more yrs
Operator	Utah International, Inc.	Western Coal Co.
Draglines	3 45-yd capacity	1 10-yd capacity
Overburden (to 1st seam)	50 to 100 ft	40 to 60 ft
Maximum for mining	100 to 130 ft	About 200 ft
Mine water problems	None	Surface runoff, perched ground-water leakage
Coal production	6½ to 7 million tons/yr	25,000 tons/week/ generating unit
Coal price	$2.00 to $3.00/ton	(not available)
Portion of total area worked to date	2/5	1/100
Water-quality monitoring stations	45 ground water 14 surface water	8 ground water 2 surface water
Reclamation	540 acres/yr for next 10 yrs	20 acres to date 100 acres/yr later
Irrigation water used	2,160 ac-ft/yr (180 ac-ft/mo)	40 ac-ft/yr
Water source	San Juan River	San Juan River

used in the San Juan Basin. Table 2 summarizes operational information for the major mines in San Juan County (visited 2nd Day). The coal being mined is used for generating electric power.

This guidebook was prepared specifically for the Coal Division Field Trip held in conjunction with the *89th Annual Meeting of the Geological Society of America,* November 8-11, 1976, Denver, Colorado. For more details on the geology of the field trip area, consult the following publications available from the New Mexico Bureau of Mines and Mineral Resources, Socorro, NM 87801. Copies may also be purchased at the meeting.

Geology of Sandia Mountains and vicinity, New Mexico, by V. C. Kelley and S. A. Northrop, 1975, New Mexico Bureau of Mines and Mineral Resources, Memoir 29, 136 p., $12.50.

Strippable low-sulfur coal resources of the San Juan Basin in New Mexico and Colorado, compiled and edited by J. W. Shomaker, E. C. Beaumont, and F. E. Kottlowski, 1971, New Mexico Bureau of Mines and Mineral Resources, Memoir 25, 189 p., $9.50.

Coal resources of Southern Ute and Ute Mountain Ute Indian Reservations, Colorado and New Mexico, by J. W. Shomaker and R. D. Holt, 1973, New Mexico Bureau of Mines and Mineral Resources, Circular 134, 22 p., $3.50.

Energy crisis symposium, Albuquerque, New Mexico, 1973, compiled by W. L. Hiss and J. W. Shomaker, 1974, New Mexico Bureau of Mines and Mineral Resources, Circular 140, 107 p., $2.50.

North and east sides of the San Juan Basin, 1950, New Mexico Geological Society, Guidebook 1st field conference, 156 p., $9.00.

South and west sides of the San Juan Basin, New Mexico and Arizona, 1951, New Mexico Geological Society, Guidebook 2nd field conference, 167 p., $9.00.

Defiance-Zuni-Mt. Taylor Region, 1967, New Mexico Geological Society, Guidebook 18th field conference, 239 p., $15.00.

1st Day Road Log

Albuq uerq ue—Madrid—Grants

RÉSUMÉ

Albuquerque is on the Rio Grande which rises in high southern Colorado and flows southward 1,640 mi to the Gulf of Mexico. In New Mexico the Rio Grande winds its way between staggered mountain ranges and high mesas. Near Albuquerque, the river flows along the inner valley floodplain which slopes southward about 4 ft per mile and ranges in width from 2.5 to 4 mi. The elevation of the river bed just west of downtown Albuquerque is 4,900 ft above sea level. West of the river floodplain, about 8 to 12 mi from downtown Albuquerque, the land rises through low bluffs and gradual slopes to a high mesa 5,600 to 6,000 ft above sea level. Immediately east of the river floodplain, the land rises somewhat more abruptly to the East Mesa at 5,100 to 5,300 ft above sea level, and stretches northward from Albuquerque International Airport runways nearly to 1-40. North of 1-40, the high, flat mesa disappears, and the ground slopes gradually upward from the river bottom for approximately 8 mi to the foot of the Sandia Mountains (Kelley, 1974).

The base of the mountains lies generally at 6,000 ft. The highest point on the mountain is Sandia Crest, 10,678 ft; the altitude at South Sandia Peak, directly east of Albuquerque, is 9,782 ft.

Albuquerque's neighboring mountains, the Sandias, and to a lesser extent the Manzanitas south across Tijeras Canyon, are giant blocks of the earth's crust tipped up sideways. Albuquerqueans view the bold, tipped-up side. The tipping is very much the same action and effect obtained when one steps on the edge of a loose patio brick, causing one side to rise and the other to sink.

The Sandia block tilts only 15 degrees, but because of the simultaneous subsidence of the Rio Grande trough, the block exposes a magnificent western escarpment 13 mi long and averaging 4,000 ft in height. The eastern side of the mountains corresponds to the upper surface of the tilted block, although many layers have been stripped off by erosion. The stripping of this upper surface caused the overall smooth appearance of the east slope that contrasts sharply with the irregular west side.

GEOLOGIC ROAD LOG

Mileage

000.00 STARTING POINT, intersection of 1-40 and Carlisle heading east on 1-40; Sandia Mountains 5 mi ahead. To the north (left) are the Jemez Mountains with the highest point Redondo Peak, 11,252 ft. To the northwest is the southern end of the Sierra Nacimiento, a fault block with a steep scarp on the west and a gentle slope on the east. To the west the volcanoes on Llano de Albuquerque are on the near skyline; far to the west, approximately 55 mi, is the volcanic peak of Mt. Taylor, 11,399 ft.

1-40 heads south of east to the southern end of the Sandia Mountains, then follows Tijeras Canyon between Sandia Mountains on the north and the Manzanita Mountains on the south.

The Jemez Mountains are the remnants of a relatively recent volcanic caldera. The outlying higher peaks of the range form the caldera rim, about 16 mi in diameter; the higher rounded interior peaks are resurgent domes that were intruded and extruded during the final stages of the volcano. The first ash-flow tuff sheet from the caldera is dated at 1.4 million years; the youngest widespread ash-flow tuff sheet is 800,000 years. Much more recent volcanics, primarily basaltic, occur in the area; the region has many hot springs. Union Oil Company is exploring the Valles Caldera in an attempt to develop geothermal power; they have drilled 16 wells of which 6 are probable geothermal producers.

According to Kelley (1974) probably no major city in the United States has such an array of extinct volcanoes nearby as does Albuquerque. The "Albuquerque volcanoes," only 7 mi from the center of the city, are located on the high surface west of Albuquerque. They are principally basaltic. Similar volcanic centers are located 20 and 30 mi to the north, as well as 12 and 21 mi to the south down the Rio Grande valley. The giant Valles Caldera is on the skyline 60 mi to the north; 55 air mi to the west is Mt. Taylor, normally snowcapped, rising almost half a mile above its base, reaching an elevation of 11,399 ft. Mt. Taylor is within a volcanic field of at least 200 other volcanoes and volcanic necks.

Southern Sandia Mountains straight ahead. At Louisiana Blvd., Tijeras Canyon straight ahead, Manzanita Mountains ahead to the right, and Sandia Mountains ahead off to the left on the northern skyline.

3.5

3.5 As we go under Eubank Blvd., the bold scarp of the highest part of the Sandia Mountains is off to the left, rising to 10,678 ft. Antennae of the Albuquerque TV stations are on the highest crest; the scar off to the right of that crest is manmade rock talus blasted off when the Sandia Tramway was built. The restaurant at the top of the tramway is directly above this talus scar. The lower slopes of the Sandia Mountains are Precambrian rocks capped by a thin mantle of Mississippian and Pennsylvanian rocks which form the layered sequence at the top. Straight ahead on the right (south) side of Tijeras Canyon the same sequence can be seen with mostly Precambrian rocks, relatively structureless, overlain by the bedded late Paleozoic sedimentary rocks.

3.2

6.7 Tramway Blvd., Exit is 0 on Kelley's (1974) road log in the Scenic Trips to the Geologic Past No. 9, *Albuquerque—Its Mountains, Valley, Water, and Volcanoes.* Western Skies Motor Hotel to the right (south); the exclusive Four Hills residential area to the right at the base of the Mazanita Mountains.
0.2

6.9 Enter Tijeras Canyon. Thickness of valley fill to the west of the Sandia Mountains is several thousand feet at this point on the downthrown side of the faults marking the western edge of the Sandia Mountains. In most places these faults are buried by the material eroded from the mountains and spread out into the valley. To the south along the Four Hills road, 0.4 mi south from the Western Skies Motor Hotel, the fault zone is exposed with Precambrian granite on the east and Cenozoic sandstones on the west.

Throughout the Sandia Mountains two of the rock units, the Sandia Granite (Precambrian) and beds of Pennsylvanian age, are at the surface in about 70 percent of the bedrock area. Numerous fault lines cut across all the formations, demonstrating the considerable breaking of the crust that occurred during uplift and deformation of the Sandia area. The principal faults are the Sandia and Tijeras faults. The Sandia fault is situated along the western base of the mountains; it is mostly a zone of fracturing covered by the Quaternary alluvial materials.

The Tijeras fault, traced by Tijeras Canyon and 1-40, is an older break that probably occurred millions of years ago, probably prior to uplift of the mountains. Perhaps the greatest significance of the Tijeras fault is that it greatly weakened the rocks by grinding and shearing, thus allowing erosion of Tijeras Canyon and the mountain pass. This pass has substantially influenced the location and development of Albuquerque, allowing access to the east and the direct routing of 1-40 through the mountain barrier.

An entrance to Tijeras Canyon, outcrops of the Sandia Granite are in the roadcuts and in the surrounding hills. The outcrops are residual erosional boulders formed by weathering away of the edges of the jointed blocks of granite, not stream-derived erosional boulders. In several of the roadcuts for the next 3 mi note the gradation of these boulders downward into the blocky fresher granite. Inclusions of earlier metamorphic rocks can be seen in the Sandia Granite.
2.4

9.3 Village of Carnuel. Trees here are mostly juniper of the Upper Sonoran life zone; along Tijeras Creek native mountain cottonwoods grow. Side road on the right leads south across Tijeras Canyon. The pinkish hill to right consists of granite gneiss called the Tijeras Gneiss. To the left on the high mountain crest, the layered sedimentary limestone, shale, and sandstone are Pennsylvanian units capping the Sandia Granite which is about 1.4 billion years old. Notice the weathered bouldery granite outcrops giving way at high altitutde to the bold, craggy, and pinnacled outcrops.
0.6

9.9 The Sandia Granite grades into the pinkish Tijeras Gneiss.
0.5

10.4 Ahead on the left side of the highway, gray quartzite comprises the knob-like hill to the left of the road. In the roadcut, the rocks are faulted and sheared gneiss. *Sharp left turn ahead.* Pits in the hillside are supposedly gold prospect pits.
0.7

11.1 Terrace gravel in the roadcuts indicate a higher position for Tijeras Creek before it eroded to its present level. Piñon trees now intermix with the juniper. Note the somber dark-green and brownish rocks on the canyon slopes to right. These are metamorphosed greenstones which are part of the metamorphic sequence older than the Sandia Granite. This Tijeras Canyon pass between the Sandia and Manzanita Mountains was used for centuries by Indians, Spanish explorers, traders, trappers, and the '49ers. The mountain ranges, both north and south, top 10,600 ft. The complex of canyons crossing here resemble open scissors, the translation of "Tijeras," the name of the village about 2 mi ahead.
0.8

11.9 On the right Pennsylvanian rocks at the canyon bottom rest on Precambrian; on the left the Precambrian rocks are high on the mountain side and occur in the roadcut ahead.
0.3

12.2 Highway cuts through Pennsylvanian outcrops of gray and red shales interbedded with gray limestone. They dip steeply here as a result of the dragging action along the Tijeras fault.
0.6

12.8 Village of Tijeras ahead was founded in 1856; in the roadcuts are the reddish-brown mudstone and sandstone of the Abo Formation (Permian) which overlies the Pennsylvanian strata in this area. The Abo red beds were deposited by rivers on a vast floodplain that graded southward into a shallow sea.
0.3

13.1 Tijeras Village and school on right; large Ideal Cement Plant on the south. In the quarries to the right of plant, both limestone and shale are quarried as raw materials for the manufacture of cement. This plant was built in 1957, is very modern in design, and is fully automated. Its present cement capacity is rated at 3 million barrels per day. Road to the south leads to Mountainair.
0.5

13.6 Turn northward (left), on NM-14. Red beds of the Abo Formation (Permian) form the outcrops. Northward on the highway, the Abo crops out in the extensive new roadcuts. The vegetation is composed mainly of piñon and several varieties of juniper, interspersed with cholla cactus and scrub oak.
0.5

14.1 Beyond the reddish outcrop, the road crosses a buried fault with the Permian faulted against the grayish-brown Cretaceous rocks. The steep ledges that cap the hills on both sides of the highway are sandstones in the Mesaverde Formation. In this area this formation contains the thin coal beds that have been mined in the downdropped wedge of the Tijeras coal basin.

A few thin coal seams occur in the basal part of the Pennsylvanian sequence in the Sandia Mountains, but most of the coal in the region is in the Mesaverde Formation. In the Tijeras coal basin, the Mesaverde coals are thin and variable, with volatile matter 31 to 36 percent, fixed carbon 36 to 54 percent, ash 8 to 31 percent, sulfur 0.8 to 3 percent, and 10,000 to 13,900 Btu/lb.

Coal was mined here as early as 1898 (Kelley, 1974), mostly for household use and smithing. The lenticular coals occur in 3 zones within the Mesaverde and have been mined at the Section 1 mine, Holmes mine, and Tocco mine. Reserves may be as much as 1.6 million tons; production has been estimated at 2,500 tons. Total thicknesses are 12 to 30 inches. On to Madrid!

0.3

14.4 Coal bed outcrops in left roadcut.

0.3

14.7 Red soil in the roadcuts on the left washed down canyons from the red Permian and Triassic rocks to the west.

0.3

15.0 Old village of San Antonio, an early trading point along the oxcart route from Albuquerque to Santa Fe.

0.3

15.3 Cedar Crest station. This area has long served Albuquerque as a mountain health resort; small quarries in the hillside produced building stone and flagstone.

0.3

15.6 Road to Casa Loma off to the left; on the right the highway follows the canyon of Arroyo San Antonio. Cretaceous outcrops on the right; slopewash and stream gravel on the left.

0.7

16.3 Cedar Crest post office to the right. Red outcrops beyond are in the Chinle Formation (Triassic) which underlies the Jurassic and Cretaceous outcrops in the ridges to the right.

0.8

17.1 Outcrop in the arroyo to the right consists of Morrison Formation and Todilto beds (both Jurassic). The Todilto gypsum was quarried here to provide gypsum for the Ideal Cement Plant. Side road to left leads to the village of Cañoncito and the Cole Springs picnic area. The valley is eroded in the reddish-brown shale of the Chinle Formation (Triassic); the ridge off to the left is an outcrop of the basal Santa Rosa Sandstone (Triassic), quarried in many places in this area for flagstone.

Note the high crest of the Sandia Mountains to the west and the regular tree-covered slope formed by the erosional stripping parallel to the eastward-dipping limestone beds of Pennsylvanian age.

0.3

17.4 Red shales and sandstones of the Chinle (Triassic) in the roadcut on right.

0.9

18.3 Summit of the hill; road crosses into the area of San Pedro Creek which drains the east side of the Sandia Mountains from here north around the mountains and empties into the Rio Grande to the northwest. South of this divide, Tijeras Creek and its tributaries drain the southeastern part of the Sandia Mountains. Along the highway are some ponderosa pines amid a forest of mixed juniper and piñon.

1.2

19.5 Junction with NM-44 at the village of San Antonito, another trading point on the old oxcart route to Santa Fe. NM-44 leads westward to Sandia Crest and to the Sandia Mountains ski area. Spectacular views of the surrounding countryside can be seen from Sandia Crest.

The wide valley here lies in the Chinle shale (Triassic). The mountain to the northeast is Monte Largo which is composed of a complex mixture of gneiss and quartzite with numerous large intrusive igneous rocks such as the Sandia Granite, all Precambrian. A plate of Pennsylvanian rocks cap South Mountain at the northern end of Monte Largo, seen as the bedded upper outcrops in the distance. San Pedro Mountains straight ahead are composed of monzonitic intrusive masses into the Pennsylvanian, Permian, and Mesozoic strata. This area has gold placers and base metal vein deposits that have been mined since 1829.

2.2

21.7 *Curve to left;* Monte Largo off to right; South Mountain (the low northern end of Monte Largo) ahead, and San Pedro Mountains straight ahead. On the slopes covered with juniper and pffion, both left and right, are sparse outcrops of the Yeso Formation (Middle Permian) composed of dolomitic limestone, pinkish siltstone, and gypsum.

0.8

22.5 *Curve to left;* San Pedro Springs is situated to the right in the grove of trees; to the left in the low juniper-covered hills is Pa-ako pueblo ruins. Surface consists of stream alluvium with outcrops of Abo and Yeso Formations (Permian).

1.0

23.5 San Pedro Arroyo directly to the right of the highway.

0.6

24.1 Sandoval-Bernalillo County line.

0.3

24.4 *Cross bridge over San Pedro Creek;* road descends through stream gravels.

0.3

24.7 Outcrops to the left are Abo Formation (Permian) overlying Pennsylvanian limestones.

1.4

26.1 Outcrop of Abo red beds in roadcuts; hills to right of highway are Precambrian quartzite

faulted up against the Abo along the extension of the Tijeras fault.
1.8

27.9 Enter Santa Fe County, leave Sandoval County
0.2

28.1 Golden Buffalo to the left, South Mountain to the right, San Pedro Mountains straight ahead. 0.7

28.8 Roadcut in Pennsylvanian limestones dipping to the north (fig. 3).
0.5

29.3 Road to San Pedro and Cedar Grove to right, NM-344. This road leads to the San Pedro mining district in the San Pedro Mountains, ahead and right of the highway. Ahead and to the left, on skyline, are the Ortiz Mountains made up mainly of monzonite intruded into the Paleozoic and Mesozoic sequence of this area (fig. 4).

The San Pedro Mountains consist of monzonite and related porphyry intruded into sedimentary rocks ranging in age from Pennsylvanian to Eocene, and are part of a horst in the Tijeras fault system. Many faults in the mountains are either nearly parallel to the Tijeras fault system or perpendicular to it; other faults radiate from intrusive centers. The main rock types are monzonite, monzonite porphyry, latite porphyry, and rhyolite porphyry. Sedimentary rocks have been extensively metamorphosed by the igneous intrusions, yielding tactite, hornfels, and marble.

Mineral deposits occur in veins and contact metasomatic deposits. The San Pedro mine has been the most important, producing more than thirteen million pounds of copper since 1900, from a contact-metasomatic deposit in limestone. Lead, zinc, and gold have been produced from mesothermal vein deposits. Gold placers have been among the richest in the state. Nonmetallic deposits include quartz sand, garnet, and limestone.

Proceeding northwestward, the hills to the left of the road are made up of Precambrian rocks overlain by Pennsylvanian limestones. Hills to the right are mainly monzonite intruded into the Pennsylvanian. After crossing the saddle, the highway leads downhill towards the village of Golden, named from the gold placers mined from 1829 to 1839.
1.1

30.4 Village of Golden; outcrops to the left are Pennsylvanian limestones on top of Precambrian.

FIGURE 3—Roadcut in Pennsylvanian, 0.7 mi north of Golden Inn and 1.3 mi south of junction with NM-344 (reference mileage 28.8).

FIGURE 4—West end of Ortiz Mountains. Golden just visible in valley (reference mileage 29.3).

0.9

31.3 Outcrops in roadcuts to left are Abo red beds (Permian) overlying Pennsylvanian limestones. Road continues down the hill along a curve to the left into the valley of Tuerto Creek. Where the highway crosses Tuerto Creek, an east-west-trending fault separates the upper Paleozoic rocks on the south from Mesozoic rocks on the north. The outcrops in the northeast bank of Tuerto Creek are Todilto limestones and gypsum (Jurassic) overlain by the Morrison (Jurassic) with Triassic red beds cropping out along the north side of the creek. The higher peaks of the Ortiz Mountains ahead to the right are Tertiary 'monzonite intruded into mainly Mesozoic rocks.
2.1

33.4 First crest of hill; view off to left of the backslope of the Sandia Mountains; northwest, the Jemez Mountains with the Valles Caldera and Redondo Peak. On skyline directly ahead in the far distance are volcanoes of the "basalts of the river" overlooking the Rio Grande gorge along the main highway from Albuquerque to Santa Fe. The stark cylinder-shaped peak on the left skyline is Cabezon Peak, an ancient volcanic neck eroded from the Mt. Taylor volcanic complex.
0.7

34.1 Ortiz Mountain Ranch entrance to right; in gulley to left are outcrops of the Chinle Formation (Triassic). Chinle also outcrops along the highway just beyond the ranch entrance (fig. 5).
1.2

35.3 Outcrops of Dakota Sandstone in ridge to right capped by craggy ridge of Tertiary monzonite. In this area the Dakota Sandstone is the basal unit of the Cretaceous, overlying the Morrison Formation (Jurassic). Down into the curve to right, Tertiary monzonite crops out beside the highway and in bold cliff in front of the highway. Here the Tertiary monzonite is intruded into the lower part of the Mancos Formation which occurs between the Dakota Sandstone and the overlying coal-bearing Mesaverde Formation. This partic-

FIGURE 5—Backslope of Sandias across Hagan Basin, 5.3 mi north of NM-344 junction (reference mileage 34.6).

ular area is called Stagecoach Canyon; the dirt road off to the right of the highway is the route followed by the stagecoaches from Golden to Madrid.

1.1

36.4 In left roadcut, note limestones and shales of the Mancos Formation intruded by Tertiary monzonite.

0.9

37.3 At crest of hill, Tertiary monzonite intruded into Mancos in roadcut on left. To right, the higher peaks of the Ortiz Mountains also consist of Tertiary monzonite (figs. 6 and 7).

FIGURE 6—ROADCUT AT CREST OF PASS. Mancos intruded and contorted by Tertiary monzonite; 9.15 mi north of NM-344 junction (reference mileage 37.3).

FIGURE 7—CREST OF PASS BETWEEN GOLDEN AND MADRID. View is toward south. Mancos Shale in roadcuts; backslope of Sandias on skyline (reference mileage 37.3).

1.7

39.0 From crest of hill, descend into Madrid valley. Sharp rounded knobs in middle distance are the Cerrillos monzonite, another series of intrusives. On the northeast skyline can be seen the Sangre de Cristo Mountains with the city of Santa Fe at their western base. Outcrops along the left side of the road are in the Tertiary intrusive monzonite. The city of Madrid is in the valley ahead. To the right front, below the gob dumps, are the coal mines of the area (fig. 8).

0.6

39.6 *Round curve to right* in lower part of hill. To right along the canyon are outcrops of Mesaverde Formation and entrances to mines in the Mesaverde coals (fig. 9).

0.5

FIGURE 8—VIEW NORTH ACROSS MADRID TO LOS CERRILLOS (center skyline). Madrid is below right end of Los Cerrillos (reference mileage 39.0).

FIGURE 9—NUMBER 4 MINE NEAR SOUTH END OF MADRID (reference mileage 39.6).

40.1 Crest of small rise; city of Madrid ahead; below the black to reddish-brown mine dumps off to the right in the arroyo are outcrops of the Mesaverde Formation and scattered dumps of waste rock at the base of abandoned mines (figs. 10 and 11).

0.8

40.9 *Cross bridge* over gulch that cuts through downtown Madrid. The sameness of the houses indicate that Madrid was a company town. In the mid- 1950's Madrid was noted for its brilliant display of Christmas decorations. Shortly thereafter the mines closed.

0.9

41.8 STOP 1. Madrid. Old coal-mine museum in downtown Madrid. The Cerrillos coal field is of particular interest because it is one of the oldest coal-mining areas in the United States and because it has produced both coking and noncoking bituminous coal and anthracite. According to Huber (undated, p. 3) coal was mined in 1835 to operate a gold mill at the nearby mining camp of Dolores. Mining on a commercial scale, however, did not commence until the railroad reached Cerrillos in the early 1880's.

Initially the railroad was interested in the bituminous coal rather than the anthracite; the earliest developments were in Waldo and Miller Gulches (more or less paralleling Madrid Canyon) a mile or two northwest of the present

Photo courtesy of Joe Huber

FIGURE 10a—MADRID, 1935. View of Jones mine dump and tipple in foreground, breaker (with smoking chimney) and townsite in middle distance; Ortiz Mountains on skyline. Madrid sill forms ridge behind breaker; coal-bearing units dip to east (left) beneath sill (reference mileage 40.1).

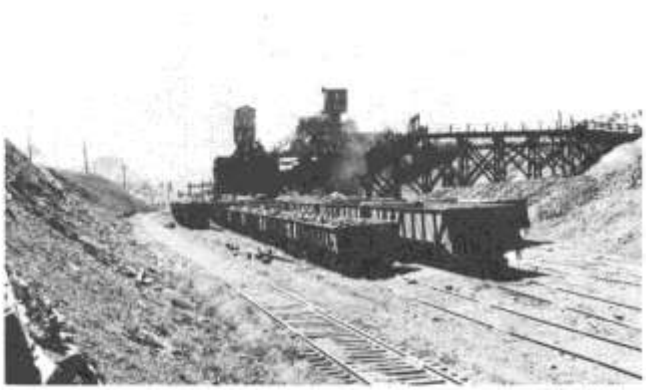


Photo courtesy of Joe Huber

FIGURE 10b—MADRID, 1935. View of Jones tipple and loading tracks from north (reference mileage 40.1).

town of Madrid. By 1889, however, the demand for anthracite had increased such that the railroad installed a spur from Waldo to Madrid. Mining economics favored the Madrid operations; the Miller and Waldo Gulch operations were soon closed.

In 1896, the Colorado Fuel and Iron Company of Pueblo, Colorado, leased the coal holdings of the Santa Fe Railway and produced a blending coal from Miller Gulch as well as bituminous coal and anthracite from Madrid. The steep dip and thin seams together with faults and dikes made mining difficult; the CF&I gave up their lease in 1906. The property was leased to George Kaseman, a prominent businessman and banker in Albuquerque. Mr. Kaseman operated the Albuquerque & Cerrillos Coal Co. until his death in 1938. Oscar Huber, who had been superintendent of the A & C operations, continued to operate the mines; eventually he purchased the Madrid properties. The property remains in the Huber family but coal has not been produced on a commercial scale since 1958.

Coal in the Cerrillos field is contained in the Mesaverde Formation (Late Cretaceous). Five principal seams have been recognized in the field. These are, in ascending order: Miller Gulch, Cook & White, Waldo, Peacock, White Ash, and **"B."** Several lesser seams are present but are too thin to mine. Generally, even the best seams were reported to be less than 5 ft thick. The White Ash, the anthracitized unit, was the most important; it is reported to average 5.5 ft thick over a considerable area (Lee, 1913, p. 301).

As none of the mines in the Madrid area are operating today, and because many of the larger producers have been shut down since before World War I, knowledge of the coal must be

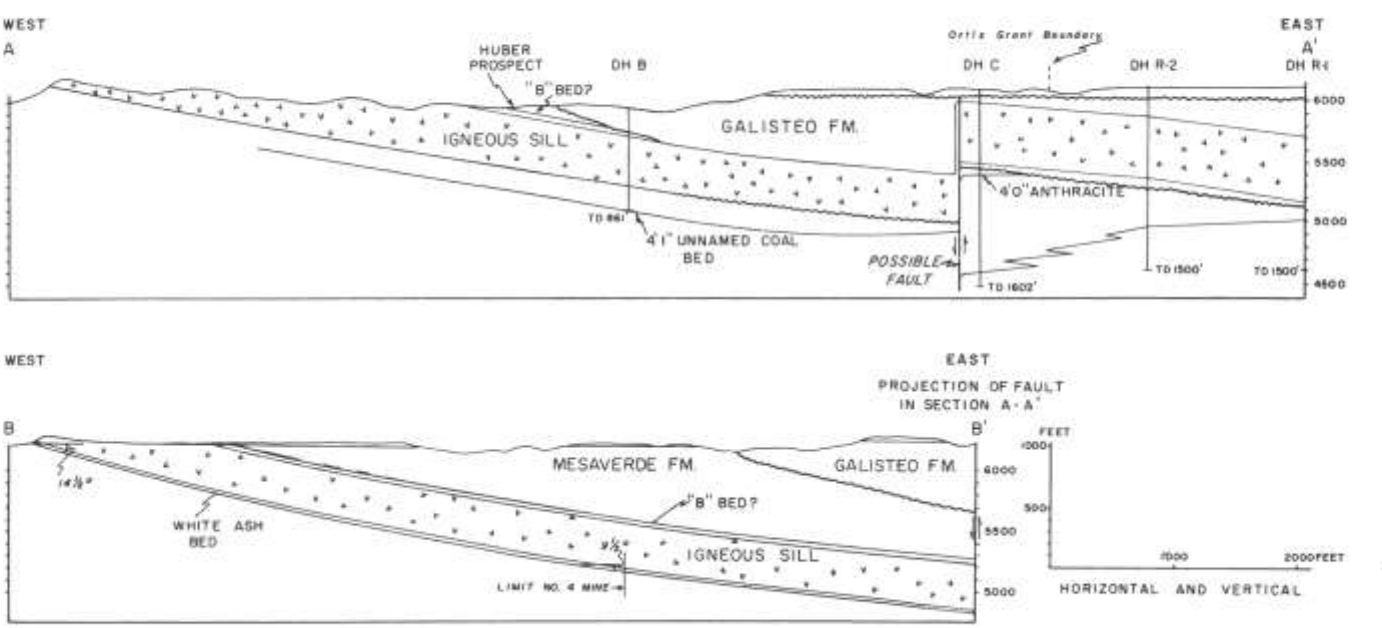


FIGURE 11—WEST-EAST GEOLOGIC STRUCTURE SECTIONS, MADRID AREA, SHOWING RELATIONSHIP OF CRETACEOUS AND TERTIARY STRATA TO IGNEOUS SILL AND POSSIBLE FAULT.

gleaned from mine maps, company records, and earlier geologic reports. Six samples collected by Lee (1913, p. 298) indicate that the categories of the coals are high volatile B and C, semianthracite, and anthracite. One of the analyses came close to meta-anthracite with a dry, ash-free analysis of 97.5 percent fixed carbon.

