Coal deposits and facies changes along the southwestern margin of the Late Cretaceous seaway, west-central New Mexico

Compiled by Gretchen H. Roybal, Orin J. Anderson, and Edward C. Beaumont

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Prepared for
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Coal Geology Division Field Trip

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