Though the major production from the Cerrillos field came principally from the bituminous coal beds, the anthracite found in the White Ash and "B" coal beds is particularly interesting. Anthracitization resulted from the injection of the Madrid sill within the coal-bearing sequence. This sill is one of several in the vicinity of Madrid and varies from 350 ft to 500 ft thick. The townsite is also underlain by a correspondingly thick intrusive sheet separating the Madrid coals from the Miller Gulch seam.

The White Ash bed, the unit most extensively mined for anthracite, lies a few feet below the bottom contact of the sill. Northward, the sill departs gradually from the coal, and the coal ceases to be anthracitized. In the Old White Ash mine anthracite was reported (Huber, p. 5) to have been mined to the south of the main entry, whereas bituminous coal was being mined on the north side of the mine. Apparently where the interval between the sill and the coal is more than about 20 ft, metamorphism is not significant. The Peacock bed, which lies about 20 ft below the White Ash, does not appear to have been appreciably affected by its proximity to the thermal source (the sill).

The general relationship of the sill to the Mesaverde and Galisteo Formations is shown in fig. 11. The upper surface of the Madrid sill is less uniform than the lower surface due to the irregular hydraulic jacking of the overburden by the sill injection. As a consequence, the development of anthracite in the overlying "B" seam is much less regular, with frequent and unpredictable pockets of natural coke associated with the anthracite.

Northward and eastward, the Mesaverde Formation is truncated by the Galisteo Formation (Tertiary). Inasmuch as the angularity between the units is slight and the Galisteo is similar in composition to the Mesaverde, the elimination of the coals northward and eastward beneath the unconformity was unrecognized prior to the work of Lee (1913). Thus, the extent of these coals, particularly the higher beds, is somewhat more limited beneath the Galisteo Basin than had previously been thought.

Structurally, the Cerrillos coal field is located on the west flank of a small, shallow basin. At Madrid the strata are inclined about 15 degrees to the east. A portion of cross section B-B' (fig. 11) is constructed on the base of the White Ash seam along the main entry of the No. 4 mine. In the 4,800 ft along the slope from the surface to the face of the mine, the dip decreases to less than 10 degrees and continues to decrease eastward. A lower bed of Mesaverde coal crops out in the southeastern part of the Basin in the Omera mine area. Higher beds, equivalent to the Madrid coals, are removed by pre-Galisteo erosion on the east flank of the Basin.

Core drilling reported by Lee (1913, Pl. XXI) and work done by the Santa Fe Railway suggest the presence of a normal fault with a throw of several hundred feet upthrown on the east. Pediment gravels associated with the Ortiz Mountains obscure the possible trace of this postulated fault. The trend of the fault trace may be nearly north-south, roughly parallel to several major dikes in the vicinity. The fault probably occurred prior to the injection of the sill; also the sill probably crosses the Cretaceous-Tertiary boundary and is totally within Tertiary strata to the east of the fault.

Proximity to the railroad, the uniqueness of the anthracite, and a general growing interest in coal provide a continuing interest in the Cerrillos coal field, particularly the Madrid area. Companies initially enthused about prospects of reopening the mines tend to cool off rapidly when faced with the facts regarding the thin seam thicknesses, the myriad of old water-filled workings, and the exorbitant cost of exploration drilling into great thicknesses of igneous rock. Additional drilling is absolutely required before even a reasonable estimate of these reserves can be attempted. The property is for sale; probably in time someone will work up the courage to explore it.

Read and others (1950, Table 14) calculated 47.5 million tons of original reserves of bituminous coal in place and 9.4 million tons of anthracite in all categories of reliability. If the postulated fault does exist somewhat as shown (cross section A-A', fig. 11), the tonnages of recoverable coal may be considerably less than the estimates by the U.S. Geological Survey.

Retrace route to Albuquerque.

0.3

42.1 Through southern outskirts of Madrid, note sills of monzonite forming ridges to right above coal mines (fig. 12).

2.0

44.1 Road curves to right along hill; San Pedro Mountains to the left and front. Note how these natural outcrops of Tertiary monzonite resemble the spoil-pile ridges of a coal strip mine (fig. 13).

3.7

47.8 Junction with NM-22 which leads off to the west

FIGURE 12—TOWNSITE FROM NORTH, ACROSS BASEBALL FIELD. Madrid sill and breaker visible at left center (reference mileage 42.1).

FIGURE 13—ROADCUT IN TERTIARY MONZONITE. View south toward peaks at west end of Ortiz Mountains (reference mileage 44.1).

through the Hagan coal basin, a small basin similar to the Tijeras coal area. Off to the southwest can be seen the backslope of the Sandia Mountains; ahead is Monte Largo with South Mountain and San Pedro Mountains to left (fig. 14).
5.4

53.2 Golden junction.
10.9

64.1 San Antonito; junction with Sandia Crest road, N M-44.
12.7

76.8 Exit Tijeras Canyon; Mt. Taylor is on the western skyline. Albuquerque eastern city limits; Western Skies Motor Hotel ahead, to left of 1-40.
7.0

83.8 Carlisle Blvd. underpass.
5.2

Note-Road log from this point to Grants was modified from that prepared for Field Trip 2, Grants Uranium Belt, led by D. G. Brookins in connection with the 29th Annual Meeting of the Rocky Mountain Section, Geological Society of America, May 19, 1976, Albuquerque.

89.0 Milepost 156 east of Rio Grande bridge on 1-40 at Albuquerque. Average annual flow is a little over 1,000,000 ac-ft per year past this point.
1.0

90.0 Top of first terrace, known as West Mesa, cut on Santa Fe Group (Miocene-Pliocene).
0.5

90.5 At 2:30 is view of Albuquerque volcanoes and associated basalt flows. Volcanoes are aligned approximately north-south, probably indicating feeders along a fault.

FIGURE 14—VIEW SOUTH FROM JUST NORTH OF GOLDEN. Abo Formation (Permian) in bluffs along creek, San Pedro Mountains on skyline center and left, South Mountain on skyline right in photo (reference mileage 47.8).

5.5

96.0 Top of second terrace, the Llano de Albuquerque surface, cut on Santa Fe Group and capped by caliche having an average thickness of about 10 ft. At 10:00 in far distance is Sierra Ladron, a large fault block of Precambrian rocks on the western margin of the Rio Grande trough.
4.1

100.1 West edge of Llano de Albuquerque. The erosional escarpment that road descends is the Ceja del Rio Puerco (brow of the dirty river). At 10:00 is Mesa Lucero. From 1:00 to 2:00 is Mesa Gigante. On the skyline at 1:30 is Mt. Taylor, a volcano of probable late Miocene to Pliocene age.
0.9

101.0 Cerro Colorado, half a mile south of road at 10:30, is an exhumed volcano of Miocene-Pliocene age.
2.2

103.2 Mesa de la Negra at 12:30 and 2:00, a localized basalt flow in Santa Fe Group.
1.3

104.5 Bridge over Rio Puerco; river marks approximate position of western margin of the Rio Grande trough with Tertiary outcrops to the east and Cretaceous outcrops to the west. The Rio Puerco contributes about 3 percent of streamflow of Rio Grande, but about 45 percent of the sediment load. Suspended-sediment concentrations of 418,000 ppm, or about 42 percent by weight, have been observed in the Rio Puerco between Cabezon and Bernardo. The only other stream exceeding this in the United States is the Paris River in Arizona.
0.7

105.2 Roadcuts in shale and sandstone of the Mesaverde Group: Gibson Coal Member or higher beds of the Crevasse Canyon Formation. 5.5

110.7 Cretaceous sandstone in roadcut (Dakota); Mancos Shale crops out below the road in valley to left.
0.5

111.2 Dakota Sandstone in Cuesta at 2:30.
0.4

111.6 Cañoncito exit.
0.2

111.8 Underpass.
0.65

112.45 East end of long roadcut in Gallup Sandstone at base of Mesaverde Group.
1.85

114.3 At 9:00 is Mesa Redonda formed of Jurassic rocks, Dakota Sandstone, Mancos Shale, overlain by Quaternary basalt. Note faulted syncline at 3:30.
1.25

115.55 Sign, Los Lunas Exit, 1 mi. Mesa Gigante north of highway.
0.75

116.3 Overpass.
0.1

116.4 Exit. Mesa Gigante at 3:00.
1.95

118.35 Correo Sandstone Member of upper Chinle Formation in cliffs on right.
2.15
120.5 Outcrops of Correo Sandstone close to road at 3:00.
0.65
121.15 Overpass. *Cross tracks* of AT&SF (Atchison, Topeka, and Santa Fe) Railway.
1.6
122.75 Bridge over Rio San Jose. Valley cut in Chinle Formation.
1.75
124.5 Overpass.
1.45
125.95 Mesita exit.
0.07
126.02 Overpass.
0.62
126.64 Note slumpage features at 12:00. Todilto gypsum is not present here; slumping of Summerville and Bluff may have resulted from solution of gypsum. Difference in dip of lower and upper beds may indicate that slumping occurred in Jurassic time. Sandstone dikes in these exposures may be related to slumping.
0.5
127.14 Sandstone dikes at 11:30 and 12:30.
0.6
127.74 Deep roadcut in Bluff Sandstone.
0.15
127.89 West end of cut. East end of Laguna basalt flow occupies valley floor north of highway.
0.5
128.39 East end of long cut in Bluff Sandstone.
0.15
128.54 Basalt dike in Bluff Sandstone, both sides of roadcut.
2.0
130.54 Laguna Pueblo at 3:00.
0.3
130.84 Bridge crossing Rio San Jose.
0.3
131.14 *Cross* Rio San Jose. Highway traverses Laguna flow for next 1.5 mi.
3.8
134.94 Exit to Acoma, Paraje, and Casa Blanca.
2.0
136.94 *Cross* AT&SF railroad tracks.
1.3
138.24 Overpass. Roadcuts in Dakota Sandstone.
0.85
139.09 In next few tenths of a mile are a series of roadcuts in Brushy Basin Member of Morrison Formation overlain by Dakota.
1.55
140.64 Acoma and San Fidel exit.
0.8
141.44 We have now climbed through the Morrison and Dakota sections and are riding on the dip slope of the Dakota Sandstone.
1.65
143.09 Overpass.
3.5
146.59 Overpass.
0.5
147.09 Between 9:00 and 3:00, exposures of uppermost Tres Hermanos Sandstone Member of Mancos Shale.
1.35
148.44 Railroad underpass.
0.7
149.14 Now proceeding through McCartys basalt flow, no more than 2,000 years old. Fragments of Indian pottery have been found enclosed in basalt. Source is not Mt. Taylor but near eastern edge of Zuni Mountains, 10-12 mi southwest of highway.
1.0
150.14 Note pressure ridges in basalt and perched water ponds.
3.55
153.69 Overpass. Quemado turn off.
3.4
157.09 At 3:00 on the skyline the dark rock is a basalt flow conforming to an old topography. White material below the basalt is pumice that has been quarried intermittently in this area for years and used as lightweight aggregate.
3.85
160.94 Grants exit. *Leave* 1-40. END OF 1ST DAY ROAD LOG.

2nd Day Road Log

Grants-Farmington

RÉSUMÉ

The second day includes six stops, covers approximately 187 miles, and traverses the western margin of the San Juan Basin. The first leg of the trip, from Grants to Thoreau, follows a broad valley cut in Permian and Triassic rocks. A line of cliffs bordering the valley on the north presents magnificent exposures of the section from the upper part of the Chinle Formation through the Dakota Sandstone. From Thoreau northward, the route crosses successively younger rocks, including all of the principal coal-bearing zones in the Cretaceous stratigraphic sequence. The first stop, in Satan Pass, offers an excellent view of the complex transgressive-regressive relationships in the southern part of the Basin. The second stop, near **Crownpoint,** provides a closer look at the Gibson Member coals of the Crevasse Canyon Formation and broad view of the stratigraphy. From Crownpoint the route passes out of marine shales of the Mancos Shale and upward through the Point Lookout Sandstone into the coal measures of the Cleary Member of the lower Menefee Formation, then follows a stratigraphic position in the lower Menefee to Seven Lakes. At Seven Lakes the route turns north again to cross the remainder of the Menefee, more or less perpendicular to the strike. The coal-bearing upper Menefee is then seen at the **third stop** within Chaco **Canyon National Monument.**

Beyond Chaco Canyon, the route crosses another transgressive-regressive sequence, through the Chacra tongue of the Cliff House Sandstone, the Lewis Shale, and the Pictured Cliffs Sandstone into the coal-bearing lower Fruitland Formation seen at the **fourth stop near Escavada Wash.** From that point, the route ascends still further in the section into the Kirtland Shale then doubles back across the sequence again to the uppermost Menefee, seen at the **fifth stop,** in **Tsaya Canyon.** From Tsaya Canyon the route again ascends through the section, with a **sixth stop** at the Fruitland coals exposed near **Bisti,** and reaches the Nacimiento Formation (Tertiary) before descending again as the road enters the valley of the San Juan River at Farmington.

The emphasis of the road log is on broad stratigraphic relationships, the environments of deposition, and the many oscillations of the late Cretaceous shorelines in this region. The geology and stratigraphy of the San Juan Basin is shown in the accompanying map (fig. 15) and cross section (fig. 16).

GEOLOGIC ROAD LOG

Mileage

000.00 **STARTING POINT,** Holiday Inn east edge of Grants, New Mexico. *Turn north* toward Grants on US-66.
0.55

0.55 Overpass. Highway crosses AT&SF railroad tracks. Basalt-capped mesa from 11:00 to 3:00 is Grants Ridge; the basalts flowed from Mt. Taylor (3:00) onto a terrane of Permian and Triassic sediments which are preserved beneath the erosional remnants of the cap. Pumice mine can be seen as a white patch high on the slope.
0.8

1.35 Junction with NM-53 to San Rafael and El Morro.
0.45

1.8 Excavation in landslide debris composed of Chinle Formation shales and blocks of Tertiary basalt which have rolled down from the top of the ridge. Quaternary basalt flows in valley floor to left.
0.2

2.0 Roadcuts in landslide debris. Houses along right side of road are built on landslides.
0.1

2.1 Overpass. Cross AT&SF railroad tracks.
0.3

2.4 Enter Milan, New Mexico.
1.3

3.7 Intersection. *Turn left* onto road that connects with **1-40** access road.
0.15

3.85 *Turn right* and enter westbound 1-40.
1.1

4.95 San Andres Limestone prominently displayed in bluffs at 10:00; north slope of Zuni Mountains visible to left of road. This ancient positive feature marking the southern boundary of the San Juan Basin has been positive to some extent throughout most of the periods of geologic time in this region. In the core of the Zuni Mountains, Precambrian granite is overlain by sediments of Pennsylvanian age which are in turn overlain by Permian rocks, the youngest of which, the San Andres Limestone, is exposed in this vicinity in roadcuts ahead.
1.3

6.25 Vertical-walled roadcuts exposing wavy-bedded arenaceous limestone of the San Andres. 0.7

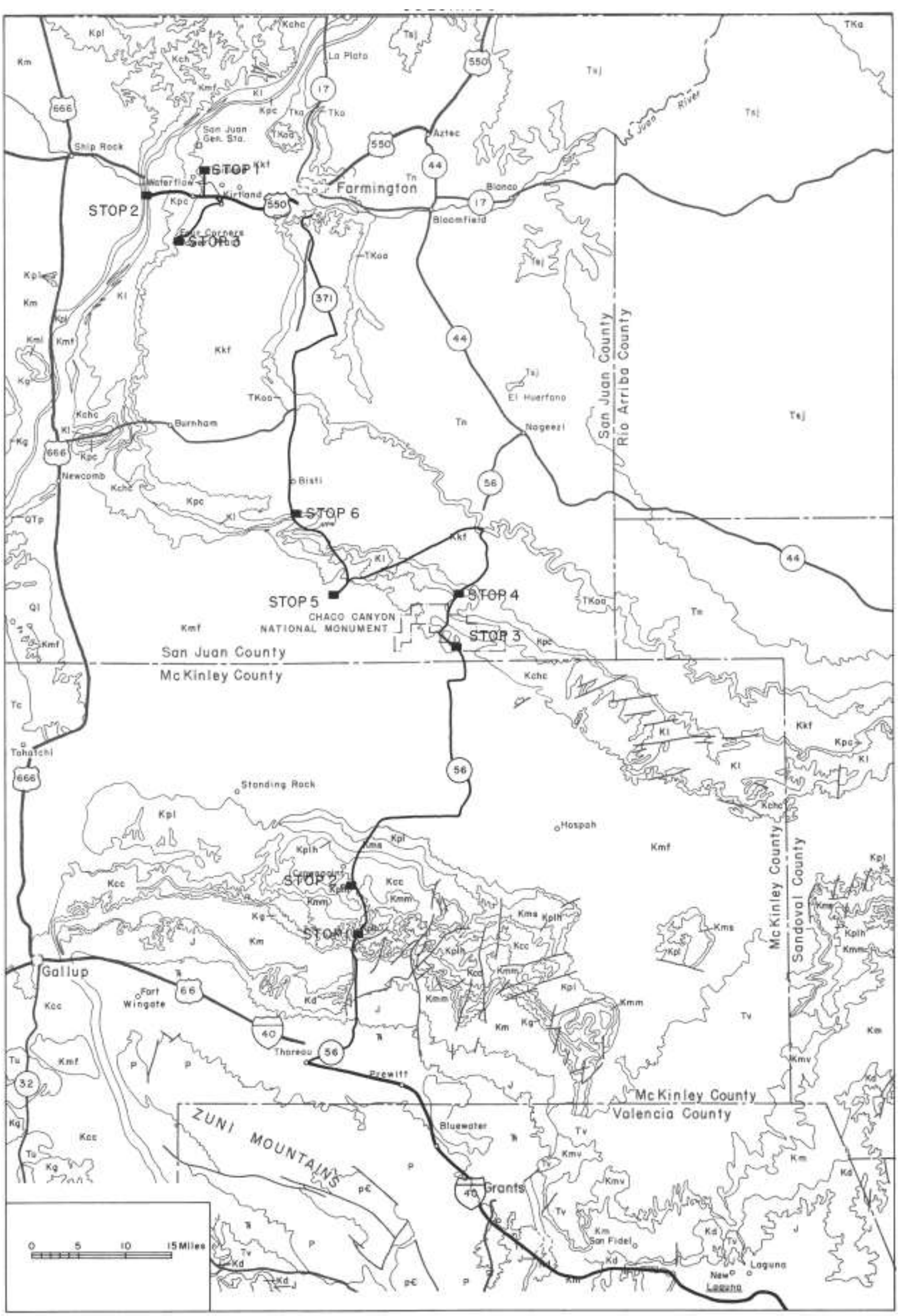
6.95 Underpass.
0.9

7.85 1-40 descends westward into the Bluewater Valley through roadcuts in San Andres Limestone.
0.6

8.45 Haystack Mountain at 2:00, site of the initial discovery of uranium (in the Todilto Limestone) in the Grants uranium district. Manufacturing plant in the foreground is the Anaconda uranium mill; in background between the Anaconda mill and Haystack Mountain is El Tintero hill (the ink well), a relatively youthful volcanic cone from which basaltic lavas flowed.
1.6

10.05 Mouth of Bluewater Canyon at 9:00 with village of Bluewater in foreground.
0.8

10.85 Underpass at the Bluewater exit.


STOP 1
STOP 2
STOP 3
STOP 4
STOP 5
STOP 6
Farmington
Aztec
Bloomfield
Blanco
Ship Rock
Waterflow
Kirtland
San Juan Gen. Sta.
La Plata
Burnham
Newcomb
Bisti
El Huerfano
Nageezi
CHACO CANYON
NATIONAL MONUMENT
San Juan County
McKinley County
Rio Arriba County
Sandoval County
Valencia County
Tohatchi
Standing Rock
Hospah
Gallup
Fort Wingate
Thoreau
Prewitt
Bluewater
Grants
San Fidel
Laguna
New Laguna
ZUNI MOUNTAINS
San Juan River
0 5 10 15 Miles

EXPLANATION

Quaternary	Ql	Landslides
	QTp	Pediment/terrace gravel and sand
Tertiary	Tu	Tertiary, undifferentiated
	Tc	Chuska Formation
	Tv	Tertiary volcanics
	Tsj	San Jose Formation
	Tn	Nacimento Formation
	TKa	Animas Formation
	TKoa	Ojo Alamo Sandstone
Cretaceous	Kkf	Kirtland and Fruitland Formations
	Kpc	Pictured Cliffs Sandstone
	Kl	Lewis Shale
Mesaverde Group (Kmv)	Kch	Cliff House Sandstone (Kchc, Chacra tongue)
	Kmf	Menefee Formation
	Kpl	Point Lookout Sandstone
	Kms	Satan Tongue of Mancos Shale
	Kplh	Hosta Tongue of Point Look Sandstone
	Kcc	Crevasse Canyon Formation (includes, in descending order, Gibson Coal Member, Dalton Sandstone Member, and Dilco Coal Member)
	Kmm	Mulatto Tongue of Mancos Shale
	Kg	Gallup Sandstone
	Km	Mancos Shale (main body of Mancos)
	Kd	Dakota Sandstone
Pre-Cretaceous	J	Jurassic, undifferentiated
	Ŧ	Triassic, undifferentiated
	P	Permian, undifferentiated
	p€	Precambrian, undifferentiated

FIGURE 15—GEOLOGIC MAP OF SAN JUAN BASIN WITH TRIP ROUTE AND STOPS FOR 2ND AND 3RD DAY ROAD LOGS (modified from Dane and Bachman, 1965).

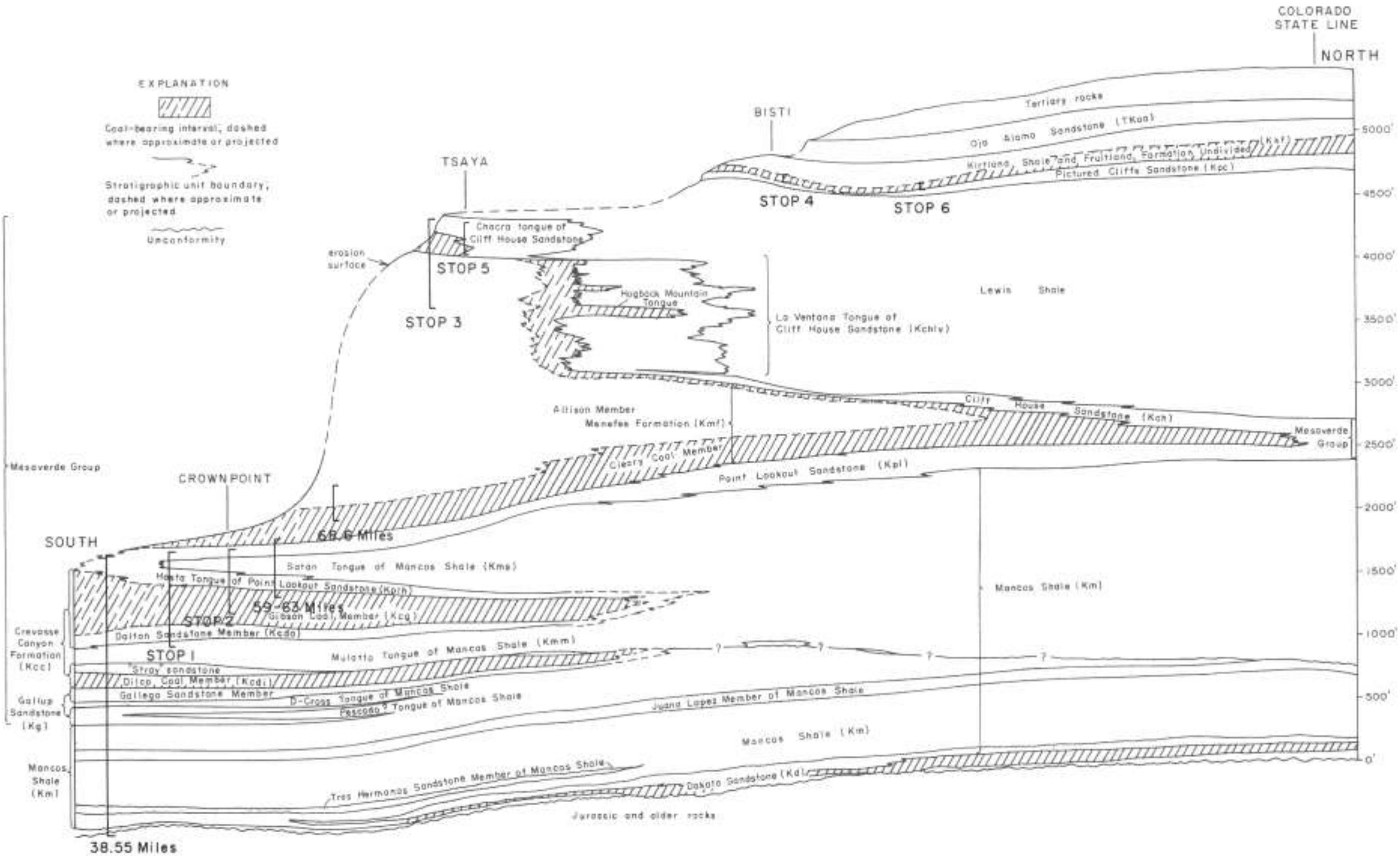


FIGURE 16—DIAGRAMMATIC NORTH-SOUTH CROSS SECTION OF WESTERN SAN JUAN BASIN SHOWING STRATIGRAPHIC NOMENCLATURE AND RELATIONSHIP OF CRETACEOUS UNITS. Brackets mark parts of section seen at stops and selected mileages on 2nd day road log. Horizontal distances not to scale. Modified from a section by E. C. Beaumont, 1971.

1.6

12.45 Chinle Formation (Triassic) resting on San Andres Limestone (Permian) at 10:00 to 11:00.

1.1

13.55 Highway rises into resistant area held up by the Sonsela Sandstone Bed, which occurs within the Petrified Forest Member of the Chinle Formation.

0.2

13.75 Roadcut, in which a channel within the lower Chinle is well exposed, on the left side of the highway.

0.25

14.0 McKinley County line.

0.8

14.8 Good view of Haystack Mountain and El Tintero at 2:30 and 3:00.

2.4

17.2 Highway is passing through low hills held up principally by the Sonsela Sandstone Bed.

0.45

17.65 Sonsela sandstone well exposed in roadcut. Note the typical purplish tones in both the shales and the sandstones of the Chinle Formation.

0.25

17.9 Roadcut; channeling and crossbedding in the Chinle Formation are well exhibited.

0.2

18.1 Rodeo grounds at 3:00. From this locality one has an excellent view of the Wingate Cliffs from 12:00 to about 3:00 in which the uppermost Triassic and the entire Jurassic sequence is prominently displayed. In ascending order, the sequence exposed is: the uppermost Petrified Forest Member of the Chinle Formation (red shales), the Owl Rock Member of the Chinle (darker shales), and the red sandstone assigned by some workers to the Wingate Sandstone, all Triassic; and the massive, orange cliff-forming sandstone of the Entrada Sandstone, the thin cap of gray Todilto Limestone, and the slope-forming Cow Springs Sandstone and Morrison Formation, all Upper Jurassic. Eastern terminus of the Wingate Cliffs marks the position at which the Bluewater fault downdrops younger Morrison strata on the east side against the massive Entrada Sandstone on the west.

0.7

18.8 Tank on hill at 3:00 in Sonsela Sandstone Bed. Location of the now defunct Malco Oil refinery at Prewitt, New Mexico.

0.75

19.55 Roadcut in Chinle.

0.25

19.8 Underpass.

1.1

20.9 Roadcut in sandstones and shales of the Chinle Formation.

2.0

22.9 Roadcuts in the Sonsela Sandstone Bed for next 0.4 mi.

1.2

24.1 Roadcuts in the Petrified Forest Member of the Chinle.

0.6

24.7 Roadcut in the Petrified Forest Member of the Chinle.

0.7

25.4 Panoramic view across valley to northwest of the upper part of Triassic sequence and the entire Jurassic.

1.0

26.4 Roadcut. Purplish sandstones and shales in the Petrified Forest Member of the Chinle.

3.0

29.4 Thoreau exit. *Turn off to right.*

0.5

29.9 Stop sign. Intersection with frontage road; *turn left;* El Paso Natural Gas Company pumping station on south side of 1-40.

0.25

30.15 Stop sign; *turn right* on NM-57.

0.25

30.4 AT&SF railroad tracks. To left (west) is the staging area where massive loads destined for the Four Corners Power Plant and San Juan Generating Station are transferred from flat cars to off-road trucks.

0.1

30.5 *Bear right* on NM-57.

0.55

31.05 Milepost 1.

0.4

31.45 Thoreau cemetery on right.

0.65

32.1 Milepost 2.

0.9

33.0 Cliffs to. north display Chinle through Dakota (fig. 17).

0.3

33.3 Entrada and Todilto in cliff at left (fig. 18).

2.65

35.95 Todilto Limestone at 10:00 is being quarried for road material.

2.4

38.35 Remnant of coal in the Dakota Sandstone in roadcut, both sides of road. The coal is just above rocks of the Morrison Formation (Juras-

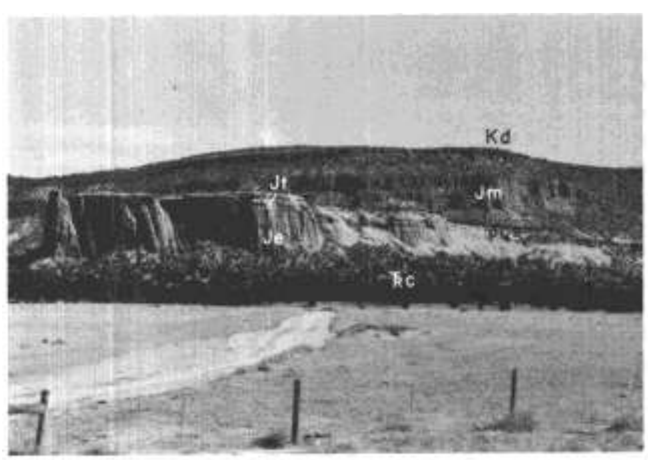


FIGURE 17—VIEW OF TRIASSIC AND JURASSIC SEQUENCE IN CLIFFS EAST OF THOREAU. R̄c—Chinle Formation; Je—Entrada Sandstone; Jt—Todilto Limestone; Jcs—Cow Springs Sandstone and Summerville Formation; Jm—Morrison Formation; Kd—Dakota Sandstone (reference mileage 33.0).

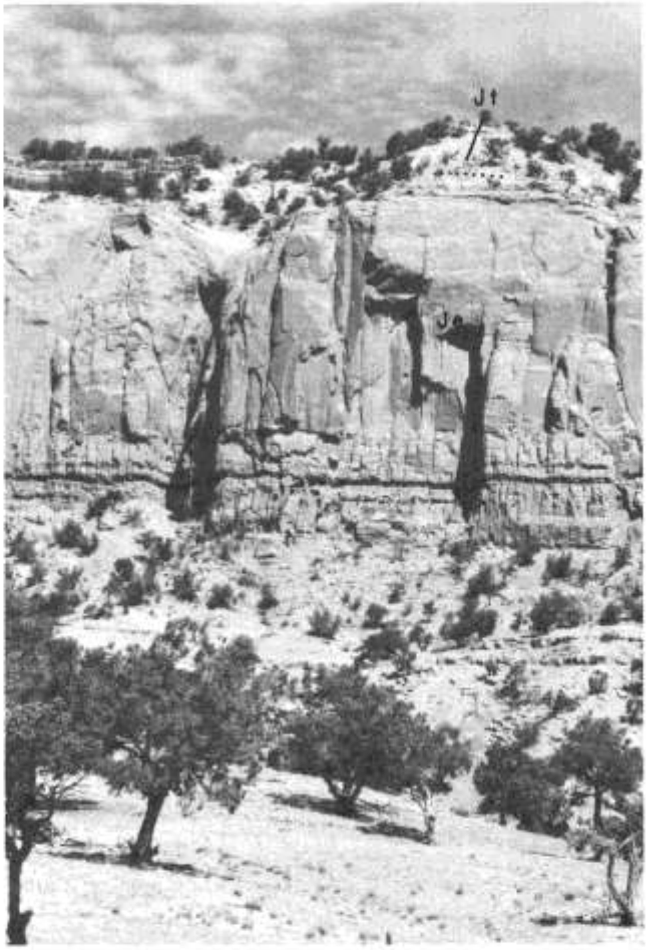


FIGURE 18—Cliff of Entrada Sandstone (Je) capped by Todilto Limestone (Jt) (reference mileage 33.3).

sic), and thus is probably the lowest Cretaceous coal in the San Juan Basin. The Dakota is broken here by several small faults and is in fault contact with the Morrison just east of the road (fig. 19).

0.2

38.55 Panoramic view of the Cretaceous stratigraphy beginning with the Dakota on the near side of the valley; the soft Mancos Shale in the valley; the Gallup Sandstone and the various members of the Crevasse Canyon Formation in the far cliffs culminated by the Point Lookout Sandstone which is visible in Hosta Butte, the prominence on the skyline at 10:30.

0.5

39.05 Milepost 9.

2.0

41.05 Milepost 11.

1.0

42.05 Smith Lake Mercantile and Rod's Indian Jewelry on right side of highway.

0.75

42.8 Road to left leads to Pinedale. The road is traversing the upper part of the lower Mancos Shale.

0.3

43.1 Gallup through Dalton exposed in cliffs on right (fig. 20).

0.25

43.35 Roadcut in transition zone between the Mancos Shale and the overlying Gallup Sandstone. The lower tan sandstone cliffs are in the Gallup Sandstone and are overlain by the slope-forming, nonmarine, coal-bearing Dilco Coal Member of the Crevasse Canyon Formation. The coal in the Dilco in this area is limited to 1 to 3 thin seams ranging from 1 1/12 to 3 ft thick (Sears, 1936, pl. 12). In this vicinity the shore-marginal transitional sandstone, which should be present between the Dilco Member and the overlying Mulatto Tongue of the Mancos Shale, is absent. The shale-on-shale contact, however, is marked by a thin (essentially one clast thick) layer of pebbles and cobbles of quartzite, leading to the conclusion that the sandstone facies may have been deposited but was later winnowed away leaving only the very coarsest material. An interesting aspect of this layer of quartzite clasts is the fracturing that has occurred in these units after they were emplaced in the shale bed. The individual pebbles and cobbles are fractured and partially healed with calcitic cement; in most instances very small offsets can either be seen or

FIGURE 19—Exposure of lowest Cretaceous coals in San Juan Basin (arrow). Faulted remnants of coal beds near the base of the Dakota Sandstone (reference mileage 38.35).

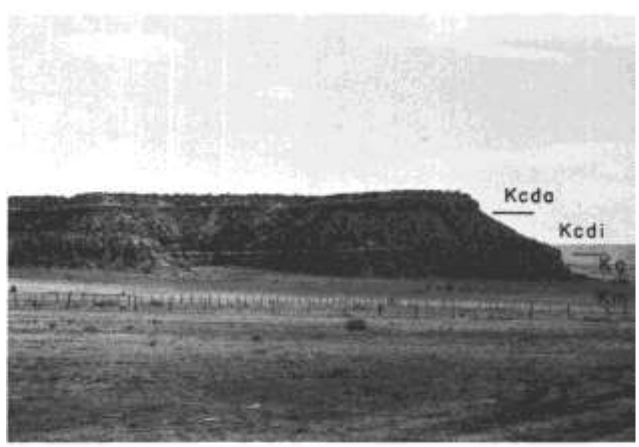


FIGURE 20—Outcrops of Gallup Sandstone (Kg). Dilco Coa Member (Kcdi), and Dalton Sandstone Member (Kcda) o Crevasse Canyon Formation, overlying the Mancos Shale (Km) across highway from Smith Lake School (reference mileage 43.1).

felt on the surfaces of the clasts. Stresses sufficient to fracture rock fragments that had already survived the trials of transportation would appear unlikely in this area of relatively minor tectonic activity.

0.3

43.65 Road is in the upper part of the Dilco Coal Member close to the contact with the overlying Mulatto Tongue.

0.5

44.15 Roadcut in the Dilco Coal Member.

0.3

44.45 Bend in the road; good view of the Mesa de los Lobos region. We are close to the Dilco-Mulatto contact; sandstones to the right of the highway are in the Dilco Member. The open area from 12:00 to 2:00 is formed in the soft shale of the Mulatto Tongue. The sandstones in the prominence jutting southward from the lower part of Mesa de los Lobos are part of the Dalton Sandstone Member of the Crevasse Canyon Formation, which, in turn, is overlain by the Gibson Coal Member. The Gibson forms the rather long slope below the upper sandstone cliffs and contains several prominent but lenticular sandstone beds. Note the red-clinkered shales sloughed from the lower part of the Gibson down across the Dalton Sandstone. The Gibson at this locality is over 300 ft thick and contains thin coals throughout. In the upper 60 ft, two or three beds ranging in thickness from 2 1/2 to 4 ft are present (Sears, 1936).

0.55

45.0 Milepost 15. Road in Mulatto Tongue.

0.2

45.2 Roadcuts in sandy shale of Mulatto Tongue.

0.5

45.7 Lower scalloped sandstone cliffs to right of highway formed by Dalton Sandstone (fig. 21).

0.75

46.45 Entrance to Satan Pass. Relatively steep east dip in this area is associated with a north-trending minor monoclinal fold compounded by a series of normal faults. Faulting, uncommon in the San Juan Basin, occurs with greater frequency in this area. The concentration of small faults here is probably responsible for the combination of erosional features that produced the Satan Pass. Mesa de los Lobos includes the prominent Dalton Sandstone as the cliff at the middle of the slope, underlain by the Mulatto Tongue of the Mancos Shale, overlain by the Gibson Coal Member of the Crevasse Canyon Formation, and capped by the Point Lookout Sandstone. Several faults intervene between the view point and the mesa (fig. 22).

0.55

47.0 Milepost 17. Lower cliffs to the right of the highway are Dalton Sandstone. Note the sharp change in dip between the sandstone in the lower part of the mesa to the right of the highway and the shale beds exposed in the gulley immediately to the right of the highway. The Mulatto-Dilco contact is exposed in this gulley. Coal beds visible on left side of highway as we approach this point are in the Dilco Member. The lower prominent cliffs are the Dalton Sandstone above the Mulatto Tongue, overlain by the lower part of the Gibson Coal Member. A prominent medial sandstone is visible in the upper part of the Gibson. At this locality the Gibson contains four or five thin beds of coal, none of which is over 2 1/2 ft thick (Sears, 1936). The upper cliff is formed by the Point Lookout Sandstone. From 10:00 to 12:30 the Dalton Sandstone forms more cliffs in the face of the mesa but is interrupted by faulting. The upper slopes are in the Gibson, capped by the cliff-forming Point Lookout. Near the righthand (east) end of the Mesa de los Lobos on the west side of Satan Pass, the thickened Point Lookout Sandstone is interrupted about midway by a narrow bench. This bench marks the position of the southwest-thinning Satan Tongue of the Mancos Shale

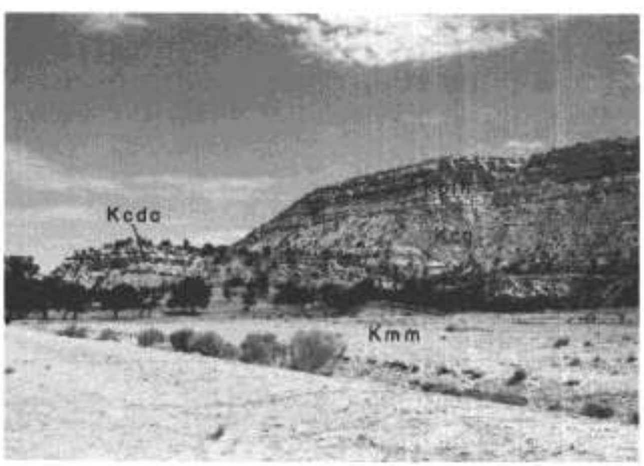


FIGURE 21—View of Dalton Sandstone Member (Kcda) and Gibson Coal Member (Kcg) of Crevasse Canyon Formation, capped by Hosta Tongue of Point Lookout Sandstone (Kplh). Road in Mulatto Tongue of Mancos Shale (Kmm) (reference mileage 45.7).

FIGURE 22—View of Mesa de los Lobos. Section ascends from Mulatto Tongue of Mancos Shale (Kmm) through Dalton Sandstone Member (Kcda), and Gibson Coal Member (Kcg) of Crevasse Canyon Formation, capped by Hosta Tongue (Kplh) and main body of Point Lookout Sandstone (Kpl), separated by thin Satan Tongue of Mancos Shale (Kms) (reference mileage 46.45).

which provides the means of subdividing the Point Lookout Sandstone into the main body above and the Hosta Tongue below. The coalescence of these units is believed to be the principal reason for the presence of this major linear physiographic feature, Mesa de los Lobos, paralleling the depositional strike. An analog of this feature is located along the strike to the northwest in the Black Mesa Basin where the north-facing facade of the Black Mesa is held up by the Yale Point Sandstone believed by the writers to represent a similar situation-the coalescence of the transgressive and regressive sandstones into the massive Yale Point Sandstone. The lower sandstone at 12:00, observed to be dipping about 15 degrees to the east, is the Dalton Sandstone Member underlain by the Mulatto Tongue in a fault relationship with the units exposed at the cliff face. Two or more faults occur between the Dalton and the cliff face.

0.4

47.4 Excellent exposure of the contact between the gray shales of the Mulatto Tongue and the Dalton Sandstone at 3:00.

0.85

48.25 **STOP 1. Satan** Pass. Good view of the stratigraphic succession from 12:00 to 2:00. Prominent, massive Dalton Sandstone cliffs are overlain by the Gibson Member of the Crevasse Canyon and capped by the Point Lookout Sandstone with a faint suggestion of a Satan Tongue interval midway in the sequence. At 11:00 a fault in the Point Lookout is indicated to be downthrown to the east by the drag. From 10:00 to 11:00 to the right of the fault, the lower slopes are in the Gibson Coal Member within which a prominent medial sandstone is visible. The lowermost massive cliff above the Gibson is the Hosta Tongue of the Point Lookout overlain by the slope-forming Satan Tongue of the Mancos Shale and finally by the main body of the Point Lookout Sandstone to the top of the cliff. The road at this locality is in the Dalton Sandstone.

0.5

48.75 At 3:00 faulted stratigraphic relationships visible.

0.3

49.05 Low cliffs on both sides of highway formed by Dalton Sandstone.

0.4

49.45 Descending the north side of Satan Pass; highway in Mulatto Tongue.

0.5

49.95 Mulatto Tongue and Dalton Sandstone from 12:00 to 3:00.

0.95

50.9 Hosta and Satan Tongues of the Point Lookout Sandstone and Mancos Shale visible in upper cliffs underlain by the slope-forming Gibson Coal Member, containing scattered streaks of burned coal. The strata in this area are dipping gently to the north and northeast on the Chaco Slope sector of the San Juan Basin as described by Kelley (1950).

0.85

51.75 Highway ascends from Mulatto Tongue into the Dalton Sandstone.

0.2

51.95 Milepost 22. A strong possibility that several drill rigs will be visible at the time of field trip inasmuch as this location is part of Conoco's Crownpoint uranium prospect. The frequency of white plastic hole markers attests to the concentration of drilling and the probability that ore has been discovered here.

1.7

53.65 Small bluff at 10:00 exposing shale and coal in the lower part of the Gibson Member.

0.3

53.95 Milepost 24.

0.1

54.05 Intersection. *Turn left on road to Crownpoint.*

0.4

54.45 **STOP 2. Crownpoint.** Shales and coal beds in the upper part of the Gibson exposed beneath the Hosta Tongue is low mesas on both sides of road fig. 23). Studies have been conducted on Crevasse Canyon Formation because of its fossil pollen content.

0.4

54.85 *Enter Crownpoint, New Mexico.* Bluffs capped by light-colored Hosta Sandstone Tongue rim the village.

0.15

55.0 Stop sign; *continue straight ahead.*

0.15

55.15 Stop sign; *turn right.*

0.2

55.35 Stop sign; *turn left.*

0.25

55.6 Coals and shales in the Gibson Member exposed to the left of the highway and in the gulley on the right side. Coal and shale exposed in road-building activities associated with uranium exploration. Mesa de los Lobos from 9:00 to 11:00 on skyline with Point Lookout Sandstone; Satan Tongue, and Hosta Tongue of the Point Lookout

FIGURE 23—VIEW SOUTH FROM STOP 2. Gibson Coal Member (Kcg) overlain by Hosta Tongue (Kplh). Curious topography on slope between road and mesa cap is the result of intensive uranium exploration; holes to the Westwater Canyon Member of the Morrison Formation (about 2,400 ft) have been drilled on close spacing by Conoco (reference mileage 54.45).

in the upper part of the mesa. Note the increased thickness of the Satan Tongue here as compared with that viewed within Satan Pass.
0.6
56.2 Church; outcrops of coal to right of road.
0.25
56.45 Coal in the Gibson Member.
0.15
56.6 End of pavement; *turn right.*
0.5
57.1 Stop sign. Junction with pavement. *Turn right.*
0.3
57.4 Sandstone bluffs on either side of the highway are in lower part of Hosta Tongue and underlain by Gibson Member.
0.6
58.0 Crownpoint High School at 3:00.
0.25
58.25 Road junction; road in the Hosta Tongue descending into the upper part of the Gibson Coal Member. Heart Rock carved from the Point Lookout Sandstone, visible in distance at 12:00. Cliffs visible from 11:00 to 12:00 in the Point Lookout Sandstone.
0.9
59.15 Stop sign. Junction with NM-57; *turn left.*
0.55
59.7 Cliffs at 1:00 formed by the Point Lookout.
0.75
60.45 Highway traversing Hosta Tongue.
1.3
61.75 Milepost 28.
0.6
62.35 Road junction. *Turn right,* following NM-57. Road straight ahead at this junction is NM-371 leading to La Vida Mission, Bisti, and Farmington. NM-57 at this locality coincides with Navajo Hwy. 9. Scattered outcrops of Point Lookout Sandstone to right, next few tenths of a mile.
1.8
64.15 Road bends to left. Cleary Coal Member of the Menefee Formation underlies the covered area at 9:00 and is visible to a small degree in the lowest part of the near cliffs.
0.85
65.0 Becenti Bros. ranch road on left.
1.4
66.4 Roadcut in Cleary Coal Member.
2.2
68.6 Bluffs from 12:00 to 2:00 are sandstones in the middle barren portion of the Menefee Formation and are immediately overlying the Cleary Coal Member. This zone of lenticular sandstone bodies occurs in this position with varying degrees of development within the Menefee throughout the region.
0.75
69.35 Road turnoff to right; Heart Rock visible in middle distance at 3:00. For the next several miles the road traverses the monotonous middle barren portion of the Menefee Formation consisting of alternating lenticular sandstones and drab shales.
1.5
70.85 Bridge.
4.55
75.4 Seven Lakes oil field. Oil was discovered in 1911 at 300 to 400 ft in the Mesaverde Group; by 1950, more than 50 tests had been drilled, but only a few achieved commercial production (fig. 24).
0.55
75.95 Road junction; *turn left* toward Chaco Canyon National Monument on unpaved NM-57.
0.4
76.35 Cattleguard.
1.15
77.5 Sandstones in middle Menefee.
3.85
81.35 Cattleguard.
1.85
83.2 Cattleguard.
1.45
84.65 Panorama. In the distance Chacra tongue of Cliff House Sandstone can be seen from about 1:00 to 3:00 on the skyline, with Fajada (girdled or banded) Butte capped by Chacra standing isolated to the left of the main escarpment.
0.25
84.9 Roadcut. Carbonaceous material in the Menefee visible as we slowly traverse the section into the upper transgressive coal-bearing sequence (in the Menefee) occurring immediately beneath the Chacra tongue.
3.3
88.2 Cattleguard.
1.7
89.9 Cattleguard.
1.35
91.25 Cattleguard.
1.15
92.4 Cattleguard; road bends to right.
1.35
93.75 Fajada Butte 7:00.
0.9
94.65 **STOP 3. Chaco Canyon National Monument** Cattleguard. Chacra tongue sandstone caps Fajada Butte, 9:00 to **11:00,** with upper part of upper Menefee coal zone at the base of the cliff.

The major stratigraphic units exposed in the

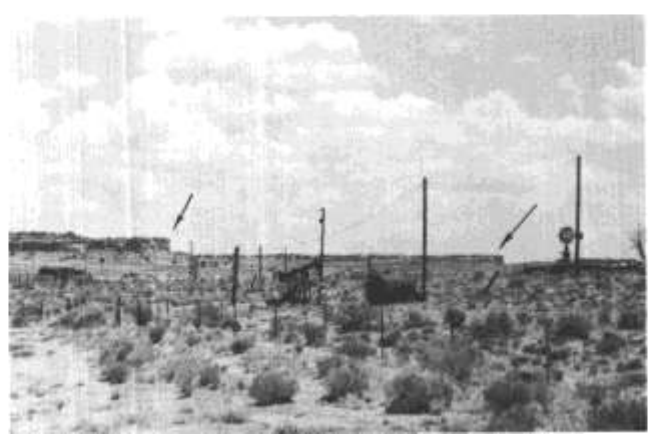


FIGURE 24-View OF SEVEN LAKES OIL FIELD. Cliffs in background (arrows) are sandstones in Menefee Formation above the Cleary Coal Member (reference mileage 75.4).

Chaco Canyon area are illustrated in figs. 25a and 25b. A stop will be made at the fossil localities 15 and 16 of Siemers and King (1974; see fig. 25b) to discuss the general stratigraphy of the area and observe the strata and fossils exposed there.

At Chaco Canyon the Cliff House Sandstone varies in thickness from about 85 to 94 m (280-310 ft). Locally as much as 50 m (165 ft) of the uppermost part of the Menefee Formation is well exposed beneath the Cliff House. North of the canyon the Lewis Shale forms a broad, soil-covered slope (fig. 25a), but on the mesas just south of the canyon the Lewis and upper few meters of the Cliff House have been removed by erosion.

Along most of the south-facing scarps of West Mesa, South Mesa, and Chacra Mesa the Cliff House Sandstone consists of a sequence of thick, cliff-forming sandstone units and slope-forming sandy shale and shaly sandstone units. At Chaco Canyon three subunits of the Cliff House Sandstone (hereafter referred to as the lower, middle, and upper units) are generally well defined throughout the canyon and along Chacra Mesa (fig. 25a). These units show relatively little lithologic variation along depositional strike; however, there is considerable variation (especially in the middle unit) at right angles to the depositional strike.

The lower and upper sandstone units are everywhere cliff formers. The lower unit forms a cliff 20-30 m (65-100 ft) high which dominates the view from within the canyon. This unit is composed of friable, orange-weathering, very fine grained, generally well-sorted sandstone which displays low-angle (less than 10°) cross stratification. Large, brown-weathering, oblate-spheroidal, calcite-cemented sandstone concretions (fig. 25d) and a few thin calcite-cemented sandstone beds are locally abundant. Such conspicuous beds and concretions are the most fossiliferous parts of the Cliff House Sandstone. Except for the upper 10 m, the upper cliff-forming unit is similar to the lower one. The top 10 m of the upper unit is an extremely friable, light-colored (almost white), moderately high-angle cross-stratified sandstone that is slightly coarser grained and better sorted than underlying sandstones of the upper unit.

On the north side of the canyon, the middle unit contains numerous beds of soft sandy shale and clayey sandstone and siltstone. These are interbedded with resistant sandstones which are similar to those in the lower unit. Because of the non-resistant character of the shaly beds, the middle unit generally forms a slope between the lower and upper cliffs (fig. 25a). Toward the south there is a profound facies change within the middle unit. At the southernmost exposures, along the south-facing West Mesa, South Mesa, and Chacra Mesa scarps, the middle unit is an interval of thin, light-colored, high-angle cross-stratified lenses of sandstone, and interbedded sandy carbonaceous shale and lignite. Thus, to the north the middle unit resembles the Lewis Shale, and to the south it resembles the Menefee Formation, illustrating the laterally intertongued relationship of those two units with the Cliff House Sandstone.

The lower Menefee-Cliff House contact is generally conformable and commonly sharp, and is usually placed just above the highest lignite seam or carbonaceous shale bed and near the base of the lower cliff-forming, orange-weathering sandstone. The contact of the middle and upper units of Cliff House Sandstone is similar to that of the lower unit with Menefee Formation.

The underlying Menefee Formation exposed at Chaco Canyon is characterized by lenses of light-colored, friable, fine-grained to very fine grained, moderately well sorted sandstone with moderately high angle (15-20°) cross strata. These are interbedded with carbonaceous shale, weathered lignite and thin low-grade coal seams. Orange-red clayey sandstone beds, which result from burned out coal seams, are locally abundant in the Menefee, although not particularly common in the main section of the Chaco Canyon National Monument area.

Sandstones in all of the units, including the Menefee, consist of about 65-70 percent sand-size and silt-size framework grains and 30-35 percent void space, matrix, and cementing material. The framework is commonly composed of 55-65 percent quartz, 25-40 percent rock fragments and 5-10 percent feldspar. Rock fragments are predominantly chert and other sedimentary rock types (especially shaly siltstone and silty claystone and shale). A few volcanic fragments are also always present. Significantly, transported dolomite rhombs are commonly quite abundant (to 15% of all framework grains) in the cliff-forming Cliff House Sandstone units, but apparently are absent in the Menefee sandstones and in the upper light-colored sandstone of the upper unit.

Matrix and/or cementing material is mainly iron oxide and iron-stained clay, but there is some silica and calcite cement. Calcite is especially abundant in the large concretions. Clays are mainly authigenic kaolinite but also occasionally include abundant illite, Ca-montmorillonite and mixed layer illite-montmorillonite. Pore space comprises much of the non-framework portion of the sandstones. Porosities usually range from 25 to 30 percent (over 25 samples were analyzed by Core Lab, Denver).

The Lewis Shale is very poorly exposed in the study area. Where observed it consists of sandy and silty shale which contains isolated calcareous concretions. Clay minerals in the Lewis Shale are predominantly Na-montmorillonite but also contain some illite and mixed layer illite-montmorillonite and a little kaolinite.

The exceptionally well exposed strata of the Cliff House Sandstone in the Chaco Canyon National Monument area are profusely fossil-

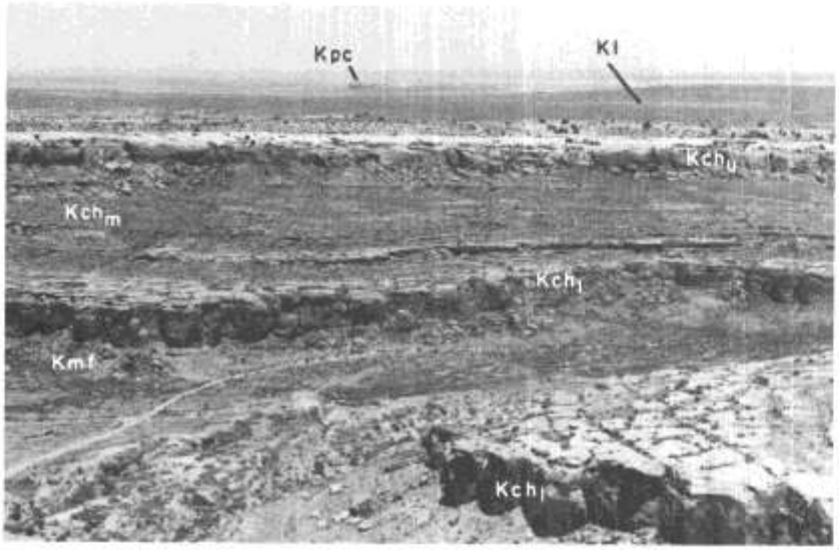


FIGURE 25a—Low-angle oblique airphoto of stratigraphic units along north side of Chaco Canyon (SW¼ sec. 17, T. 21 N., R. 10 W., view northwest). Cliff House Sandstone is subdivided into lower cliff-forming sandstone unit (Kch_l), middle slope-forming sandstone and shale unit (Kch_m), and upper cliff-forming sandstone unit (Kch_u). Upper unit also includes the light-colored, irregular cliff- and slope-forming sandstone above the upper cliff and is overlain by the poorly exposed, soil-covered Lewis Shale (Kl). The Pictured Cliffs Sandstone (Kpc) is visible in the distance. The upper few meters of the Menefee Formation (Kmf) are exposed below the lower cliff. Canyon floor is underlain by Holocene alluvium.

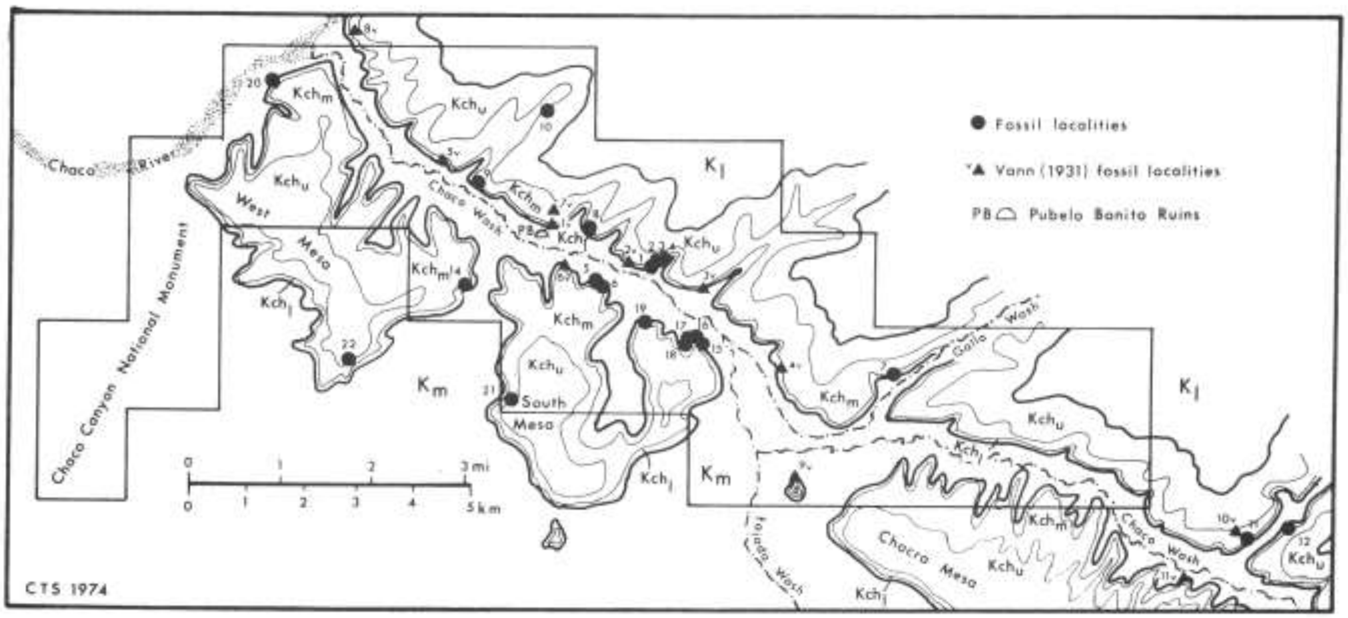


FIGURE 25b—Geologic map and fossil localities in Chaco Canyon (from Siemers and King, 1974).

FIGURE 25c—Accumulation of whole, articulated *Inoceramus* shells in friable sandstone at fossil locality 15 (fig. 25b of Siemers and King, 1974).

FIGURE 25d—Slightly ferruginous, calcite-cemented sandstone concretions at top of lower, cliff-forming sandstone at fossil locality 16 (fig. 25b of Siemers and King, 1974).

iferous, containing a diverse macroinvertebrate fauna and abundant trace fossils. Four distinct fossil assemblages were recognized by Siemers and King (1974). Assemblages 1 (fig. 25c) and 4 (fig. 25d) can be observed at fossil localities 16 and 15, respectively (fig. 25b). The significance of the assemblages will be discussed in the field.

The overall Menefee-Cliff House-Lewis sequence is a transgressive one; however, the main body of the Cliff House Sandstone in Chaco Canyon represents deposition during a near standstill of the strandline. Rapid accumulation of marginal marine sediments was keeping pace with basin subsidence. Minor regressions occurred when sediment accumulation exceeded subsidence and minor transgressions occurred when subsidence exceeded sediment accumulation.

Of significance to the understanding of the overall sedimentary environment for the sequence in question is the interpretation of the Menefee Formation. Beaumont, Shomaker and Kottlowski (1971) interpreted the upper coal-bearing part of the Menefee to be a result of "lagoonal or paludal" deposition occurring contemporaneously with Cliff House sand deposition and offshore Lewis Shale deposition. Fluvial and deltaic conditions prevailed landward from the coastal lagoons. According to their (Beaumont, Shomaker and Kottlowski, 1971) strati-dynamic model, there is a direct relationship between the rate of migration of a shoreline and the attendant environments of deposition. Thickest coal deposits occur during near stillstands of the shoreline; such deposits would not be developed during rapid shifts of the shoreline. Stagnant, poorly drained swamps behind an island barrier would accumulate organic debris; such environments would be prohibitive to most faunal elements and thus explain the lack of any trace of faunal biogenic activity (body fossils and/or trace fossils) in upper Menefee deposits. Two characteristics of the Menefee are difficult to explain by the lagoonal model: 1) the absence of brackish-water fauna so characteristic of modern coastal lagoons, and 2) the presence of well-developed channel sandstone bodies in the upper part of the Menefee. Another significant feature is the presence of several fresh-water gastropod genera, but the total lack of brackish-water mollusks (especially bivalves) in the Cliff House fauna. Perhaps a model of delta deposition could better explain the Menefee Formation. More study, however, is needed before such characteristics can be adequately explained.

The Cliff House Sandstone probably represents, for the most part, deposition in the lower to upper shoreface zone of a barrier island beach front. Lower, middle and upper shoreface environments are represented respectively by: 1) very fine grained silty and clayey bioturbated sand (especially common in the middle slope-forming unit), 2) moderately low-angle trough cross-stratified, fine-grained sand with less abundant, but well-developed, burrows (mostly *Ophiomorpha),* and 3) sub-parallel stratified, fine-grained to medium-grained sand containing locally abundant shell accumulations (assemblage 1). The coarsening upward trend is typical for such shoreface deposits. The lower shoreface facies may grade laterally and/or vertically into Lewis Shale type deposits; such transitional zones contain assemblage 2 accumulations. Shifting tidal channels, laterally adjacent to the barrier islands along depositional strike, are represented by the *Inoceramus-filled* troughs.

The Cliff House lithosome overlies, is laterally adjacent to, and intertongues to the south with the Menefee lithosome. The main body of the Lewis lithosome lies to the north. Cliff House Sandstone deposition in the Chaco Canyon area ended when subsidence overcame sediment accumulation, the shoreline migrated to the south, and offshore marine sediments of the Lewis Shale accumulated above the Cliff House.

0.75

95.4 Road junction; road to right leads to Visitors' Center. *Continue straight ahead.*

0.3

95.7 Excellent exposure of upper part of Menefee and overlying Chacra tongue. Immediately below massive sandstone note thin sandstone laminae oriented on forest slope. Point bar type deposition visible in the Menefee sand at midslope.

2.9

98.6 Note ruins on either side of road.

0.2

98.8 *Cross* Chaco Wash; narrow bridge.

0.1

98.9 Stop sign. *Turn left.*

0.25

99.15 Pueblo del Arroyo.

0.25

99.4 Massive Chacra tongue sandstone forms spectacular cliffs to right of road.

0.2

99.6 Kin Kletso on right.

0.2

99.8 Chacra sandstone talus is burying Kin Kletso. Note oblique shear plane in Chacra across wash. 0.25

100.05 Sharp turn to left.

0.2

100.25 Casa Chiquita; *sharp turn to right;* ascend hill through Chacra. Chacra sandstone in this locality is about 300 ft thick (Siemers and King, 1975). The thickness of the Chacra sandstone attests to the long period during which the shoreline oscillated in this area.

1.55

101.8 *Sharp turn to left.*

0.05

101.85 *Turn to right.*

0.25

102.1 Road junction and information sign near the top of the Chacra sandstone. Mesa at 3:00 capped by the Pictured Cliffs Sandstone. Interval between the road and the base of the Pictured Cliffs is occupied by the Lewis Shale.

0.25

102.35 Cattleguard; boundary of Chaco Canyon National Monument.
0.85

103.2 Road junction, *continue straight ahead.* Burn in distant valley at 2:00 is associated with Fruitland Formation in Kimbeto Wash.
0.15

103.35 Narrow bridge across Escavada Wash; roadcut at south end of bridge is in Pictured Cliffs Sandstone. "Red dog" (also erroneously called scoria) is the closest thing to a satisfactory road-surfacing material that can be found in this region.
0.55

103.9 Road junction.
0.7

104.6 Road in Fruitland Formation. Fruitland prospecting permits in this area belong to Ark Land Co. (Arch Minerals Corp.).
0.6

105.2 Cattleguard. Outcrops of Fruitland Formation among scattered sand dunes. *Be ready to turn off road in about 0.3 miles.*
0.3

105.5 *Pull off on dirt tracks that angle to right* of the main road into the Fruitland exposed area. Fairly good exposures of Fruitland coal, baked and unbaked shale, and sandstone to the right. Fruitland coal is burned throughout this region.
0.2

105.7 **STOP 4. Escavada Wash.** Coals and shales of Fruitland Formation (fig. 26). *Turn around. Return to main road.*
0.2

105.9 *Re-enter main road; turn right.*
0.85

106.75 Road traversing covered uppermost part of the Fruitland or the lowermost part of the Kirtland Shale.
3.45

110.2 Road junction; *continue straight ahead on NM-57.* Road to right leads to Kimbeto; Kimbeto Wash visible to right of road. Note abundant sand dunes on lee side of wash.
0.75

FIGURE 26—Basal Fruitland Formation badlands, partly burned, near Kimbeto Wash at Stop 4 (reference mileage 105.7).

110.95 Dark shale of the Kirtland Shale exposed to left of road.
2.1

113.05 Sandstones with ferruginous caps in Kirtland Shale.
2.45

115.5 Road junction; *bear left; go across cattleguard and bear hard left on road that is not "red dogged."* Road traverses sand deposits on Kirtland Shale in a westerly direction for the first couple of miles, then bears off to the southwest toward the outcrop area of the Fruitland Formation.
2.15

117.65 Cattleguard; *slow,* trough.
0.8

118.45 Hosta Butte visible on skyline at 10:00.
0.3

118.75 Chacra sandstone forms the linear mesas in the middle ground from 9:00 to 10:00. Vista at 3:00 of the badlands topography in the Kirtland Shale.
0.3

119.05 Shiprock at 1:00 in distance, approximately 60 mi to the northwest.
2.85

121.9 Cattleguard.
2.4

124.3 Black Lake Ranch area. The Fruitland Formation containing thick coals underlies the sand-and soil-covered flat. Eastern Associated Coal Co. has a 3-section lease drilled in 1975; in spring and summer of 1976 the adjoining preferential lease-right application area was drilled by Eastern Associated Coal Co. in a cooperative arrangement with the U.S. Bureau of Land Management and the U.S. Geological Survey.
0.95

125.25 Black Lake Ranch Headquarters at 9:00.
0.75

126.0 Fruitland outcrops in this area obscured by a rather thick mantle of sandy soil; dark-gray and light-gray banded shales in low hill from 1:30 to 2:00 are outcrops of Kirtland Shale.
0.4

126.4 Small butte at 11:00 capped by Pictured Cliffs Sandstone, as is the broader hill to the left of the butte.
0.2

126.6 Flat area to the left of the road is Black Lake!
0.95

127.55 Cattleguard.
0.35

127.9 Outcrop of Fruitland coal visible on hillside about half a mile in the distance at 2:00.
0.25

128.15 Pictured Cliffs Sandstone visible to right of road; road descends through Pictured Cliffs.
0.35

128.5 Butte across valley at 11:00 capped by Pictured Cliffs underlain by Lewis Shale (fig. 27).
0.2

128.7 Outcrop of Pictured Cliffs at 3:00.
0.45

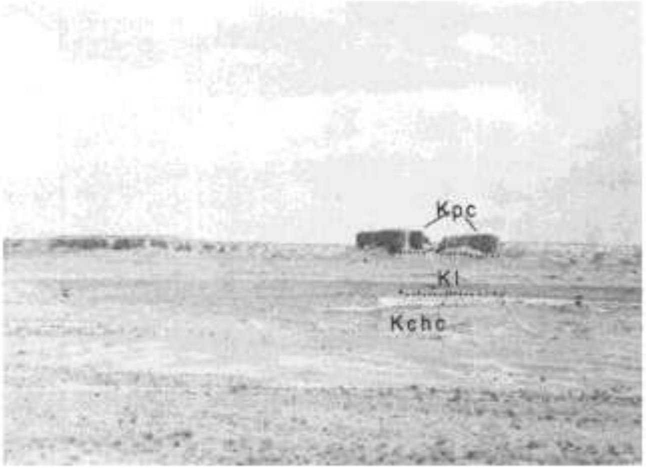


FIGURE 27—Small buttes of Pictured Cliffs Sandstone (Kpc). Lewis Shale (Kl) and upper transitional sandstones of the Chacra tongue of the Cliff House Sandstone (Kchc) are below (reference mileage 128.5).

129.15 Burned Fruitland Formation visible 1:30 to 2:30 in hillside above thin Pictured Cliffs Sandstone.
0.35
129.5 Sandstones in valley from 10:30 to 11:00 are Chacra sandstone below the Lewis Shale.
0.45
129.95 Lewis Shale in this area is quite thin; the entire sequence, measuring over 2,000 ft thick 30 miles to the north, is contained between a sandstone butte and the exposures in the valley at 9:30.
0.35
130.3 Transition between the Lewis and the Pictured Cliffs clearly visible at 3:00 in the low cliffs.
1.35
131.65 Road junction; *continue straight ahead.*
0.25
131.9 Good view of Chacra sandstone in water gap at 9:30.
0.3
132.2 Road junction; *bear left.*
2.2
134.4 Road descends through Chacra sandstone in Tsaya Canyon. Clinkered shale in canyon walls from 9:30 to 10:30 is in the upper coal zone of the Menefee Formation. At 3:00 is the pinchout of part of a coal seam beneath Chacra sandstone (fig. 28). Examine this after visiting major coal outcrop.
0.2
134.6 Tsaya Trading Post of yesteryear with old coal mine beneath the cliffs behind the trading post; the coal is very sandy.
0.4
135.0 At 9:00 to the left of the Mission School coal are outcrops in the upper Menefee coal zone.
0.1
135.1 **STOP 5. Tsaya Canyon.** This drainage is cut northeast-southwest, or perpendicular to the regional late Cretaceous shoreline trend (northwest-southwest), affording an excellent opportunity to study landward-seaward facies changes associated with San Juan Basin coals. Depart vehicle opposite road to mine. Note

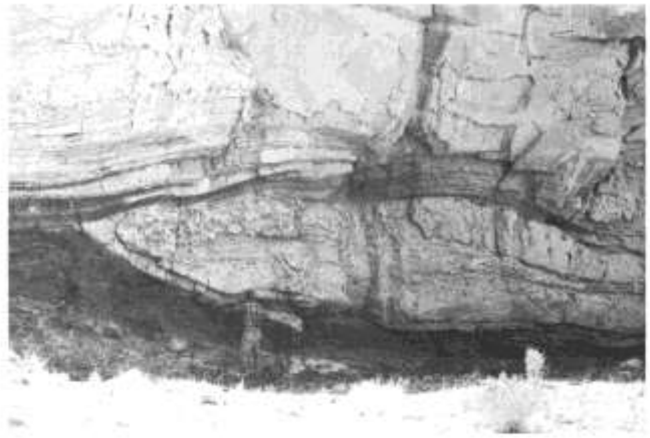


FIGURE 28—The end of a coal bed. Menefee Formation coal pinches out into the Chacra tongue of the Cliff House Sandstone (stop 5, reference mileage 134.4).

faulted upper Menefee coal in roadcut on east side of road, and walk to mine to view upper Menefee coal overlain by transgressive Chacra sandstone (fig. 29). Return to vehicle and as you drive "seaward" (northeast) back up canyon to the coal pinchout passed at mileage **134.4,** try to trace coal (or baked shale) along the way. Leave vehicle opposite pinchout and examine coal and associated sediments.

At the mine coal is about 6 ft thick and relatively clean. At southwestern edge of pinch-out exposure, less than a mile seaward, coal may be observed to split into two thin beds of sandy to detrital coal. The lower of these coal beds grade further seaward into coaly sandstone; upper bed is cut out entirely by overlying Chacra sandstone.

Here is a seaward gradation from clean, in situ coal through sandy coal and detrital coal, to coaly sandstone. The in situ coal is interpreted to be a coastal swamp deposit. The sandy coal could have developed where storm washover or wind brought sand from the beach into the seaward parts of the swamp. The detrital coal and coaly sandstone observed here may be explained in a number of ways, two of which are: **1)** erosion by streams of in situ coastal-swamp or

FIGURE 29—Portal of Tsaya or La Vida mine. In an uppermost Menefee Formation coal (stop 5, reference mileage 135.1).

floor-basin peat, transport to shorezone, and redeposition offshore to later produce detrital coal and coaly sandstone, or 2) erosion by waves of in situ coastal-swamp peat, after storm scour had exposed it at beach, followed by redeposition offshore to produce detrital coal and coaly sandstone. The latter may better explain the specific sequence seen at the pinchout (fig. 30).

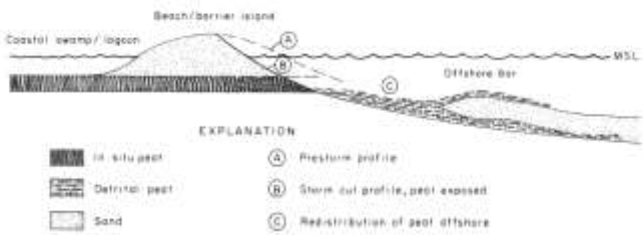


FIGURE 30—INTERPRETIVE CROSS SECTION ILLUSTRATING POSSIBLE ORIGIN OF DETRITAL COAL AND COAL PINCHOUT IN TSAYA CANYON. In situ peat at left now present at La Vida mine; offshore bar at right now present at coal pinchout (stop 5, reference mileage 134.4).

Another interesting feature here is the character of the Chacra sandstone. Although generally transgressive, Chacra sandstone beds immediately overlying the Menefee coal at pinchout suggest, in ascending order: deposition in shoreface, beach, and coastal dune environments (Kottlowski, 1971). Such a sequence is clearly regressive or progradational (fig. 31a). Its presence in an otherwise transgressive unit may be explained in at least two ways: 1) a minor regression within overall transgression; initial transgressive record was poorly preserved owing to rapid shoreline migration or subsequent erosion; or 2) transgression of Late Cretaceous seas normally progressed by steps, each involving a landward advance of the shoreline followed by a period of stillstand accompanied by seaward progradation of shorezone deposits (under conditions of abundant sediment supply), the long term net result being transgression (fig. 31b). *Retrace route out of canyon.*

3.0

138.1 Road junction; *continue straight ahead.*

0.6

138.7 Road junction; *continue straight ahead.*

0.5

139.2 Cattleguard.

1.0

140.2 Crossroads. *Continue straight ahead.* Road to left leads to Dog Eye Pond.

0.8

141.0 Road traversing lower part of Fruitland. Note burned areas.

0.3

141.3 Fruitland Formation well exposed in badlands to left of road.

2.2

143.5 Road junction; road to right (San Juan County Hwy. 8) leads to Split Lip Flats.

0.55

144.05 Cattleguard.

0.15

144.2 *Cross* Denatzin Wash.

0.65

144.85 At 9:00 on skyline is a "peninsula" of Fruitland

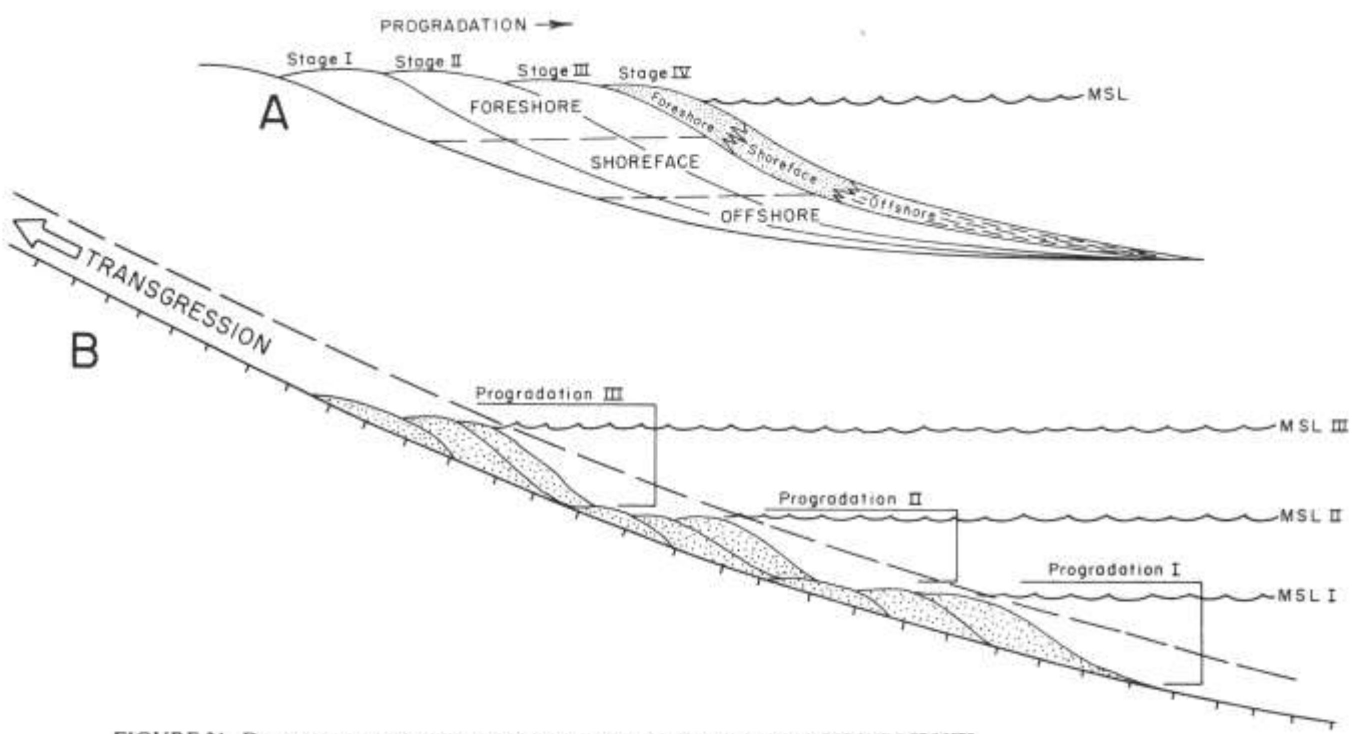


FIGURE 31—DIAGRAMMATIC CROSS SECTIONS SHOWING DEVELOPMENT OF SHOREZONE DEPOSITS.

A—Ascending sequence of offshore-shoreface-foreshore sediments generated under conditions of regression or progradation (modified from Harms, 1975, fig. 5-2).

B—Net transgression of shoreline made up of several individual advances followed by stillstand and progradation of shorezone deposits.

capping the hill and underlain by thin Pictured Cliffs Sandstone and thin Lewis Shale. Chuska Mountains, Tertiary-capped remnant of earlier landscape, on skyline from 10:30 to 12:00; Beautiful Mountain, an outlier of Chuska Range, at **11:00;** Bennett Peak in the distance below the skyline to the left of Beautiful Mountain. Road is in sand-covered Fruitland Formation. Coal in this area is under lease to Western Coal Co., a joint subsidiary of Public Service Company of New Mexico and Tucson Gas and Electric. Lease known informally as the Bisti lease.
2.2

147.05 Road junction to left; *continue straight ahead.* Road goes 4 mi west to El Paso Natural Gas Company's White Rock compressor station and points south.
0.1

147.15 Panorama of well-exposed Fruitland badland; position of coals clearly marked by burn zones. In this area are at least 5 coal beds with some economic potential. This area was drilled in 1961 in a reconnaissance manner. With the aid of the excellent exposures, the intricacies of the coal bed relationships presumably have been determined, although admittedly more drilling is needed.
1.15

148.3 **STOP 6. Bisti.** Badlands carved from lower Fruitland shales, sandstones and coal.
0.1

148.4 Roadcut in Bed 5.
1.05

149.45 *Cross* Hunter Wash.
0.1

149.55 Burned out remains of Bisti Trading Post to right of road. To west, pits were dug to Fruitland coal (fig. 32).
0.3

149.85 Road rises into upper part of Fruitland Formation.
0.55

150.4 The barren shales can probably be placed in the lower part of the Kirtland Shale. The road is paralleling the eastern boundary of the Navajo Reservation, which in this area is also the eastern boundary of the 40,287-acre El Paso Natural Gas Co. and Consolidation Coal Co. coal lease, the proposed site for two large gasification units. This lease is estimated to contain 709 million tons of recoverable coal to the 150-ft overburden surface. The fence on the left marks the Navajo Reservation boundary.
2.10

FIGURE 32—FRUITLAND FORMATION COAL BED EXPOSED IN PIT IN FLOOR OF VALLEY OF HUNTER WASH. About 1.6 mi west of Bisti (reference mileage near 149.55).

152.5 Area of sand dunes blanketing Kirtland Shale.
0.85

153.35 Road junction; *continue straight ahead.* Road to right leads to Huerfano.
0.75

154.1 Outcrops of Kirtland Shale from 10:00 to 11:00.
0.75

154.85 Cattleguard. Road is crossing from Kirtland Shale into overlying Ojo Alamo Sandstone (Cretaceous-Tertiary).
8.9

163.75 Pump jacks and tanks from 2:00 to 4:00 are at the west end of the Bisti oil field. Oil from this field is produced from the Gallup Sandstone (Upper Cretaceous) by an elaborate tertiary flood system.
0.4

164.15 Cattleguard.
0.3

164.45 Outcrops of Nacimiento Formation (Tertiary) in badlands on right of road.
1.5

165.95 Concrete pad in the roadway covers a pipeline. Nearly all of the material used in the construction of the Four Corners Power Plant was transported overland at tremendous cost from the Santa Fe's main line west of Grants. These pads date from that episode.
0.35

166.3 Road junction; *turn right.*
1.05

167.35 Cattleguard. Highline at 12:00 is 345 kilovolt line carrying power from the Four Corners Power Plant to Albuquerque.
1.25

168.6 *Cross under* power line.
0.7

171.4 Junction with paved road; *turn left onto NM-371.*
2.2

173.6 Road to right to Navajo Indian Irrigation Project. *Continue straight ahead.*
3.8

177.4 Hogback Mountain formed by the Cliff House Sandstone visible at 9:30; Shiprock in the background. Four Corners Power Plant at 10:00.
4.65

182.05 Road is in the Ojo Alamo. Panoramic view, using main microwave towers as 12:00, as follows: on the left, bluffs of Farmington Sandstone Member in the middle ground; behind the Farmington Sandstone or in the distance at about 10:30 is the San Juan Generating Station belonging to Public Service Company of New Mexico and Tucson Gas and Electric. At 11:00 to 12:00 is Mesa Verde, site of many cliff dwellings, in southwestern Colorado. This is the type loca-

lity of the Mesaverde Group (in the geologic literature Mesa Verde is spelled "Mesaverde"); the Cliff House Sandstone caps the mesas. Farmington, New Mexico is visible at 1:00.
1.25

183.3 Road descends in a series of curves through the Ojo Alamo Sandstone. Note the thin band of purplish shales assigned to the McDermott Formation. In canyons to east Ojo Alamo can be seen to interfinger with overlying Nacimiento Formation.
0.65

183.95 In the roadcuts, pebble bands and lenses may be seen underlying the massive sandstones which are in turn underlain by the purplish, volcanic-derived McDermott Formation.
0.55

184.5 Top of Twin Peaks capped with high level San Juan terrace gravels.
1.35

185.85 *Cross San Juan River.*
0.3

186.15 Road junction; city limits of Farmington. END OF 2ND DAY ROAD LOG.

3rd Day Road Log

Farmington Area

RESUME

The third-day log begins at the west edge of Farmington and follows the valley of the San Juan River westward to the outcrop of the Fruitland Formation near the western rim of the San Juan Basin. The **first stop is at the San Juan mine** of Western Coal Company, where the Fruitland coal can be seen in detail. The route then continues westward and downsection through the Pictured Cliffs Sandstone, the Lewis Shale, and the Mesaverde Group, to the Hogback monocline which forms the steeply upturned rim of the Central Basin as recognized by Kelley (1951). The **second stop** is in the **Hogback, where the** Point Lookout Sandstone, the Menefee Formation, and the Cliff House Sandstone are magnificently displayed in cross section.

From the Hogback, the route is retraced to Fruitland, then turns south where it crosses the San Juan River to **STOP 3,** the **Navajo mine,** on the Navajo Reservation. From the mine, the route returns to Farmington.

GEOLOGIC ROAD LOG

Mileage

000.00 **STARTING POINT** at west "Y" in Farmington, junction of Broadway and Main, *heading west* on US-550. Ojo Alamo Sandstone across river at 8:00. Farmington is located at the confluence of the Animas and San Juan Rivers; the La Plata River flows into the San Juan just west of town-thus the Navajo name, Totah (three waters). The town is built on a series of well-developed river terraces as well as on the floodplain.

0.6

0.6 At 1:00 to 3:00 is the airport terrace, one of several terrace levels ranging from a few feet to several hundred feet above the present river level. These features are actually outwash terraces, traceable to late Pleistocene moraines in the San Juan Mountains, Colorado (Richmond, 1965). Although only 3 terraces have been recognized along the La Plata River, 6 distinct terrace levels have been identified along both the Animas and San Juan Rivers (Pastuszak, 1968; Bandoian, 1969). The gravels generally range from 10 to 30 ft in thickness and consist of a variety of igneous, metamorphic, and sedimentary rock types. Because of the abundance of well-rounded, siliceous, metasedimentary clasts, these gravels are among the hardest and best in the state. Several commercial gravel operations are active in the area.

0.75

1.35 Junction of West Main and Apache.

0.4

1.75 Farmington Sandstone and Kirtland Shale visible in cliffs along the north side of San Juan River at 11:00.

0.1

1.85 *Cross La Plata River.* Farmington Sandstone, in this area 460 ft thick, is a medial member of the Kirtland Shale and is visible on both sides of the river. The Farmington is generally weakly cemented and does not form particularly prominent cliffs as does the Ojo Alamo.

2.65

4.5 Farmington Sandstone visible capping bluffs on south side of the river from 9:00 to 11:00.

0.5

5.0 Hogback Mountain, Four Corners Power Plant visible from 11:00 to 12:00. Massive sandstone that forms the backbone of Hogback Mountain is a tongue of Cliff House Sandstone (equivalent to the La Ventana Tongue) which pinches out northward and is probably responsible for the termination of Hogback Mountain to the north. Present on the back-slope, or east side of the Hogback, is a tongue of Menefee Formation about 200 ft thick containing several coal beds, one of which is about 21 ft and another about 10 ft thick.

1.7

6.7 Approximately opposite the erosional edge of the Farmington Sandstone (9:00); the interval below it, exposed for several miles along the bluffs, is the lower Kirtland Shale.

1.3

8.0 The north end of the Navajo open pit mine is coming into view at 11:00 on the skyline, to the right of the power plant.

0.5

8.5 Junction of NM-40. Road to left leads to the village of Kirtland; the road to the right leads to the El Paso Natural Gas sweetening plant. Note flare on hill. Throughout this region the contact between the Kirtland and the underlying Fruitland Formation is not distinct. The Fruitland tends to contain more sandstone along with the coal.

1.5

10.0 At 12:00 the north extension of the Great Hogback is visible with the Cliff House Sandstone forming the skyline.

0.7

10.7 Highway crosses approximate contact between the Fruitland and the Kirtland. Note carbonaceous shale along ditch bank to the right.

0.5

11.2 Coal sloughed beneath the terrace gravels in old mine area. This coal is on fire in places; smoke and steam are often visible during the winter months.

0.1

11.3 Note Pictured Cliffs Sandstone on south side of river, also beneath us.

0.2

11.5 Road rises on Pictured Cliffs very near the contact with the overlying Fruitland Formation.

0.7

12.2 Primitive tipple at 3:00. Fruitland coal originally mined by underground methods here despite thin roof overlain by unconsolidated terrace gravels. Reportedly shut down due to hazardous conditions. Recently purchased and converted to strip mine by new owner, but frequent fires and presence of old collapse-filled drifts make this venture marginal even as a two-man operation. Coal is sold locally for domestic-heating use.

0.2

12.4 Pictured Cliffs Sandstone in roadcut on right side of road very near the type locality of the Pictured Cliffs Sandstone. The Pictured Cliffs in this area is 200 to 250 ft thick with a rather thick transition zone with the underlying Lewis Shale. The massive sandstone in the cliffs to the right of the road is the site of the petroglyphs from which the formation derived its name. Some intertonguing between the Pictured Cliffs and the overlying Fruitland occurs at this locale, with a thin coal bed lying beneath a typical Pictured Cliffs Sandstone at the top of the bluffs. Probably this lower coal bed on the north side of the river is the lowest and one of the principal coal beds mined in the Navajo mine south of the river. Road skirts the Pictured Cliffs for the next 1.25 mi.

0.75

13.15 Shiprock is visible at 11:00 through the gap in the Hogback.

0.5

13.65 Road junction; road to San Juan Generating Station. *Turn right.*

0.3

13.95 Lewis Shale with numerous concretionary layers prominently displayed to the left of the highway.

0.55

14.5 The road is traversing the nebulous transition zone between the Lewis and the Pictured Cliffs. 0.5

15.0 San Juan mine visible to the right of the road.

0.4

15.4 San Juan Generating Station visible at 12:00.

0.45

15.85 At 3:00 construction area about half a mile in distance is site where new dragline will be erected.

0.55

16.4 Road junction. *Turn right;* road marked San Juan mine, Utah International, and Western Coal Co. San Juan Generating Station to north (fig. 33). Twin Peaks visible in distance and fairly good panorama of the San Juan mine; note the increasing dip of the formations to the north as the strata become involved in the northeast-trending Hogback monocline.

0.3

16.7 **STOP 1. San Juan mine.** Office of Western Coal Co. Western Coal Co. personnel will lead our tour of San Juan mine from this point; road log mileage will resume here after mine tour. The tour will include a stop on the rim of the upper river terrace at the south edge of the mine. Panoramic view from the range-pole used by the New Mexico Coal Surfacemining Commission for periodic inspection photographs of the San Juan mine; stacks of San Juan Generating Station at 12:00. From 9:00 to 10:00 on the skyline, the irregular, scalloped ridge of Cliff House Sandstone forming east slope of the Hogback; about 10:00, the Pictured Cliffs Sandstone and Lewis Shale dipping 3 or 4 degrees to the east; from 1:30 to 2:00, Mesaverde Formation; from 1:00 to 1:30, the Cliff House Sandstone in the Hogback dipping down from Mesaverde Formation into the San Juan Basin; about 1:30, thin sandstones in the Fruitland dipping 6 or 8 degrees to the southeast; about 12:00, between the terrace and the power plant, the top of the Pictured Cliffs Sandstone, and the base of the Fruitland Formation (marked by clinkered shale); at 1:00, strip pits visible in foreground with reclaimed sites beyond; from the strip pits around to 3:00, vast expanses of Kirtland Shale with the Ojo Alamo capping the mesa in the distance; about 7:00, the Four Corners Power Plant; at 7:30, Hogback Mountain with the massive Cliff House Sandstone (La Ventana Sandstone Tongue?), and about 9:00, Shiprock visible to the left of the Cliff House over the top of the terrace. "Red-dog" area in the foreground at 12:00 produces material used as road metal. Ash disposal in strip pit can be seen at the base of the gravel terrace at 12:00. The San Juan mine is in the southern part of the Fruitland coal field and is the field's only producing operation. Aside from a small strippable area just north of the mine, the remainder of the field tips too steeply for conventional surface mining. The Fruitland field includes the Fruitland Formation coal from the San Juan River northward and northeastward to the New Mexico-Colorado State line, about 25 mi. Several minable coal seams occur in most areas in the Fruitland Formation in this field. The "main bed" in the southern part, being mined by Western Coal Co., averages about 16 ft thick. In the northern area near the Colorado line, one of the thicker seams has a maximum thickness of 50 ft. Coal on the Western Coal Company's lease is high-volatile C and B bituminous. The average of many analyses, on an as-received basis, is:

Moisture	10.7%	Ash	15.0%
Volatile matter	35.8%	Fixed carbon	38.1%
Sulfur	0.86%	Btu/lb	10,200

FIGURE 33—SAN JUAN GENERATING STATION, UNITS 1 AND 2 (reference mileage near 16.4).

Reserves of strippable coal beneath overburden of less than 250 ft are estimated at 158 million tons. Most of these strippable reserves are within the San Juan mine lease area. See table 2, p. 6 for further operational data.

Retrace route to US-550.

0.3

17.0 Road junction; *turn left on pavement.*

0.75

17.75 Dam for raw water storage visible off to right of road about 0.25 mi.

0.2

17.95 Four Corners Power Plant, 12:00; Hogback Mountain, 1:00.

0.85

18.8 Pictured Cliffs Sandstone cropping out beneath terrace gravels from 9:00 to 11:00 (fig. 34).

0.9

19.7 Stop sign; junction with US-550; *turn right.*

0.7

20.4 *Descend* from lowest terrace level to San Juan floodplain.

0.3

20.7 *Cross* Shumway Arroyo.

2.6

23.3 Cliff House Sandstone dipping toward us (east) at 12:00.

1.1

24.4 Turquoise Bar on right.

0.5

24.9 Cliff House Sandstone, about 650 ft thick at this locality, is underlain by the upper carbonaceous and coaly zone of the Menefee Formation. The middle part of the Menefee Formation is barren (fig. 35). Lower sandy and coal-bearing zone in the Menefee overlies the Point Lookout Sandstone forming the prominent ridge on the west. Dirt road leads to numerous small coal mines in the lower part of the Menefee to the north (figs. 36 and 37).

0.9

25.8 **STOP 2. Hogback.** *Pull off road and park* (as construction permits). Climb to crest of Point Lookout Sandstone for breathtaking view of excellent exposures of Mesaverde Group at Hogback as well as the San Juan River terraces (fig. 38). While on ridge observe upward transition from shoreface, through beach, to dune depositional environments preserved in uppermost Point Lookout Sandstone. This sequence and overlying coals of lower Menefee Formation attest to regressive character of the lower part of the Mesaverde deposits.

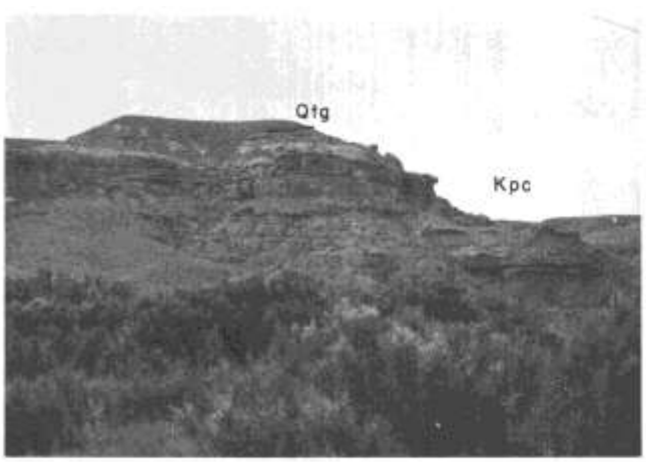


FIGURE 34—VIEW EAST AT EXPOSURE OF LEWIS SHALE (Kl). Overlying units are Pictured Cliffs Sandstone (Kpc) capped by terrace gravels (Qtg); at western edge of type locality of Pictured Cliffs. Note gradational nature of Lewis-Pictured Cliffs contact (reference mileage 18.8).

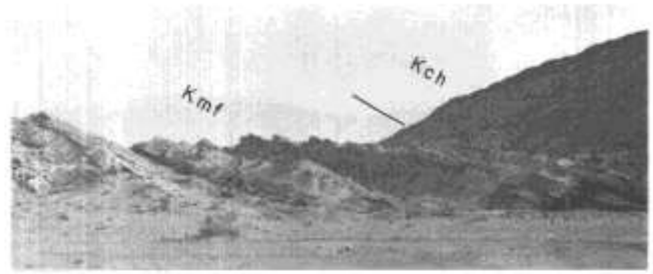


FIGURE 35—VIEW NORTH AT MIDSECTION OF THE HOGBACK. Low cuestas are Menefee Formation (Kmf); bulk of ridge on right is lower part of Cliff House Sandstone (Kch) (reference mileage 24.9).

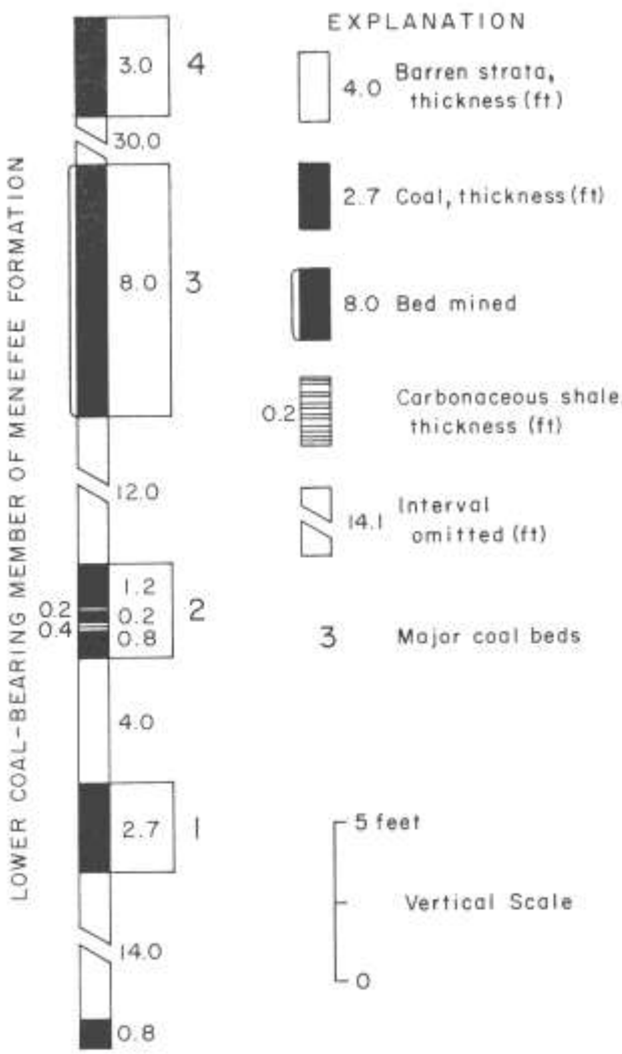


FIGURE 36—SECTION AT HOGBACK NO. 2 MINE SHOWING THICKEST COAL ACCUMULATION NEAR STOP 2. Modified from Hayes and Zapp, 1955, sheet 2. Mine is shown in fig. 37.

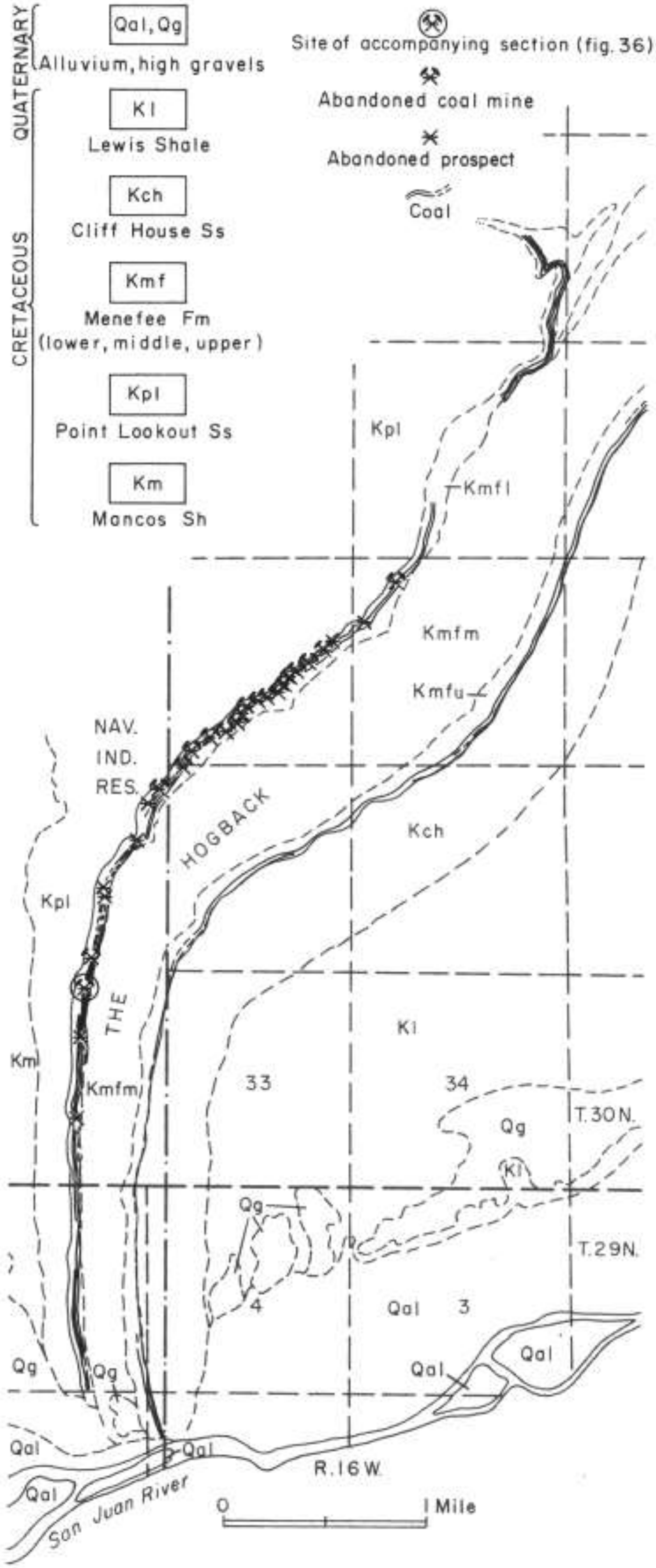


FIGURE 37—GEOLOGIC MAP OF HOGBACK IN VICINITY OF STOP 2. Coal beds and former mines are in lower part of Menefee Formation. Modified from Hayes and Zapp, 1955, sheet 1.

FIGURE 38-VIEW SOUTH AT CONTINUATION OF HOGBACK ACROSS SAN JUAN RIVER. Note truncation and development of high terrace on strata of the Mesaverde Group (reference mileage 25.8).

Next, walk down the dip slope of Point Lookout to lower Menefee coals exposed along dirt road that roughly follows Point Lookout-Menefee contact.

Note that middle barren part of Menefee consists predominantly of mudstones alternating with sandstone bodies that are discontinuous along strike. These record fluvial deposition that may have occurred on the coastal plain. *Turn around,* retrace route eastward along U.S. 550.

1.4 (more or less)

27.2 Turquoise Bar on left.

6.7

33.9 Pumping station from San Juan River for San Juan Generating Station and mine.

0.2

34.1 Intersection; *swing half right* onto *NM-489.*

0.95

35.05 *Cross* creek.

0.35

35.40 Enter village of Fruitland; road intersection; *turn right on county road 82.*

0.4

35.8 *Cross* San Juan River on sloping, narrow bridge.

0.05

35.85 You are now on the Navajo Indian Reservation; alcoholic beverages are prohibited. Coals and shales of Fruitland Formation are revealed in a roadcut along the river terrace at 10:00.

0.2

36.05 *Road swings sharply to right.*

0.2

36.25 *Sharp left turn.*

0.5

36.75 *Sharp right turn.* Northernmost reclaimed spoil piles visible at 9:00, after turn.

0.25

37.0 Thin coal in the Fruitland in the roadcut at 9:00.

0.3

37.3 Pictured Cliffs Sandstone visible in roadcut on left. Contact between Pictured Cliffs and Fruitland in the roadcut.

0.3

37.6 Good view of reclaimed spoil from 9:00 to 12:00. Compare configuration and lushness of vegetation between the recently reclaimed spoils to the left and the unmined area to the right of the road. Pictured Cliffs Sandstone visible in scattered outcrops to right of highway.

0.85

38.45 Road follows the contact between the Pictured Cliffs and the Fruitland.

1.05

39.5 Road is in the Fruitland Formation. Morgan Lake (2:00) is a manmade lake that supplies water to the cooling system for the Four Corners Power Plant.

0.3

39.8 Hogback Mountain visible behind Four Corners Power Plant. Two smaller stacks at the right of Four Corners Power Plant belong to units 1, 2, and 3; two larger stacks belong to units 4 and 5.

1.45

41.25 Mine haul road; stop sign. *Cross with extreme caution.*

0.7

41.95 STOP 3. Navajo mine. Utah International Navajo mine office. Utah International personnel will lead our tour of Navajo mine from this point; road log mileage will resume here after mine tour.

Retrace route.

0.7

42.65 *Cross mine haulage road with caution.* Causeway across the east flank of Morgan Lake.

2.4

45.05 San Juan Generating Station at 11:00; Mesa Verde on skyline in the distance behind the plant.

1.55

46.6 *Sharp right turn,* descend into Pictured Cliffs.

0.25

46.85 Coal visible at the Pictured Cliffs-Fruitland contact at about 1:00 in the cut at the north end of the mine area.

0.25

47.1 *Sharp left turn.*

0.5

47.6 *Sharp right turn.*

0.25

47.85 Sharp left turn.

0.2

48.05 *Cross* San Juan River, the Boundary of Navajo Reservation.

0.4

48.45 Stop sign; road junction; *continue around island; turn half left.*

0.8

49.25 Note oil well at 9:00.

0.05

49.3 *Turn right and enter* US-550 eastbound along the margin of floodplain and *ascend* to the first terrace level.

2.05

51.35 Road junction at 550 Cafe and Conoco station.

2.85

54.2 Road ascends hill onto the top of the Farmington Sandstone. Greenish cast of the upper part of the Kirtland and the Farmington has led to speculation regarding the presence of volcanic debris in these units.

2.5

56.7 Crest of hill; airport on Airport terrace level visible at 11:00. Farmington Sandstone outcrops visible in the flanks of the terrace.

0.95
57.65 La Plata road junction, NM-17. *Continue straight ahead.*
0.1
57.75 *Cross* La Plata River.
1.8
59.55 West "Y" traffic light; *turn left* onto Main Street.
0.15
59.7 Airport road, *turn left.*
0.15
59.85 *Cross* bridge over Farmington Glade.
0.15
60.0 Stop sign, Apache Street; *continue straight ahead.*
0.25
60.25 Ascend through Farmington Sandstone Member which is capped with terrace gravels.
0.15
60.4 Municipal Drive; *turn left.*
0.1
60.5 Navajo Street; *turn left.* Ascend through cut in Farmington Sandstone Member and terrace deposits.
0.7
61.2 Farmington Municipal Airport. END OF 3RD DAY ROAD LOG.

Contributed Papers

CRETACEOUS ROCKS IN THE AREA OF MADRID COAL FIELD, NEW MEXICO

by George 0. Bachman, *U.S. Geological Survey, Denver*

The Madrid coal field, about 33 km south of Santa Fe, New Mexico (fig. 1), is preserved in a structural basin that has been disrupted by the Cerrillos and Ortiz intrusive masses. The basin is a faulted, asymmetrical syncline whose axis strikes generally north-south. The central portion of the basin is filled by Tertiary sedimentary and volcanic rocks that rest unconformably on the Cretaceous coal-bearing sequence.

The western margin of the structural basin is situated on the eastern margin of the Rio Grande depression. Rocks of Triassic and Jurassic age are exposed in north-trending hogbacks along this margin. In the hogback area the Dakota Sandstone rests on the Morrison Formation (Jurassic) and marks the base of the Cretaceous sequence.

The Madrid coal field is about midway between the Raton and San Juan Basins; the Cretaceous rocks exposed in the vicinity of Madrid are significant in the study of regional correlations between the two basins. Unfortunately, much of the stratigraphic section is shaly and poorly exposed. Variable dips, together with faulting and poor exposures, contribute to the problem of accurately measuring and describing these rocks. The characteristics of the Cretaceous rocks in the vicinity of Madrid are shown in fig. 2.

DAKOTA SANDSTONE

In northern and central New Mexico the Dakota Sandstone commonly includes three rock units: a ledge-forming sandstone at the base, carbonaceous shale in the middle portion, and sandstone at the top. In the vicinity of Madrid the Dakota is typical in its threefold division, but in detail these divisions are somewhat more complex: the basal sandstone locally contains granule conglomerate and reworked sediments from the underlying Morrison Formation. Although a hiatus appears at the base of the Dakota, this reworking is intricate; at places the lithologies of the Dakota and Morrison Formation interfinger.

The sandstone beds in the Dakota are generally medium grained, yellowish brown, cross laminated, and form prominent ledges. The middle shale beds are brown where sandy, and dark gray where carbonaceous. A layer of dark-brown concretions (as much as 60 cm in diameter) is present about 4.8 m above the base of the shale unit. The Dakota ranges from 24 to 40 m thick in the Madrid area.

MANCOS SHALE

The term Mancos Shale is used here, as in parts of the San Juan Basin, as a formation to include all strata between the Dakota Sandstone and the overlying Mesaverde Formation. However, in a limited area on the western side of the Madrid coal field, stratigraphic units within the Mancos are well exposed and map-

FIGURE 1—INDEX MAP SHOWING LOCATION OF MADRID COAL FIELD AND SURROUNDING GEOGRAPHIC FEATURES.

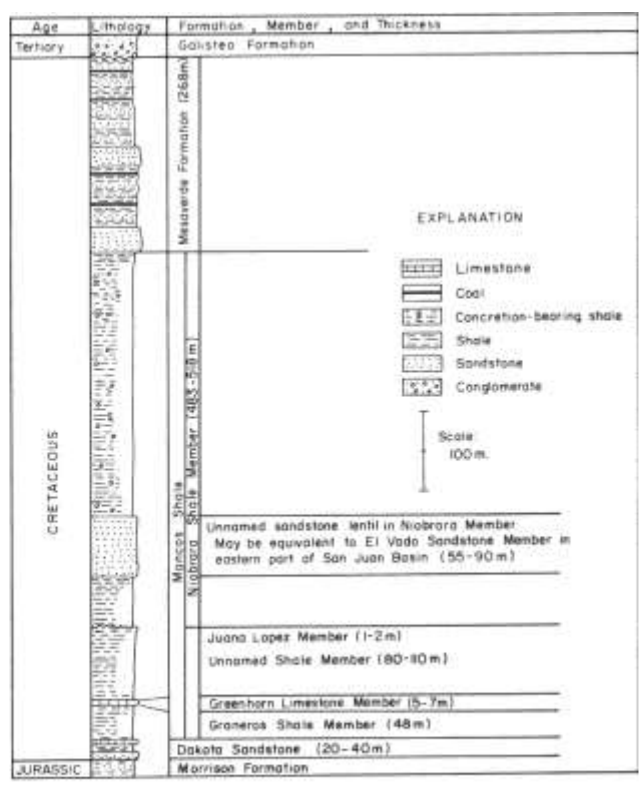


FIGURE 2—GENERALIZED COLUMNAR SECTION SHOWING LITHOLOGY OF CRETACEOUS ROCKS IN VICINITY OF MADRID, NEW MEXICO.

pable. Nomenclature of these units is derived from both the San Juan and Raton Basins and they are included as members of the Mancos.

GRANEROS SHALE MEMBER—The Graneros Shale Member, 48 m thick, rests conformably and in gradational contact with the Dakota Sandstone. The basal 5 m of the member consists of interbedded sandstone and shale. The sandstone beds resemble some beds in the Dakota and are yellowish brown, medium grained, well sorted, and consist mainly of quartz. The upper part of the member is silty to sandy, medium gray and thin bedded.

GREENHORN LIMESTONE MEMBER—The Greenhorn Member consists of medium- to light-gray, fine-grained, argillaceous limestone and interbedded medium- to dark-gray calcareous shale. Bedding is thin and platy throughout the member. A layer of bentonite about 2 cm thick was noted 3.7 m above the base at one locality. The member ranges from 5 to 7 m thick.

UNNAMED SHALE MEMBER—The unnamed shale member overlies the Greenhorn Member and underlies the Niobrara Member. In the Madrid coal field the upper contact of the unnamed shale member is more easily determined than in the San Juan Basin in northwestern New Mexico. Within the Madrid area the distinctive Juana Lopez Member marks the top of rocks of Carlile age and the "younger Carlile rocks of the east and south sides of the San Juan Basin are missing" (Dane and others, 1966, p. 10).

In the Madrid area the unnamed shale member consists of poorly exposed medium-gray to dark-gray sandy shale and some thin beds of yellowish-brown siltstone. Scattered yellowish-brown sideritic concretions as much as 60 cm in diameter are present. Poor exposures prevent precise measurement of this interval, but it appears to be about 80 to 110 m thick.

JUANA LOPEZ MEMBER—The type locality for the Juana Lopez Member is about 8 km northwest of the town of Madrid in the Mesita de Juana Lopez Grant (sec. 32, T. 15 N., R. 7 E.). The member was named by Rankin (1944); a reference locality was established in the eastern part of the San Juan Basin by Dane and others (1966). Northwest of Madrid the member is well exposed, consisting of fetid bioclastic limestone 1-2 m thick. The limestone is medium gray to yellowish brown with individual beds 2-4 cm thick. At the reference locality on the east side of the San Juan Basin, the Juana Lopez Member is 28 m thick (Dane and others, 1966, p. 10-12).

NIOBRARA MEMBER—Overlying the Juana Lopez Member disconformably in the Madrid area, the Niobrara Member consists of three parts: a basal medium-gray shale about 73 m thick; a sandstone lentil that ranges from 55 to 90 m thick; and an upper concretion-bearing shale about 355 m thick.

The basal shale is medium gray and thinly bedded. The sandstone lentil is light yellowish gray, argillaceous, fine grained and well sorted. Individual beds are thin and average about one centimeter thick. In the vicinity of Madrid the lentil thickens southward; it is 55 m thick north of Galisteo Creek and thickens to 90 m about 8 km south of Galisteo Creek. In the Hagan coal basin the thickness is 72 m. This sandstone lentil may be equivalent to the El Vado Sandstone Member of the Mancos Shale in the northeastern part of the San Juan Basin where the El Vado is 26 m thick (Landis and Dane, 1967, p. 8-9). This correlation is based on lithology and stratigraphic position.

The upper concretion-bearing shale is moderately well to poorly exposed, but the large yellowish-brown concretions that weather from this interval are distinctive markers on the landscape. Many *of* these concretions are more than 60 cm in diameter. Where observed, the shale is medium to dark gray and yellowish brown. The ammonites *Clioscaphites vermiformis* (Meek and Hayden) and *Placenticeras (Stantonoceras) syrtale* (Morton) were identified from this interval by W. A. Cobban of the U.S. Geological Survey (written communication, December 14, 1967). The thickness of 355 m for this interval in the Madrid area is comparable with the thickness of 320 m estimated for this interval on the eastern side of the San Juan Basin (Landis and Dane, 1967, p. 9).

MESAVERDE FORMATION

The Mesaverde Formation, well exposed in the vicinity of Madrid, is the coal-bearing unit in this area. It includes yellowish-brown to yellowish-gray, coarse- to medium-grained sandstone, yellowish-gray sandy to carbonaceous shale, and coal.

The sandstone beds range from thin interbeds in shale to thick ledges. About 3 km northwest of Madrid a prominent sequence of sandstone beds marks the base of the Mesaverde and rests with apparent conformity on the Niobrara Member of the Mancos Shale west of Miller Gulch. The sandstone beds form a series of prominent ledges and cliffs about 35 m thick that strike north-south, generally parallel to Miller Gulch. In the Hagan Basin southwest of Madrid, Stearns (1953) recognized a sandstone within the Niobrara Member as a basal tongue of the Mesaverde. He named this the Cano Member (Stearns, 1953, p. 971) and believed that it wedged out toward the Madrid and Omera coal fields where the Cano is absent.

Above the basal sandstone is a sequence of thin sandstone beds, sandy and carbonaceous shale, and coal. These beds are about 85 m thick and are well exposed in the Miller Gulch drainage.

Overlying these beds in Miller Gulch is a second sequence of ledge-forming sandstones 23 m thick that forms the divide between Miller Gulch and Waldo Gulch. Waldo Gulch is a second strike valley that has cut into a coal-bearing sequence of shale, sandy shale, and thin beds of sandstone overlying the sandstone ledges. This coal-bearing sequence is about 125 m thick and is exposed nearly to the top of the prominent ridge east of Waldo Gulch where the Galisteo Formation rests on the Mesaverde with a pronounced erosional unconformity.

Erosion cut a deep and irregular surface into the Mesaverde Formation between Cretaceous time and deposition of the overlying Galisteo Formation of Eocene and Oligocene(?) time (Stearns, 1943). Consequently, the preserved thickness of the Mesaverde varies greatly in the Madrid area. Northwest of Madrid, in the vicinity of Miller and Waldo Gulches, the Mesaverde is 268 m thick. Near the old Omera mine workings, about 17 km southeast of Madrid, the thickness may not be over 30 m. Sandstone beds in the Galisteo Formation at many places east of Madrid and north of the Omera mine resemble some beds in the Mesaverde and may reflect reworking of Cretaceous sands into the Galisteo.

The coal beds that were mined near the town of Madrid since the early part of the century (Lee and Knowlton, 1917, p. 206) are overlain by a Tertiary monzonitic sill that has altered the lower grade coal to anthracite at many places. This sill is related to the Ortiz Mountain intrusive mass; recent work by H. H. Mehnert of the U.S. Geological Survey on K-Ar dating of the Ortiz intrusive indicates that it is about 34.0 ± 2.2 m.y. (H. H. Mehnert, written communication, April 5, 1976).

AVAILABILITY OF GROUND WATER FOR COAL DEVELOPMENT IN SAN JUAN BASIN, NEW MEXICO

by

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William J. Stone, *Hydrogeologist, New Mexico Bureau of Mines & Mineral Resources*

INTRODUCTION

Large reserves of coal occur in the San Juan Basin of northwestern New Mexico, but water is required to develop this resource. Water is needed for washing coal, reclamation, boiler feed, cooling, and other general uses. Water will also be required as a process fluid in the proposed gasification plants. Although surface water is used in present operations, virtually all of the surface water in northwestern New Mexico has been appropriated, the largest single claimant being the Navajo Tribe for their irrigation project south of Farmington. Thus, water for future industrial or municipal use must be either ground water or negotiated surface water. According to average annual water uses in the San Juan River Basin (Cooper and Trauger, 1967), ground water accounts for only 0.45 percent of all water used. Ground water has been previously ignored for several reasons: surface water is readily available, ground water is often deep and saline, and little is known of the occurrence and availability of suitable supplies.

in July of 1972, the New Mexico Bureau of Mines & Mineral Resources undertook a study of ground-water supplies in the San Juan Basin to determine the availability of ground water for coal surface-mining. The initial project was supported in part by a grant from the New Mexico Water Resources Research Institute, and by contributions from El Paso Natural Gas Company, Peabody Coal Company, and Western Coal Company.

Except for minor participation in well planning and aquifer testing for two of the industrial participants, the study has to date consisted mostly of gathering basic data. The study is presently continuing as a cooperative effort of the New Mexico Bureau of Mines & Mineral Resources and the U.S. Geological Survey; in 1974 the scope was expanded beyond the original proposal. Details of the broader project and preliminary results have been summarized by Stone and Kelly (1975) and Stone (1976).

Although the project area includes the entire San Juan Basin, this paper deals with only two of several areas in which strippable coal is known to exist. Area 1 includes the area of strippable coal in the Fruitland Formation; Area 2 covers strippable coal in the Menefee and Crevasse Canyon Formations (fig. 1). These specific areas were chosen because development there is expected to be large; Area 1 alone may reach 30-40 million t/yr. Development of Fruitland coals is already under way north of Area 1 and should move into Area 1 within the next decade. Area 2 is the next most attractive target for coal stripping; its development should follow soon after that of Area 1.

Sources of Information

Data on potential ground-water supplies have been derived almost entirely from oil and gas well logs and drill-stem tests. Few wells have been drilled through all of the major potential aquifers; thus, the information available is inadequate for an accurate appraisal. Only four water wells, for example, have actually tested the Westwater Canyon Member of the Morrison Formation, probably the principal aquifer available to coal operations; only one water test has penetrated the underlying Entrada Sandstone.

Published data were relied upon for information regarding the shallowest aquifers presently tapped by wells. These sources include Cooley and others (1969), Cooper and John (1968), Davis and others (1963), Kister and Hatchett (1963), and McGavock and others (1966). Some information on deeper aquifers is from Berry (1959).

Much of the testing in deeper aquifers has been done by companies. Because the details of their tests remain proprietary, they can be used only to shape general statements for publication.

Regional Setting

The physiography, climate, geology, and coal resources of the San Juan Basin are summarized in the introduction of this guidebook. For greater detail on the geology and strippable low-sulfur coal resources of the San Juan Basin, see Shomaker and others (1971). For the general stratigraphic framework, see the table inside the back cover and the regional stratigraphic cross section of the San Juan Basin (road log fig. 16, p. 20).

Declaration of San Juan Water Basin

Because of growing interest in ground-water resources in northwestern New Mexico, due to increasing pressure on surface water supplies, the State En-

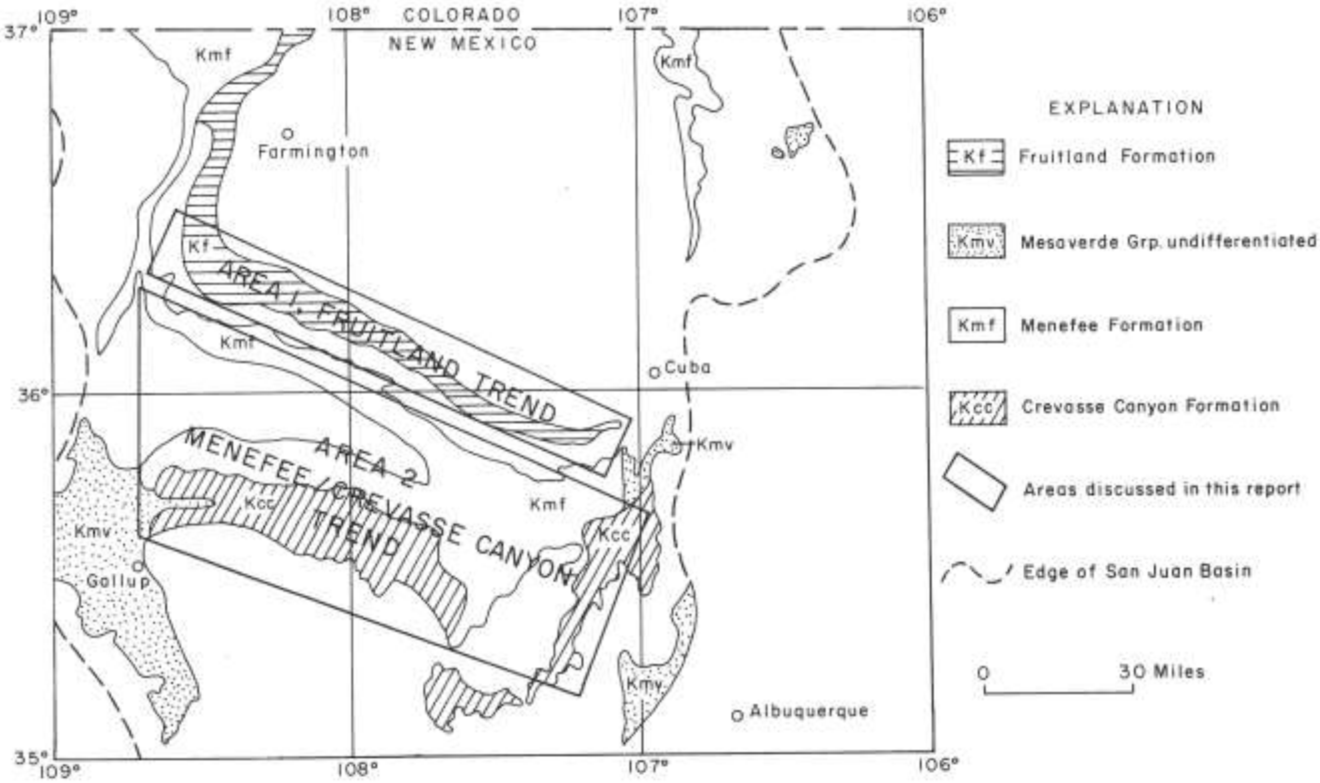

FIGURE 1—LOCATION OF STRIPPABLE LOW-SULFUR COAL IN NEW MEXICO PORTION OF SAN JUAN BASIN (SHOMAKER AND OTHERS, 1971) AND AREAS DISCUSSED IN THIS PAPER.

gineer issued Special Order 124 on July 29, 1976, declaring the San Juan Basin an underground water basin. The new basin covers about 10,000 sq mi and coincides with the New Mexico portion of the San Juan River drainage basin. It also essentially coincides with the New Mexico portion of the San Juan structural basin, the main exception being that the southwestern corner near Gallup (the Gallup sag) is not included in the declared water basin.

The purpose of declaring such basins is to protect existing surface water rights from impairment by groundwater development in areas not administered by the State Engineer. Once a basin is declared, groundwater development is carefully regulated. The significant ramifications of basin declaration and means of regulation include:

1) An application to appropriate ground water must be filed with State Engineer Office prior to drilling
2) Once application is approved, a public notice must be published
3) If the approved application is protested, hearings are conducted
4) If no protest is filed, drilling may proceed but only by a driller licensed by State Engineer
5) Well construction and completion must be carried out in accordance with State Engineer specifications
6) Driller must file a properly executed well record and log within 10 days of completion of the well
7) After the well is completed, applicant for appropriation must file a "Final Inspection and Report" accompanied by a plat properly locating well. Report must be prepared by a registered professional engineer or registered land surveyor
8) Upon receipt of "Final Report," State Engineer issues a "Certificate and License to Appropriate"
9) Owner of a water right within a declared basin cannot change location or use of a well without approval of State Engineer
10) Owner of a water right within a declared basin cannot modify, clean, or repair a well without a valid permit from State Engineer.

HYDROGEOLOGY OF AREA 1—FRUITLAND TREND

Beneath the Fruitland Formation in Area 1 are three stratigraphic units that yield water in significant quantity, thus are considered major potential aquifer. In descending order these units are: the Gallup Sandstone (where present), the Westwater Canyon Sandstone Member of the Morrison Formation, and the Entrada Sandstone (fig. 2). The Pictured Cliffs Sandstone, Cliff House Sandstone, Point Lookout Sandstone, and Dakota Sandstone yield some water and are considered minor potential aquifers. Other units at still greater depth have some potential, but none have been tested near Area 1; the depths involved are so great (in excess of 6,000 ft) that they are of little interest.

Major Potential Aquifers

GALLUP SANDSTONE—The Gallup Sandstone (Late Cretaceous) is developed as a permeable sandstone only beneath the western end of the Fruitland trend. North of a NW-SE line, crossing the trend obliquely in T. 22 N., R. 11 W. (fig. 3), the massive, permeable Gallup gives way to much less permeable argillaceous rocks; the Gallup can be considered an aquifer in Area 1 only west of R. 11 W.

The Gallup has been penetrated by many oil and gas

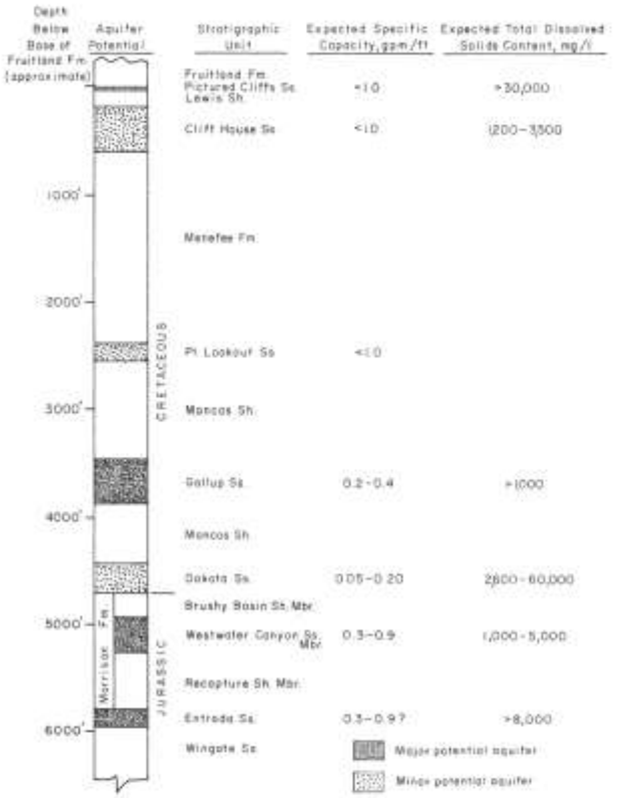

FIGURE 2—STRATIGRAPHIC COLUMN FOR AREA 1 SHOWING MAJOR AND MINOR POTENTIAL AQUIFERS AND THEIR EXPECTED CHARACTERISTICS.

tests in the vicinity, and is known to yield significant amounts of fresh water under artesian pressure. Three water wells, the El Paso Natural Gas Co. Burnham No. 1, the Apache 1 Foshay oil test (in which several zones including the Gallup have been tested for water yield), and the U.S. National Park Service "Fields" well at Chaco Canyon National Monument, have been tested for water production from the Gallup near the Fruitland trend. All are shown in fig. 3.

The thickness of permeable Gallup Sandstone in the three wells is as follows: E.P.N.G. Burnham No. 1, about 130 ft; Apache 1 Foshay, about 130 ft; and

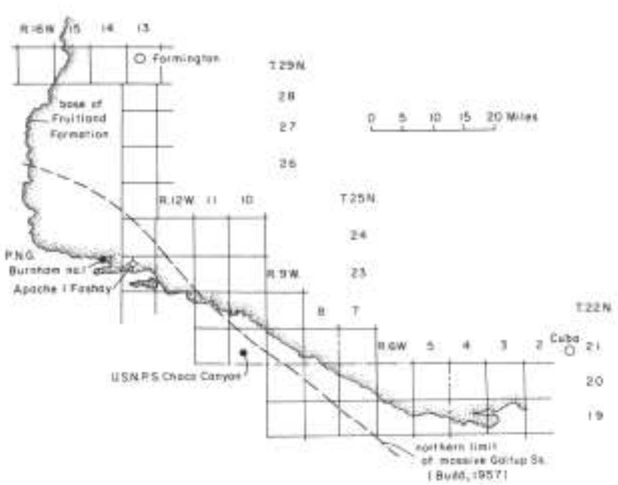

FIGURE 3—MAP SHOWING NORTHERN LIMIT OF WATER PRODUCTION FROM MASSIVE GALLUP SANDSTONE AND ITS RELATIONSHIP TO OUTCROP OF FRUITLAND FORMATION.

Chaco Canyon well, about 170 ft. The Chaco Canyon well is the only one completed in the Gallup; it reached the Gallup at 2,907 ft, and produces at a specific capacity of about 0.3 gpm/ft. Shut-in pressure was 176 psi, or 407 ft, just after the well was completed. Water quality is only fair, with total dissolved solids about 1,800 mg/1 (of which sulfate constitutes about 580 mg/1, chloride about 45 mg/ 1, and bicarbonate about 200 mg/1). At 0.3 gpm/ft, the well could probably be depended upon for a long term yield (pumping) of 300 gpm or more.

Transmissivity of the Gallup was calculated at about 900 gpd/ft. Wells closer to the Fruitland trend (hence closer to the limit of the massive Gallup sand development) would reflect somewhat lower transmissivity. Beyond the limit, the fine- to medium-grained, clean, fairly well sorted sandstones are replaced by interbedded thin sandstones and siltstones. These rocks would be expected to yield very poor quality water and have very low transmissivity.

WESTWATER CANYON SANDSTONE MEMBER—The Westwater Canyon Sandstone Member is the middle of three members generally present in the Morrison Formation (Jurassic). It is highly variable in composition, but in most areas consists of fine-grained sandstone in one to four massive beds. Near the west end of Area 1 the Westwater Canyon is found at a depth of about 5,000 ft below the base of the Fruitland, and consists of 180 to 220 ft of relatively permeable sandstone. Near the eastern end of the Fruitland trend, the Westwater Canyon is slightly shallower (about 4,600 ft below the base of the Fruitland) and consists of a number of sandstone beds separated by shales.

At present, only one well (El Paso Natural Gas Co. Burnham No. 1, SW 1/4 NW 1/4 sec. 3, T. 23 N., R. 14 W.) produces from the Westwater Canyon; one other well nearby (Apache 1 Foshay, SW 1/4 NW 1/4 sec. 9, T. 23 N., R. 13 W.) has been extensively tested for water supply potential in Area 1. The test results for these two wells are still considered proprietary.

A number of wells have been completed in the Westwater Canyon near the southern rim of the San Juan Basin; the electric log characteristics of the Westwater Canyon in these wells indicate similar water-bearing properties to those observed for this unit in the few deep oil and gas tests along the Fruitland trend. Wells in the Westwater Canyon in Area 1 will yield water of fair to poor quality, 1,000 to 5,000 mg/1 total dissolved solids; transmissivity will be in the range 2,000 to 3,000 gpd/ft. Specific capacity will probably be in the range 0.3 to 0.9 gpm/ft. The water is known to be under artesian pressure; in the western part of Area 1 a well completed in the Westwater Canyon can be expected to flow.

Because of the depth to the top of the formation, a great drawdown range is available; even at a specific capacity of 0.3 gpm/ft, pumping several hundred gpm should be possible.

ENTRADA SANDSTONE—The Ent: ada Sandstone (Jurassic) and the underlying Wingate Sandstone (Triassic) form an aquifer system probably carrying saline water along the Fruitland trend (fig. 2). The transmissivity of the unit is probably comparable to that of the Westwater Canyon. Depth to the top of the Entrada is about 5,800 ft below the base of the

Fruitland near the western end of Area 1, and about 6,000 ft near the eastern end.

Water in the Entrada can be expected to be saline, because of the presence of anhydrite and other readily soluble minerals in the overlying Todilto Limestone. One sample, near the western end of the Fruitland trend, had a total dissolved solids content of 15,021 mg/1, primarily constituted of sodium sulfate and chloride. Although several hundred gpm could be produced from the Entrada, the poor water quality is a strong deterrent to development.

Minor Potential Aquifers

PICTURED CLIFFS SANDSTONE—The Pictured Cliffs Sandstone (Late Cretaceous) is the next unit beneath the Fruitland Formation, and the first aquifer that would be disrupted by strip mining. The unit consists of fine-grained marine sandstone, ranging in thickness from 0 to 900 ft regionally but is quite thin in Area 1. Several water wells have been completed in the Pictured Cliffs along the Fruitland trend in San Juan County. Yields are generally low; quality is generally poor, deteriorating with distance from outcrop. Total dissolved solids values of 30,200 to 37,800 ppm (highly saline to brine) have been observed in San Juan County (Stone and Kelly, 1975). Wells near the outcrop produce small amounts of good quality water.

CLIFF HOUSE SANDSTONE—We include in this formation all the units of the Late Cretaceous transgressive sandstone zone between the continental Menefee Formation (beneath) and the marine Lewis Shale (above), namely, the main body of the Cliff House, the La Ventana Tongue, and the Chacra tongue (see fig. 16, p. 20).

The Cliff House consists primarily of irregularly bedded, fine-grained, argillaceous sandstone varying greatly in thickness. Near the western end of the Fruitland trend the Cliff House is about 360 ft thick. It is thinner to the east beneath the Fruitland outcrop, and breaks up into a zone of sandstones a few tens of feet thick.

The Cliff House yields water to a number of wells along the Fruitland trend. Specific capacities of Cliff House wells are generally low (less than 1 gpm/ ft); the shallowness of the aquifer precludes large capacity wells. Well performance is highly variable from place to place because of the great variation in thickness and character of the aquifer.

Water quality is generally marginal, with specific conductance commonly in the range 1,500 to 5,000 micromhos, and total solids contents of 1,200 to 3,500 mg/1. The waters are high in sodium and potassium, bicarbonate and sulfate, and moderately high with respect to chloride (often approaching 100 mg/1).

POINT LOOKOUT SANDSTONE—The Point Lookout Sandstone (Late Cretaceous) lies between the Menefee Formation above and the Mancos Shale below. In Area 1 no wells are known to produce from this unit, although it should be hydrologically similar to the Cliff House and Pictured Cliffs Sandstones, with small yields and, except near outcrops, poor quality.

DAKOTA SANDSTONE—The Dakota Sandstone, mostly of Late Cretaceous age, is a complex unit of lenticular, very poorly sorted sandstones, conglomerates, shales, and coal. The Dakota occurs about 4,500 ft below the Fruitland trend near the western end of the trend, and about 4,100 ft near the eastern end of the trend. The Dakota commonly consists of three or four principal sandstones, separated by relatively impermeable shale; the aggregate thickness of sandstone is generally about 120 ft.

No water wells have been completed in the Dakota, and no water-supply tests have been conducted along the Fruitland trend. Drill-stem test information indicates that the Dakota is saturated, and that artesian pressure is sufficient to cause flow at the surface in most areas along the trend. Transmissivity is very low; water quality is extremely variable but generally poor.

Eleven analyses of water taken from the Dakota during drill-stem testing along the Fruitland trend east of R. 10 W. indicate a range of total dissolved solids of 2,611 to 59,259 mg/ 1. The analyses are predominantly high in sodium chloride and bicarbonate.

Because of the variable makeup of the Dakota, reliable predictions of well yield along the Fruitland trend cannot be made. However, the apparent lower permeability of sandstones of the Dakota compared with other aquifers in the vicinity, and the large proportion of interbedded shale, seem to indicate that specific capacities of wells completed in the Dakota might be very low, perhaps 0.05 to 0.20 gpm/ft. This low specific capacity, coupled with the poor quality of water, makes the Dakota a minor target for water supplies.

HYDROGEOLOGY OF AREA 2— MENEFEE-CREVASSE CANYON TREND

Beneath the surface in Area 2 are four stratigraphic units that will yield significant amounts of water. In descending order these are the Dalton Sandstone Member and "stray" sandstone of the Crevasse Canyon Formation, the Gallup Sandstone, and the Westwater Canyon Sandstone Member of the Morrison Formation (fig. 4). The Dakota Sandstone is little used as a water supply owing to low yields and poor water quality and is considered only a minor potential aquifer for Area 2. Several deeper stratigraphic units are known to yield water elsewhere but little is known of their water-bearing characteristics in Area 2. These units include, in descending order, the Bluff Sandstone, the Summerville Formation, the Todilto Limestone, the Entrada Sandstone, the Wingate Sandstone (all Jurassic), several sandstone beds of the Chinle Formation (Triassic), the San Andres Limestone and Glorieta Sandstone (both Permian). Of these units, probably only the San Andres-Glorieta aquifer has real potential; it yields considerable water to wells south of I-40.

Major Potential Aquifers

DALTON SANDSTONE MEMBER—The Crevasse Canyon Formation (Late Cretaceous) constitutes the lower part of the Mesaverde Group and lies between the Gallup Sandstone (below) and the Point Lookout Sandstone (above). The Dalton Sandstone is the middle of three members recognized in the Crevasse Canyon in the southern part of the basin and overlies the Mulatto Tongue of the Mancos Shale. In outcrop the Dalton is generally clean, white to buff, massive sandstone, ranging in thickness from about 35 to 200 ft (Cooper and John, 1968). Near Crownpoint, electric logs show the

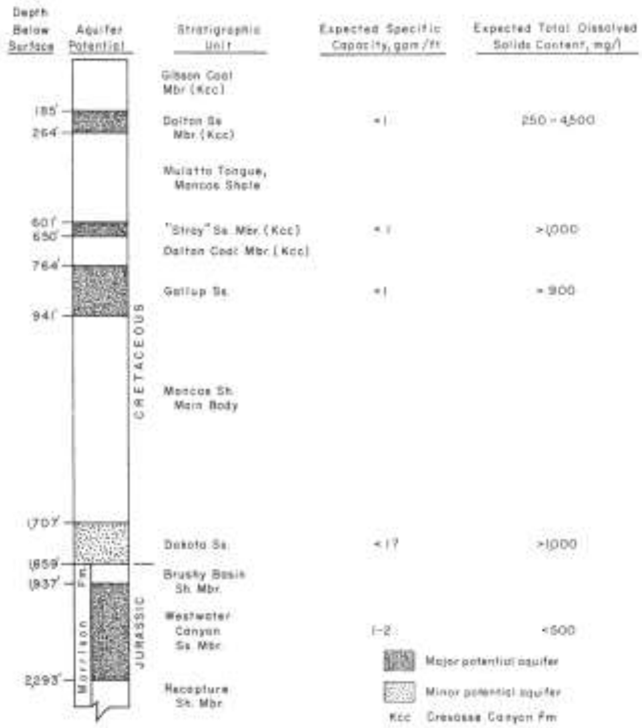

FIGURE 4—STRATIGRAPHIC COLUMN FOR AREA 2 SHOWING MAJOR AND MINOR POTENTIAL AQUIFERS AND THEIR EXPECTED CHARACTERISTICS.

Dalton to be mostly massive sandstone but with one or more shale interbeds, each a few feet in thickness. The thickness of resistive sandstone near Crownpoint averages 84 ft, ranging from 51 to 101 ft.

Several wells penetrate the Dalton in the Crownpoint area, but casing has been set through that interval. In a well at the Government Farm, the Dalton Sandstone was encountered between 50-118 ft below the surface. Water level during drilling (cable tools) of the Dalton interval reportedly stood at 45 ft, probably near a true static water level. In a well in sec. 35, T. 17 N., R. 11 W., the Dalton yielded 45 gpm with a drawdown of 70 ft below a static water level of 90 ft for a specific capacity of 0.64 gpm/ft.

Dalton waters are generally high in sulfate, sodium, and bicarbonate; quality deteriorates with distance from outcrop. Water from a well in sec. 20, T. 15 N., R. 6 W. had a dissolved solids content of 243 ppm, most of which was bicarbonate; a well in sec. 4, T. 14 N., R. 8 W. yielded water having a dissolved solids content of 4,470 ppm, including 2,880 ppm sulfate (Cooper and John, 1968, p. 34).

"STRAY" SANDSTONE—Below the Mulatto Tongue of the Mancos Shale but above the Dilco Coal Member of the Crevasse Canyon Formation, there is a massive sandstone unit known informally as the "stray" sandstone (Late Cretaceous). This unit varies greatly in thickness and is absent altogether in some areas near Crownpoint. In sec. 33, T. 17 N., R. 12 W. thickness is 11 ft; in sec. 20, T. 17 N., R. 12 W., 45 ft; and in sec. 24, T. 17 N., R. 13 W., slightly greater than 60 ft. The "stray" was encountered at a depth of 445 ft in a well in sec. 28, T. 17 N., R. 12 W. A bailing test of this well in 1968 yielded 15 gpm with a drawdown of about 50 ft from a static water level of 1 ft for a specific capacity of 0.3 gpm/ft. Quality of this water was poor with 980 ppm bicarbonate, 400 ppm sulfate, and 20 ppm chloride. Two wells drilled at Crownpoint in 1926 may have drawn water from the "stray" sandstone. The deeper of these produced 51 gpm from zones at depths of 525-576 ft, 666-680 ft, and 700-750 ft with a drawdown of 71 ft, from a static water level of 245 ft, for a specific capacity of 0.71 gpm/ft.

GALLUP SANDSTONE—The Gallup Sandstone (Late Cretaceous) is the basal unit of the Mesaverde Group; in Area 2 the Gallup occurs below the Dilco Coal Member of the Crevasse Canyon Formation but above the main body of the Mancos Shale. In the southern part of the basin, the Gallup consists of two sandstone units separated by about 90 ft of shale (a tongue of the Mancos Shale). In the vicinity of Crownpoint, a third sandstone is present, apparently equivalent to the Dilco Coal Member of the Crevasse Canyon Formation. The two lower sandstones are generally buff or light gray, fine grained and silty. The third or upper sandstone is pink, buff, or light gray, fine to medium grained with several thin shale beds and coarse-grained channel fillings locally. The lowermost unit ranges in thickness from a few feet to nearly 75 ft, the middle unit is 60-125 ft thick, and the uppermost bed is about 98 ft thick. In the Crownpoint area the three beds occur at a depth between 765 to 940 ft and have an average aquifer thickness of 103 ft, with values ranging from 54 to 167 ft.

A well in sec. 33, T. 17 N., R. 12 W. was tested at 50 gpm with unknown drawdown and at 7.5 gpm with about 17 ft of drawdown from a static water level of about 40 ft for a specific capacity of about 0.44 gpm/ft. Water in the Gallup is under artesian pressure and some wells flow at the surface. An old well in sec. 12, T. 17 N., R. 14 W. reportedly flowed 120 gpm when drilled. Total depth was 1,014 ft and production probably included the Gallup Sandstone, the "stray" sandstone, and possibly even the Dalton Sandstone.

The chemical quality of water from the Gallup in Area 2 is fair with reported dissolved solids contents ranging from 993 to 2,190 mg/1 (Cooper and John, 1968, table 3).

WESTWATER CANYON SANDSTONE MEMBER—The Westwater Canyon Sandstone is the middle of the 3 members generally recognized in the Morrison Formation (Jurassic) in the southern part of the basin and is the main unit bearing uranium ore in the Grants mineral region along the southern rim of the San Juan Basin.

The Westwater Canyon is a light-gray to pale-yellowish-brown, fine- to coarse-grained sandstone. The thickness of this unit ranges from 30 to 300 ft. Near Crownpoint the thickness of resistive sandstone in the Westwater Canyon ranges from 140 to 284 ft, averaging about 207 ft.

Two 24-hr aquifer tests conducted on this unit in the Crownpoint area indicate yields of 221 and 323 gpm with drawdowns of 195 and 201 ft from static water levels of 350 and 385 ft for specific capacities of 1.1 and 1.6, respectively. Transmissivities of 2,017 and 2,323 gpd/ft were calculated from these tests.

Water quality is generally good. The total dissolved solids content reported for water from a well in sec. 20,

T. 17 N., R. 12 W., was 447.4 mg/ 1, including 250 mg/1 bicarbonate, 118.8 mg/1 sodium, and 47.8 mg/1 sulfate.

Minor Potential Aquifers

DAKOTA SANDSTONE—The Dakota Sandstone, the basal Cretaceous unit in the San Juan Basin, occurs beneath the Mancos Shale but above the Morrison Formation (Jurassic). The Dakota occurs about 880-975 ft below the massive sandstone unit of the Gallup Sandstone, and consists of three fairly distinct beds totalling 85 to 105 ft of resistive sandstone. The Dakota is a buff to light-gray, medium-grained sandstone with lenses of coarse sandstone, conglomerate, and carbonaceous shale. Thickness of the Dakota ranges from about 50 to 150 ft in the southern part of the San Juan Basin.

The Dakota is little used as an aquifer because of low yields and poor water quality. Although commonly under artesian pressure, water seldom rises high enough to flow at the surface from the Dakota, due to its great depth.

DEEP UNITS—Known to yield water elsewhere, the following rock units have not been tested in Area 2. In descending order they are: Jurassic—Bluff Sandstone, Summerville Formation, Todilto Limestone, Entrada Sandstone, and Wingate Sandstone; Triassic—Chinle Formation; Permian—San Andres Limestone and Glorieta Sandstone. They are classified as minor potential aquifers in Area 2 because of their great depth and the general lack of information concerning their water-bearing characteristics. Further tests of these units in Area 2 could prove that some of them have potential as major aquifers for coal development.

SUMMARY

Area 1—Fruitland Trend

The Gallup Sandstone is the shallowest and most promising potential aquifer in the Fruitland trend, at least west of R. 11 W. (the approximate eastern extent of massive, permeable Gallup Sandstone). At a specific capacity of about 0.3 gpm/ ft, the Gallup may yield 300 gpm or more over a long period. The next shallowest significant aquifer in Area 1 and one that shows considerable potential as a water source is the Westwater Canyon Sandstone Member of the Morrison Formation, although results of pumping tests are proprietary. At a specific capacity of 0.3 gpm/ ft, yields of several hundred gpm should be possible. The deepest potential aquifer in Area 1 is the Entrada Sandstone. Whereas several hundred gpm could be produced from this unit, the excessive depth and the salinity of its waters make the Entrada less desirable than the other two aquifers mentioned above.

Area 2—Menefee Crevasse Canyon Trend

The best target for ground water in Area 2 is probably the Westwater Canyon Member of the Morrison Formation. Yields of 300-400 gpm of good quality water from a pumping level of 700-1,000 ft can be expected. Yields of greater than 100 gpm of satisfactory quality water may be obtained from a combined Gallup-"stray" sandstone aquifer. Wells yielding 20-40 gpm may be constructed in the Dakota Sandstone and the Dalton Sandstone Member of the Crevasse Canyon Formation. The San Andres-Glorieta aquifer yields large quantities of water south of 1-40 and is the most promising of the deep aquifers, but little is known of its characteristics in Area 2; further work is warranted.

PALYNOLOGY OF CREVASSE CANYON AND MENEFEE FORMATION OF SAN JUAN BASIN, NEW MEXICO

by Robert H. Tschudy, *U.S. Geological Survey. Denver*

INTRODUCTION

The palynology of the Mesaverde Group in the San Juan Basin and of strata of equivalent age in other areas of the Western Interior of North America has been neglected. This oversight is due, at least in part, to the fact that most rocks of this age in the Western Interior are of marine origin, thus poor rock sources for palynomorphs. A contributing factor is that these marine rocks have yielded invertebrate fossils useful in correlation and age determination.

In a preliminary effort to determine the characteristics of the fossil pollen and spore flora of the Mesaverde Group in this area, samples of coals and associated shales of the Crevasse Canyon Formation and the basal Menefee Formation were collected. Most were collected from the Dilco and Gibson Coal Members of the Crevasse Canyon Formation near Hosta Butte and Crownpoint, New Mexico (fig. 1, T. 16, 17 N.). Another sample from farther north came from the lowest coal in the Menefee Formation—probably from the Cleary Coal Member of the Menefee Formation (R. B. O'Sullivan, oral communication, 1976).

The Crevasse Canyon Formation in the Hosta Butte area overlies the Gallup Sandstone and underlies the Point Lookout Sandstone. Stratigraphic relationships have been shown by O'Sullivan and others (1972, fig. 7). The Crevasse Canyon Formation in the vicinity of Hosta Butte consists of the Dilco Coal, Dalton Sandstone, and Gibson Coal Members. The Mulatto Tongue of the Mancos Shale intervenes as a wedge between the Dilco Coal Member and the Dalton Sandstone Member. The Crevasse Canyon Formation is overlain in sequence by the Hosta Tongue of the Point Lookout Sandstone, the Satan Tongue of the Mancos Shale and the main body of the Point Lookout Sandstone. The upper part of the main body of the Point Lookout

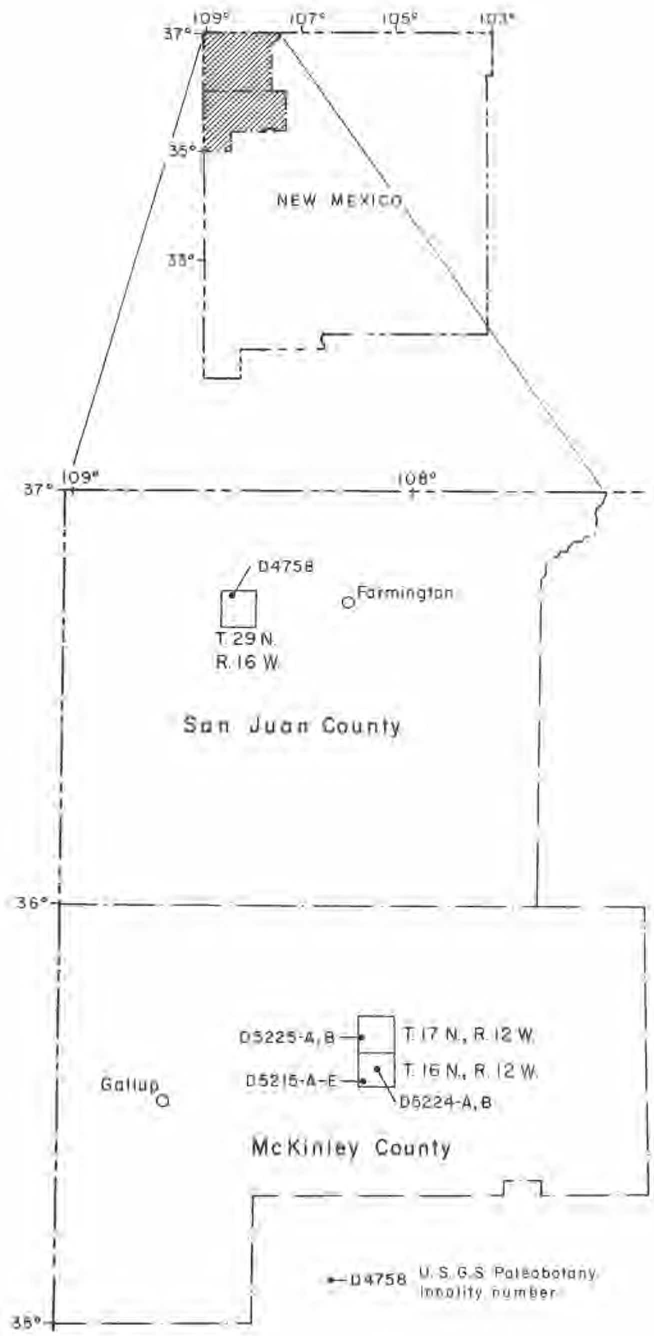

FIGURE 1 —INDEX MAP SHOWING PALYNOMORPH LOCALITIES.

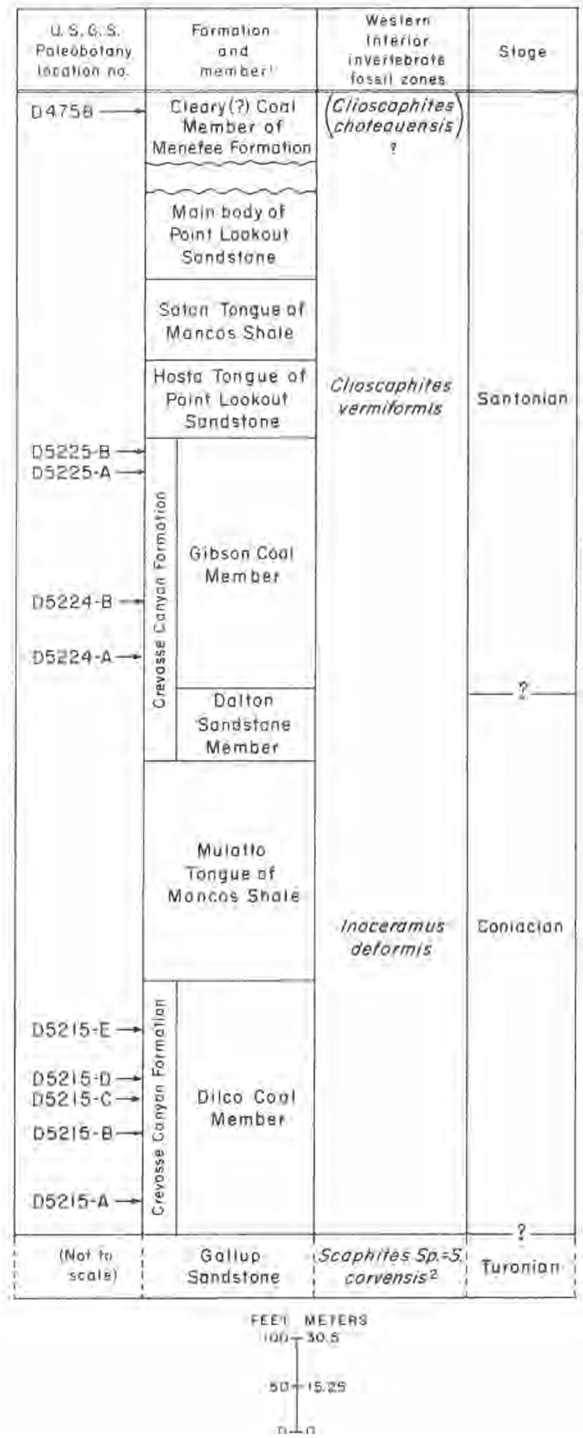

FIGURE 2—APPROXIMATE LOCATION OF PALYNOMORPH SAMPLES IN RELATION TO STRATIGRAPHY. ([1]General stratigraphy of Mancos Shale and Mesaverde Group in Hosta Butte and Crownpoint quads, personal communication from J. F. Robertson, 1976; [2]U.S. Geol. Survey, Professional Paper 521-E, p. E31.)

Sandstone has been removed by erosion in this area, but is present both northeast and southwest.

The relative stratigraphic positions of the samples from the Dilco and Gibson Coal Members of the Crevasse Canyon Formation and from the Cleary (?) Member of the Menefee Formation are shown in fig. 2.

The lowermost sample from the Gibson Coal Member is about 400 ft (122 m) above the uppermost sample from the Dilco Coal Member. The greater part of this interval consists of about 240 ft (73 m) of marine rocks of the Mulatto Tongue of the Mancos Shale and about 75 ft (23 m) of sandstone of the Dalton Sandstone Member of the Crevasse Canyon. The uppermost sample from the Gibson Coal Member of the Crevasse Canyon was collected at Crownpoint immediately below the Hosta Tongue of the Point Lookout Sandstone. The sample from the lowest coal in the Menefee Formation was provided by R. M. Kosanke and was collected from a 15-inch (37-cm) coal bed west of Fruitland, New Mexico. Locality information for all of the samples is presented in the accompanying table.

The age of the rocks in the interval shown in fig. 2 were derived from invertebrate zone fossils found in the associated marine rocks. Data concerning these Western Interior zone fossils were obtained from O'Sullivan and others (1972). *Scaphites* sp. ". . . equivalent to the zone

TABLE OF LOCALITIES AND SAMPLES

USGS Paleobotany Loc. No.	Locality	Sample No.
D5215-A	About 40 ft (12 m) above base of Dilco Coal Member of Crevasse Canyon Formation, immediately overlying basal channel sandstone; NW¼ SW¼ sec. 31, T. 16 N., R. 12 W., McKinley Co., New Mexico	RT-74-51
D5215-B	Same locality, about 72 ft (22 m) above RT-74-51	RT-74-52
D5215-C	Same locality, about 26 ft (8 m) above RT-74-52	RT-74-53
D5215-D	Same locality, about 20 ft (6 m) above RT-74-53	RT-74-54
D5215-E	Same locality, about 52 ft (16 m) above RT-74-54	RT-74-55
D5224-A	35 ft (11 m) above base of Gibson Coal Member of Crevasse Canyon Formation; NE¼ NE¼ sec. 20, T. 16 N., R. 12 W., McKinley Co., New Mexico	RT-74-56
D5224-B	Same locality about 50 ft (15 m) above RT-74-56, 15 ft (5 m) below base of middle sandstone	RT-74-57
D5225-B	Gibson Coal Member of Crevasse Canyon Formation, first coaly horizon about 3 ft (1 m) below Point Lookout Sandstone at Crownpoint; taken along new roadcut along east face of cliff; SW¼ NW¼ sec. 29, T. 17 N., R. 12 W., McKinley Co., New Mexico	RT-74-67
D5225-A	Same locality about 10 ft (3 m) below RT-74-67	RT-74-68
D4758-B	Lowest coal in Menefee Formation (O'Sullivan, personal communication, 1976); east side of dirt road ½ mi (0.8 km) north of US-550 on Navajo Reservation; middle sec. 5, T. 29 N., R. 16 W., San Juan Co., New Mexico; collected by R. M. Kosanke	RMK-3-A

of *Scaphites nigricollensis* and *S. corvensis* . . ." (O'Sullivan and others, 1972, p. E31) was found near the top of the Gallup Sandstone of the Gallup area. This fossil zone is the topmost zone in the Turonian. *Inoceramus deformis* was found in the Mulatto Tongue of the Mancos Shale in the Tohatchi area. This zone is in the lower part of the Coniacian. The Dilco Coal Member occurs between the Gallup and the Mulatto Tongue, thus all of the Dilco Coal Member in this area is of Coniacian or possibly latest Turonian age. *Clioscaphites vermiformis* was found in the Hosta Tongue of the Point Lookout Sandstone. This zone fossil occupies about the middle part of the Santonian. The Gibson Coal Member lies directly below the Hosta Tongue, consequently all the Gibson Coal Member in this area is probably of Santonian age. By inference, the basal part of the Menefee Formation in this area is about the same age. The entire sequence shown in fig. 2 is of Coniacian-Santonian age spanning an interval of about 5 m.y. (Obradovich and Cobban, 1975).

METHODS—The processing procedures employed are standard for the U.S. Geological Survey Laboratory in Denver. They are described by R. H. Tschudy (1970) and consist essentially of treating samples with hydrofluoric acid for shales, followed by Schulze solution for both coals and shales. Humates are then rendered soluble by treating with weak alkali; the residue is then washed, mounted in AYAF plastic on cover glasses, and embedded in "Histoclad" resin.

ACKNOWLEDGMENTS—I thank R. M. Kosanke, J. F. Robertson, and Bernadine D. Tschudy for assistance in collecting samples, and Sharon D. Van Loenen for preparing the samples and assisting in construction of the figures.

COMPOSITION OF FOSSIL POLLEN AND SPORE FLORA

The palynomorph fossil flora consists of a fern-conifer-angiosperm complex exhibiting remarkable qualitative and quantitative changes in a comparatively short stratigraphic interval. Conifer pollen and fern spores dominate the stratigraphically lower samples; angiosperm pollen becomes dominant in the upper samples.

The proportion of each pollen or spore group to the total palynomorph flora is shown in fig. 3. The fern component, dominant in the lower samples, is recorded as two groups of species, the monolete and the trilete types. The monolete group of spores is probably without merit for subdividing the sequence palynologically. A slight increase in percentage of monolete spores is observed in the uppermost sample from the Dilco Member; somewhat similar increases are recorded in the upper Gibson Member and Cleary (?) Menefee samples. The trilete fern spore recovery shows wide percentage fluctuations ranging from 70 percent of the total flora in the lowest sample from the Dilco Member to a minimum of 6 percent in a sample from the upper part of the Gibson Member. The meaning of the fern spore fluctuations, as well as of the percentage fluctuations of other groups, is not clear. Possibly these fluctuations are related to changing ecological conditions as the shoreline oscillated back and forth causing the advance and retreat of the land flora in the continental, somewhat flat foreland floodplain, and paludal areas.

The coniferous component of the flora is subdivided (fig. 3) into three groups: bisaccate and araucarian pollen, taxodiaceous pollen, and *Corollina* pollen. The Bisaccate pollen group (including non-bisaccate *Araucariacites)* is nowhere dominant but is present in higher percentages in the stratigraphically lower samples. High percentages of this type of pollen have been equated with relative proximity to nearby highland areas. Taxodiaceous pollen (solid bars in fig. 3) is a minor constituent of the palynomorph flora of most samples. In one sample (D5225-A coal sample from the Gibson Member), 28 percent of all palynomorphs found consisted of taxodiaceous pollen. This high percentage of taxodiaceous pollen may indicate that taxodiaceous forests were probably nearer to, or within, this coal swamp at the time of deposition, thus contributing a significantly greater amount of pollen to the deposit.

Another apparently anomalous occurrence of coniferous pollen is seen in sample D5215-D, a sample of gray shale from the Dilco Member. In this sample *Corollina* pollen is present as 30 percent of the total palynomorph count, although barely represented in other samples. *Corollina* has been shown to be an abundant constituent of many Upper Jurassic rocks (Pocock, 1962), but is seldom present in any considerable percentage in younger rocks. This high percentage of *Corollina* pollen plus the presence of *Exesipollenites*

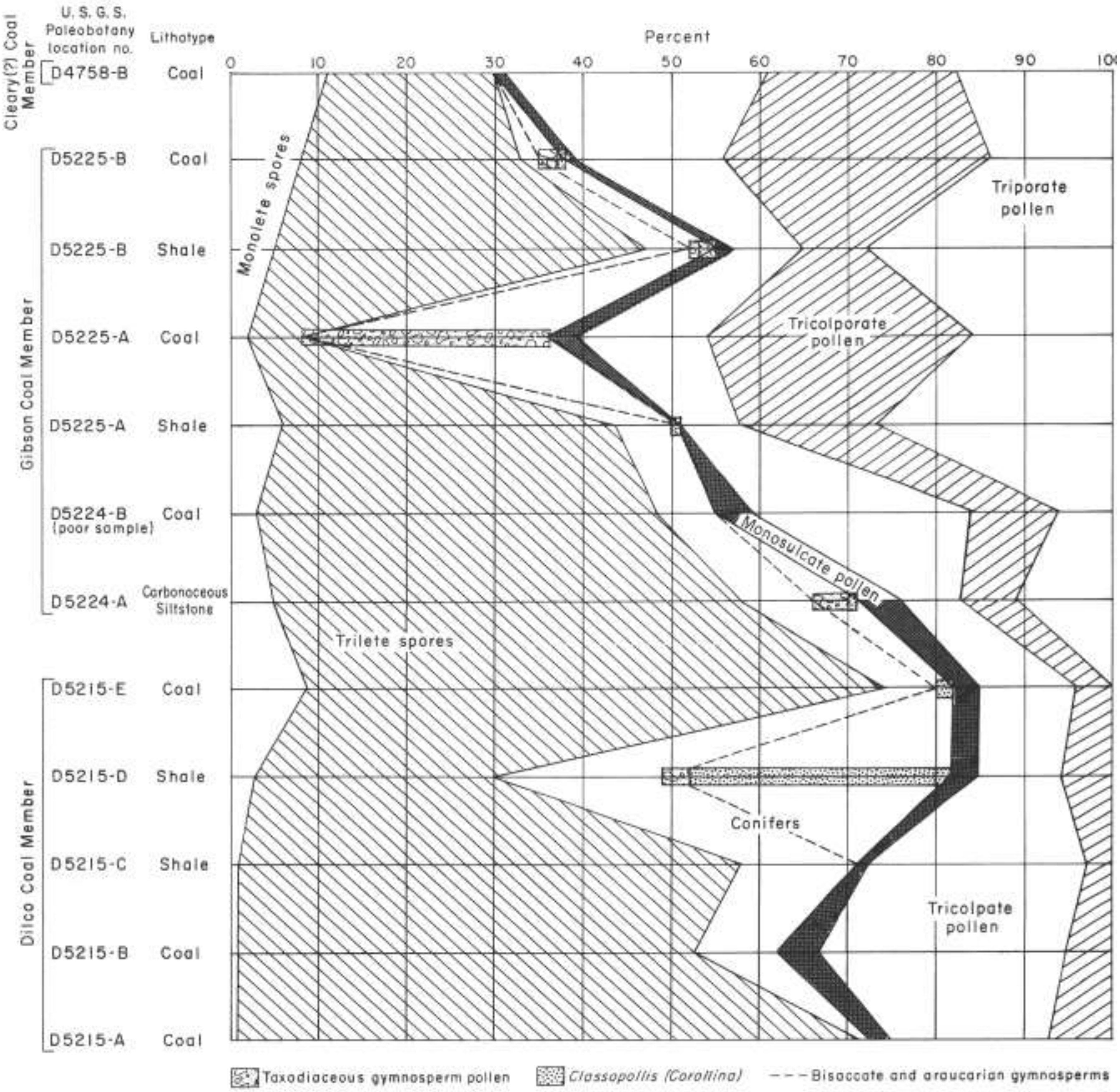

FIGURE 3—PERCENTAGE COMPOSITION OF THE PALYNOMORPH FLORA.

suggests the possibility that the palynomorph proportions of this sample may have been altered by redeposited taxa from older strata.

As shown in fig. 3, the monosulcate pollen is a minor constituent of the total pollen flora in all of the samples. This pollen group never attains a concentration greater than 5 percent.

Angiosperm pollen percentages fluctuate widely (as do fern percentages), but the trend toward a distinctly higher angiosperm component in the stratigraphically higher samples is rather obvious. This trend is not reflected in the more primitive tricolpate-type pollen, but is clearly shown by the pronounced increase in percentage of the more advanced tricolporate and triporate pollen groups in the upper samples. No triporate pollen was present in the pollen count from any sample from the Dilco Member, although a few triporate grains were observed in some of these samples upon further scanning of the slides.

VARIATION OF POLLEN RECOVERY WITH LITHOTYPE—The samples taken for palynological study consisted of coals and organic shale and siltstone. Pronounced differences in the percentage recovery of the various constituents of the flora are evident when comparing the recovery from the coals and from the shales. These differences are particularly apparent in those instances where a coal and a shale sample were taken from virtually the same stratigraphic interval (samples D5225-A coal and D5225-A shale and D5225-**B** coal and D5225-B shale). This variation demonstrates the hazards in attempting correlation of strata of unlike lithology, or those in which rapid facies changes are influencing the flora at or near the deposition site. In spite of such quantitative variations, trends in composition of the flora and abrupt qualitative changes are readily apparent.

ANGIOSPERM COMPONENT OF PALYNOMORPH FLORA

A second palynomorph count was made that ignored all taxa except those of angiospermous affinity. These data were then plotted in relation to the stratigraphic position of the samples (fig. 4). The "not determined" section of the graph records the pollen grains that could not readily be distinguished. They are, for the most part, grains of either the tricolpate or tricolporate pollen types.

The monosulcate component of the total angiosperm pollen flora shows a slight percentage increase in the coal samples from the Dilco Member. Monosulcate pollen becomes a negligible part of the pollen flora above the Dilco. Monosulcate angiosperm pollen is considered to be the most primitive type. It appears first in strata of late Barremian age in England and in strata of late Aptian or Albian age in North America (Singh, 1975). The tricolpate pollen first appears in North America in rocks of middle Albian age; the more evolutionarily advanced tricolporate pollen first appears at about the boundary between the Albian and Cenomanian Stages. Triporate pollen does not appear in the North American stratigraphic record until about middle Cenomanian time.

The tricolpate-type pollen is the dominant pollen group in all Dilco Member samples; it decreases in percentage slightly in the samples of the Gibson Member and Menefee Formation. Wide percentage variations are present, and particularly evident in the Gibson Member.

Tricolporate pollen percentages also fluctuate widely, from 9 percent in sample D5215-B from the Dilco Member to about 60 percent of the total angiosperm pollen flora in sample D5225-B coal from the upper part of the Gibson Member. No obvious trends are exhibited by this group of pollen species.

The most conspicuous change in the angiosperm component of the flora is seen in the representation of the triporate pollen group. This pollen group is virtually absent from the Dilco Member samples. It is represented by a concentration of less than 1 percent in the lowest sample and by 4 percent in the uppermost Dilco Member sample, but was not observed in any of the three intervening samples. Triporate pollen percentages increase markedly in the stratigraphically higher samples, and become the dominant forms in three of the samples from the Gibson Coal Member and subdominant in the Cleary (?) sample.

ENTRANCE LEVEL OF TRIPORATE POLLEN IN STRATIGRAPHIC RECORD—The first appearance of triporate pollen in the stratigraphic record occurs in the middle Cenomanian in eastern United States and in the upper part of the Turonian in western Canada (Singh, 1975). The virtual absence of triporate pollen in all but the uppermost sample from the Dilco Coal Member and the consistent presence of triporates above this level suggest that the practical entrance level (a level at which the plants had become sufficiently well established that they provided representative pollen in significant quantities to most samples) of triporate pollen in the San Juan Basin area occurred at a later time (Coniacian) than in other parts of North America. I have not seen triporate pollen in the Dakota Sandstone from the San Juan Basin, but I have not yet examined material from the Gallup Sandstone—a formation that is considerably higher than the Dakota Sandstone and that immediately underlies the Crevasse Canyon Formation. Whether or not occasional triporate pollen grains will be found in rocks older than the basal members of the Crevasse Canyon Formation in the San Juan Basin, thus whether or not the triporate entrance level is consistent with that reported from elsewhere in North America, has not been determined.

The consistent presence of triporate pollen in significantly higher percentages in all samples above the Dilco Coal Member provides an easily recognizable datum plane for subdividing the rock sequence palynologically.

TRIPORATE COMPONENT OF ANGIOSPERM POLLEN FLORA

The triporate pollen types observed primarily in samples of the Gibson Coal Member of the Crevasse Canyon and the Cleary (?) Coal Member of the Menefee can be conveniently subdivided into two groups—the Normapolles group of pollen genera and the non-normapolles group. Individual genera and one group of genera are plotted on fig. 5. Triporate pollen is virtually absent from all but the uppermost sample from the Dilco Coal Member. The first triporates that appear belong to the Normapolles genus *Complexiopollis*. This genus persists in comparatively low numbers throughout the Gibson Coal Member, but was not observed in the sample from the Cleary (?) Coal Member.

A different group of triporate pollen grains serves to characterize the Gibson samples, attaining 43 percent of Angiosperm pollen in the shale sample D5225-B and decreasing to 3 percent in the basal part of the Menefee Formation. These triporate specimens belong to the non-normapolles group of genera. Most of them can be accommodated in the genus *Triporopollenites.*

Other triporates belonging to the Normapolles group of pollen genera appear at successively higher levels in the Gibson sequence. The genus *Trudopollis* is present as 25 percent of the angiosperm pollen component in sample D5224-A from the lower part of the Gibson Coal Member. This genus decreases to 1 percent in the next higher sample, D5224-B, and is absent from all stratigraphically higher samples. The Normapolles genus *Plicapollis* is absent from Dilco Coal Member samples, present in a concentration of one percent in the lower two Gibson Coal Member samples, then increases to 12 percent and 8 percent respectively in the next higher shale samples, but was absent from the coals from these same two horizons. This genus also appeared as 7 percent of the angiosperm component in the sample from the Cleary (?) Coal Member.

The Normapolles genus *Pseudoplicapollis* is absent from the Dilco Coal Member and from the lower two samples from the Gibson Coal Member. This genus is confined to the upper part of the Gibson Coal Member and is apparently absent from the basal Menefee Formation sample.

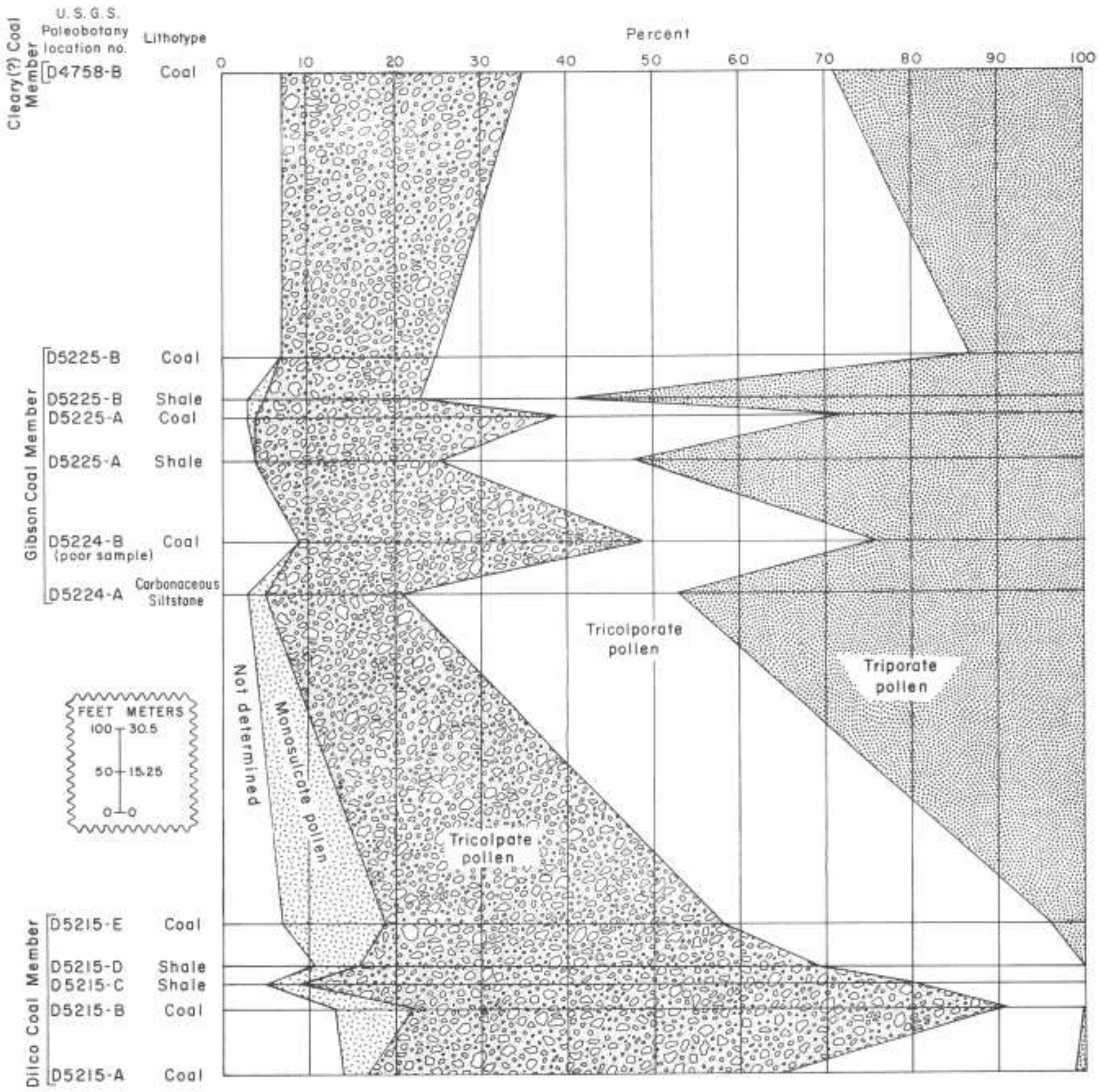

FIGURE 4—RELATIVE PERCENTAGES OF ANGIOSPERM POLLEN GROUPS.

The uppermost conspicuous pollen change is the appearance of the non-normapolles genus *Proteacidites.* One specimen was observed in sample D5224-B from the lower part of the Gibson Coal Member; the genus was not found in the intervening interval, but reappeared in a 1-percent concentration in the coal segment of the uppermost Gibson Coal Member sample, D5225-B. In the overlying Menefee Formation sample, however, the genus appeared in a concentration of 19 percent. *Proteacidites* has been observed in samples from the upper part of the Menefee Formation and from the Lewis Shale, Pictured Cliffs Sandstone, and Kirtland Shale. This genus is a common constituent of all continental post-Niobrara palyniferous samples from the Rocky Mountain region but disappears at the end of the Cretaceous.

NORMAPOLLES POLLEN IN THE SAN JUAN BASIN—Normapolles pollen genera are well represented in Upper Cretaceous rocks from eastern United States (Doyle, 1969; Wolfe and Pakiser, 1971; Groot and others, 1961; Kimyai, 1966; R. H. Tschudy, 1973; R. H. Tschudy, 1975). These pollen are generally sparse in Upper Cretaceous rocks from west of the Mississippi embayment (Brown and Pierce, 1962; Newman, 1965; Romans, 1975; Singh, 1975; Drugg, 1967; Orlansky, 1971; Sarmiento, 1957; Oltz, 1969; Norton and Hall, 1969; B. D. Tschudy, 1971, 1973). The earliest appearance of Normapolles genera in the stratigraphic record in North

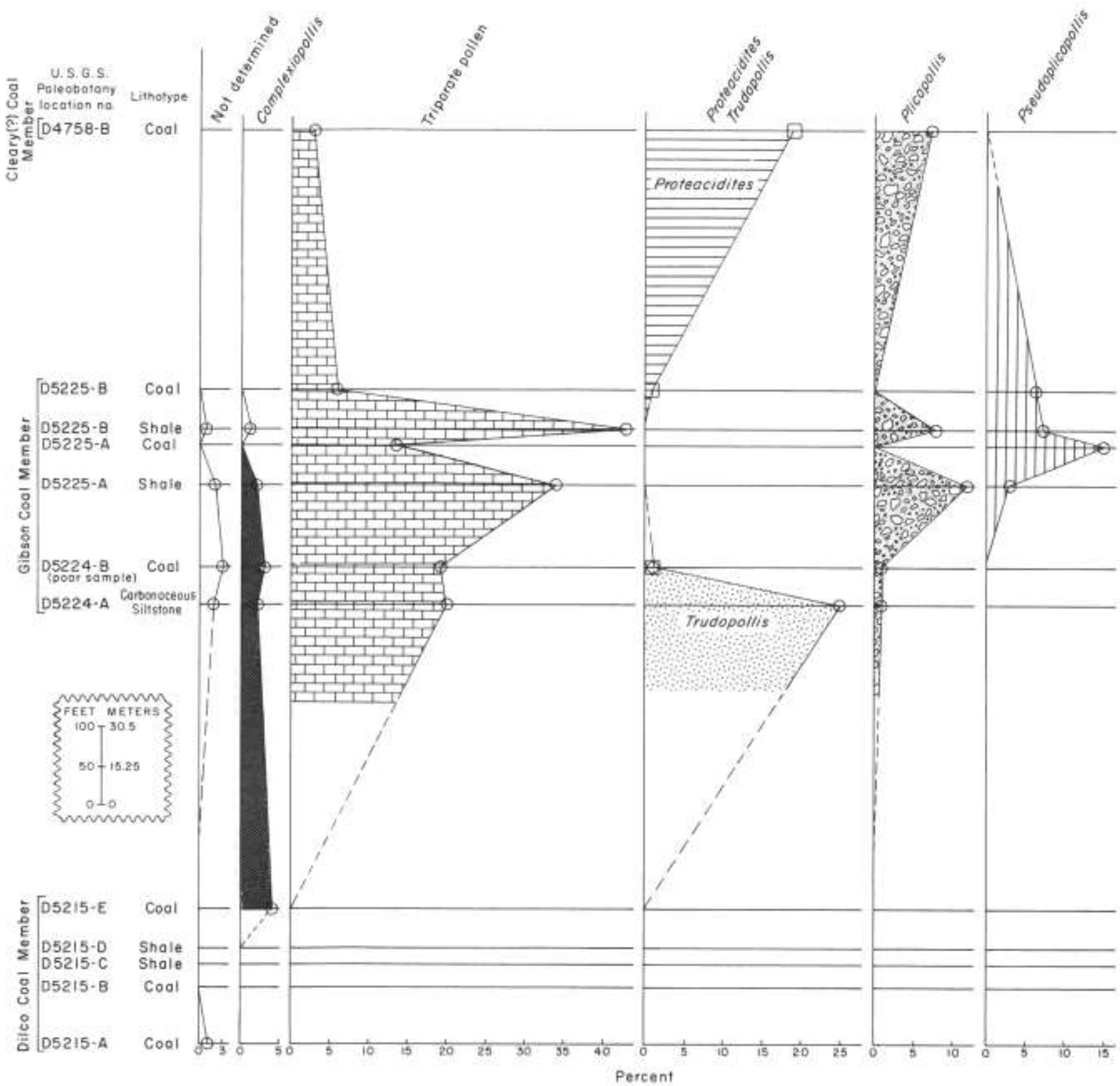

FIGURE 5—SEGREGATED TRIPORATE POLLEN GROUPS REPRESENTED AS PERCENTAGES OF TOTAL ANGIOSPERMS PRESENT.

America is in the Cenomanian. These genera in the Mississippi embayment become very common in the Campanian and Maestrichtian Stages and die out completely in middle Eocene time (R. H. Tschudy, 1975).

The high percentages of Normapolles pollen recorded from the San Juan Basin are unique for samples west of the Mississippi embayment. Previous reports indicate a very sparse representation. However, the interval examined (the Coniacian-Santonian) has not been studied palynologically in the west in detail. The high recovery values reported here indicate that more work in the interval from upper Cenomanian, Turonian, Coniacian, to Santonian would certainly be rewarding.

SUMMARY

Conspicuous pollen changes observed in the Crevasse Canyon and basal Menefee permit tentative subdivision of this interval into four pollen zones, in ascending order:

Zone 1. That confined to the lower part of the Dilco Coal Member in which triporate pollen is virtually absent; the practical entrance level of triporate pollen in the upper part of the Dilco Coal Member separates this lower unit from all younger samples

Zone 2. That confined to the lower part of the Gibson Coal Member in which *Trudopollis* is abundant

Zone 3. That confined to the upper part of the Gibson Coal Member characterized by high percentages of triporate pollen species, as well as presence of specimens of *Pseudoplicapollis* in significant percentages

Zone 4. That confined to the basal Menefee Formation and younger rocks characterized by *Proteacidites* pollen in significant numbers.

The above pollen zones occur in the stratigraphic interval between the Western Interior invertebrate fossil zones of *Scaphites corvensis* (upper Turonian) and probably that of *Clioscaphites choteauensis.* Consequently, the interval studied occurs entirely within the Coniacian and Santonian—a time interval of no more than 5 m.y.

References

Includes Introduction, Road Logs, and Contributed Papers

Bandoian, C. A., Geomorphology of the Animas River Valley, San Juan County, New Mexico: M.S. thesis, Univ. New Mexico, 88 p.

Berry, F. A. D., 1959, Hydrodynamics and geochemistry of the Jurassic and Cretaceous systems in the San Juan Basin, northwestern New Mexico and southwestern Colorado: M.S. thesis, Stanford Univ., 192 p.

Brown, C. W., and Pierce, R. L., 1962, Palynologic correlations in Cretaceous Eagleford Group, northeast Texas: Assoc. Petroleum Geologists, Bull., v. 46, no. 12, p. 2133-2157

Budd, Harrell, 1957, Facies development of the Gallup Formation: Four Corners Geol. Soc., Guidebook 2nd field conf., Geology of southwestern San Juan Basin, p. 121-127

Cooley, M. E., Harshbarger, J. W., Akers, J. P., and Hardt, W. F., 1969, Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah, with a section on vegetation by 0. N. Hicks: U.S. Geol. Survey, Prof. Paper 52I-A, 61 p., 5 pls.

Cooper, J. B., and John, E. C., 1968, Geology and ground-water occurrence in southeastern McKinley County, New Mexico: New Mexico State Engineer, Tech. Rept. 35, 108 p.

Cooper, J. B.. and Trauger, F. D., 1967, San Juan River Basin: geography, geology, hydrology, *in* Water resources of New Mexico: occurrence, development, and use: State Planning Office, p. 185-210

Dane. C. H., and Bachman, G. 0.. 1965, Geologic map of New Mexico: U.S. Geol. Survey

Dane, C. H., Cobban, W. A., and Kauffman, E. G., 1966, Stratigraphy and regional relationships of a reference section for the Juana Lopez Member, Mancos Shale, in the San Juan Basin, New Mexico: U.S. Geol. Survey, Bull. 1224-H, 15 p.

Davis, G. E., and others, 1963, Records of ground-water supplies, pt. I, Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: Arizona Land Dept., Water Resources Rept. 12-A, 159 p.

Doyle, J. A., 1969, Cretaceous angiosperm pollen of the Atlantic Coastal Plain and its evolutionary significance: Jour. Arnold Arboretum, v. 50, no. 1, p. 1-35

Drugg, W. S., 1967, Palynology of the Upper Moreno Formation (Late Cretaceous-Paleocene) Escarpado Canyon, California: Paleontographica, sec. B, v. 120, p. 1-71

Groot, J. J., Penny, J. S.. and Groot, C. R., 1961, Plant microfossils and age of the Raritan, Tuscaloosa and Magothy Formations of the eastern United States: Palaeontographica. v. 108, sec. B, nos. 3-6, p. 121-140

Harms, J. C., 1975, Stratification and sequence in prograding shoreline deposits, *in* Harms, J. C., Southard, J. B., Spearing, D. R., and Walker, R. G., Depositional environments as inferred from primary sedimentary structures and stratification sequences: Lecture notes for Soc. Econ. Paleontologists and Mineralogists Short Course No. 2, p. 81-102

Hayes. P. T., and Zapp, A. D., 1955, Geology and fuel resources of the upper Cretaceous rocks of the Barker Dome-Fruitland area, San Juan County, New Mexico: U.S. Geol. Survey Oil and Gas Inv. Map OM-144, 2 sheets

Huber, Joe, undated, The story of Madrid, New Mexico: privately published, 31 p.

Kelley, V. C., 1951, Tectonics of the San Juan Basin: New Mexico Geol. Soc., Guidebook 2nd field conf., p. 124-131

1974, Albuquerque-its mountains, valley, water and volcanoes: New Mexico Bureau Mines Mineral Resources, Scenic Trip No. 9, 106 p.

Kimyai, Abbas, 1966, New plant microfossils from the Raritan Formation (Cretaceous) in New Jersey: Micropaleontology, v. 12, no. 4, p. 461-476

Kister, L. R., and Hatchett, J. L., 1963, Selected chemical analyses of the ground water, pt. 2 *in* Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: Arizona Land Dept., Water Resources Rept. 12-B, 58 p.

Kottlowski, F. E., 1975, Report of the Coal Resources Committee: State of New Mexico, Governor's Energy Task Force, 44 p.

Landis, E. R., and Dane, C. H., 1967, Geologic map of the Tierra Amanilla quadrangle, Rio Arriba County, New Mexico (with description): New Mexico Bureau Mines Mineral Resources, Geol. Map 19, 16 p.

Lee, W. T., 1913, The Cerrillos coal field, Santa Fe County, New Mexico: U.S. Geol. Survey, Bull. 531-J, p. 285-312

Lee, W. T., and Knowlton, F. H., 1917, Geology and paleontology of the Raton Mesa and other regions in Colorado and New Mexico: U.S. Geol. Survey, Prof. Paper 101, 450 p.

McGavock, E. H., and others, 1966, Supplemental records of groundwater supplies, pt. 1-A, *in* Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: Arizona Land Dept., Water Resources Rept. 12-E, 55 p.

Newman, K. R., 1965, Upper Cretaceous-Paleocene guide palynomorphs from northern Colorado: Boulder, Colorado, Univ. Colorado Press, Ser. in Earth Sciences no. 2, 21 p.

Norton. N. J., and Hall, J. W., 1969, Palynology of the Upper Cretaceous and lower Tertiary in the type locality of the Hell Creek Formation, Montana, U.S.A.: Palaeontographica, v. 125, sec. B, nos. 1-3, p. 1-64

Obradovich, J. D., and Cobban, W. A., 1975, A time scale for the Late Cretaceous of the Western Interior of North America, *in* Caldwell, W. G. E., The Cretaceous System in the Western Interior of North America: Geol. Soc. Canada, Spec. Paper No. 13, p. 31-54

Oltz, D. F.. Jr., 1969, Numerical analyses of palynological data from Cretaceous and early Tertiary sediments in east central Montana: Palaeontographica, v. 128, sec. B. nos. 3-6, p. 90-166

Orlansky, Ralph, 1971, Palynology of the Upper Cretaceous Straight Cliffs Sandstone, Garfield County, Utah: Utah Geol. and Mineralog. Survey, Bull. 89, 57 p.

O'Sullivan, R. B., and Beikman, H. M., 1963, Geology, structure, and uranium deposits of the Shiprock quadrangle. New Mexico: U.S. Geol. Survey, Misc. Inv. Map 1-345

O'Sullivan, R. B., Repenning, C. A., Beaumont, E. C., and Page, H. G., 1972, Stratigraphy of the Cretaceous rocks and the Tertiary Ojo Alamo Sandstone, Navajo and Hopi Indian reservations, Arizona, New Mexico, and Utah: U.S. Geol. Survey, Prof. Paper 521-E, 65 p.

Pastuszak, R. A., 1968, Geomorphology of part of the La Plata and San Juan Rivers, San Juan County, New Mexico: M.S. thesis, Univ. New Mexico. 76 p.

Pocock, S. A. J.. 1962, Microfloral analysis and age determination of strata of the Jurassic-Cretaceous boundary in the western Canada plains: Palaeontographica, v. 111, sec. B, nos. 1-3, p. 1-95

Rankin, C. H., Jr., 1944. Stratigraphy of the Colorado group, Upper Cretaceous, in northern New Mexico: New Mexico School of Mines, Bull. 20, 27 p.

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

Richmond, G. M., 1965, Quaternary stratigraphy of the Durango area, San Juan Mountains, Colorado: U.S. Geol. Survey, Prof. Paper 525-C, p. 137-143

Robinson, L. D., ed., 1976, A field guide to carboniferous littoral deposits in the Warrior Basin: guidebook for field trip held in conjunction with AAPG/SEPM Convention, New Orleans, May 23-26, 1976, 81 p.

Romans, R. C., 1975, Palynology of some Upper Cretaceous coals of Black Mesa, Arizona: Pollen et Spores, v. 17, no. 2, p. 273-329

Sarmiento, R., 1957, Microfossil zonation of Mancos Group: Am. Assoc. Petroleum Geologists, Bull., v. 41, no. 8, p. 1683-1693

Shomaker, J. W., 1971, Water resources of Fort Wingate Army Depot and adjacent areas, McKinley'County, New Mexico: U.S. Geol. Survey, Open-file report, 230 p.

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

Siemers, C. T., and King, N. R., 1975, Macroinvertebrate paleoecology of a transgressive marine sandstone, Cliff House Sandstone (Upper Cretaceous), Chaco Canyon, northwestern New Mexico: New Mexico Geol. Soc., Guidebook 25th field conf., p. 267-277

Singh, Chaitanya, 1975, Stratigraphic significance of early angiosperm pollen in the mid-Cretaceous strata of Alberta, *in* Caldwell, W. G.

E., The Cretaceous System in the Western Interior of North America: Geol. Soc. Canada, Spec. Paper No. 13, p. 365-389
Stearns, C. E., 1943, The Galisteo Formation *of* north-central New Mexico: Jour. Geology, v. 51, p. 301-319
, 1953, Upper Cretaceous rocks of Galisteo-Tonque area, north-central New Mexico: Am. Assoc. Petroleum Geologists, Bull., v. 37, p. 961-974
Stone, W. J., 1976, Hydrogeologic considerations in mining and development of energy resources, San Juan Basin, New Mexico: Am. Inst. Mining and Engineering, 105th ann. mtg., preprint 76-AG-74
Stone, W. J., and Kelly, T. E., 1975, Ground water for energy development, northwestern New Mexico: Proc. 20th New Mexico Water Conf., p. 62-83
Tschudy, B. D., 1971, Two new fossil pollen genera from Upper Campanian (Cretaceous) rocks of Montana, *in* Geological Survey Research 1971: U.S. Geol. Survey, Prof. Paper 750-B, p. B53-B61
____________, 1973, Palynology of the Upper Campanian (Cretaceous) Judith River Formation, north-central Montana: U.S. Geol. Survey, Prof. Paper 770, 42 p.
Tschudy, R. H., 1970, Two new pollen genera (Late Cretaceous and Paleocene) with possible affinity to the Illiciaceae: U.S. Geol. Survey, Prof. Paper 643-F, 13 p.
, 1973, *Complexiopollis* pollen lineage in Mississippi Embayment rocks: U.S. Geol. Survey, Prof. Paper 743-C, 15 p.
1975, Normapolles pollen from the Mississippi Embayment: U.S. Geol. Survey, Prof. Paper 865, 42 p.
Vann, R. P., 1931, Paleontology of the Upper Cretaceous of Chaco Canyon, New Mexico: M.S. thesis, Univ. New Mexico, 64 p.
Wolfe, J. A., and Pakiser, H. M., 1971, Stratigraphic interpretations of some Cretaceous microfossil floras of the Middle Atlantic States, *in* Ecological Survey Research 1971: U.S. Geol. Survey, Prof. Paper 750-B, p. B35-B47

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STRATIGRAPHIC NOMENCLATURE OF FIELD TRIP AREA

Era	System	Series	Group, formation member	Thickness (ft)	Lithology
CENOZOIC	Quaternary	Holocene and Pleistocene	Undifferentiated	0 to 300	Terrace, valley, and slope alluvium; eolian sand; basalt flows
	Tertiary	Pliocene and Miocene	Santa Fe Group	0 to 13,000	Sandstone, mudstone, gravel; basalt, andesite flows
		Oligocene	Volcanics, undivided	0 to 3,000	Rhyolite, basalt
		Eocene	Galisteo and San Jose Formations	0 to 3,000	Sandstone, mudstone, conglomerate
		Paleocene	Nacimiento Formation	0 to 1,000	Mudstone, sandstone
			Ojo Alamo Sandstone	0 to 400	Conglomeratic sandstone, carbonaceous shale
MESOZOIC	Cretaceous	Upper	Kirtland Shale	300 to 1,500	Shale, sandstone
			Fruitland Formation	200 to 500	Carbonaceous shale, sandstone, coal
			Pictured Cliffs Sandstone	0 to 300	Sandstone
			Lewis Shale	0 to 2,000	Shale
			Mesaverde Group	1,000 to 3,000	Sandstone, carbonaceous shale, coal
			Mancos Shale	500 to 1,500	Shale
		Lower	Dakota Sandstone	20 to 250	Sandstone
	Jurassic	Upper	Morrison Formation	0 to 800	Mudstone, sandstone, conglomerate
			Bluff, Cow Springs, and Zuni Sandstones	200 to 500	Sandstone
			Summerville Formation	0 to 150	Mudstone, sandstone
			Todilto Formation	0 to 200	Gypsum, limestone
			Entrada Sandstone (includes Wingate)	0 to 750	Sandstone
	Triassic	Upper	Chinle Formation	1,400 to 2,000	Mudstone, sandstone, conglomerate
		Lower	Moenkopi Formation	0 to 500	Sandy shale, siltstone
PALEOZOIC	Permian	Guadalupian	San Andres Formation	0 to 150	Limestone, sandstone
		Leonardian	Glorieta Sandstone	0 to 250	Sandstone, siltstone
			Yeso Formation	400 to 700	Sandstone, mudstone, limestone
		Wolfcampian	Abo Formation	800	Sandstone, mudstone, conglomerate
	Pennsylvanian	Upper	Madera Formation	0 to 1,400	Limestone, shale, sandstone
		Middle	Sandia Formation	50 to 200	Sandstone, shale, limestone, conglomerate
	Mississippian	Osagean	Arroyo Peñasco Formation	0 to 100	Limestone
PRECAMBRIAN					Granite, gneiss, schist, quartzite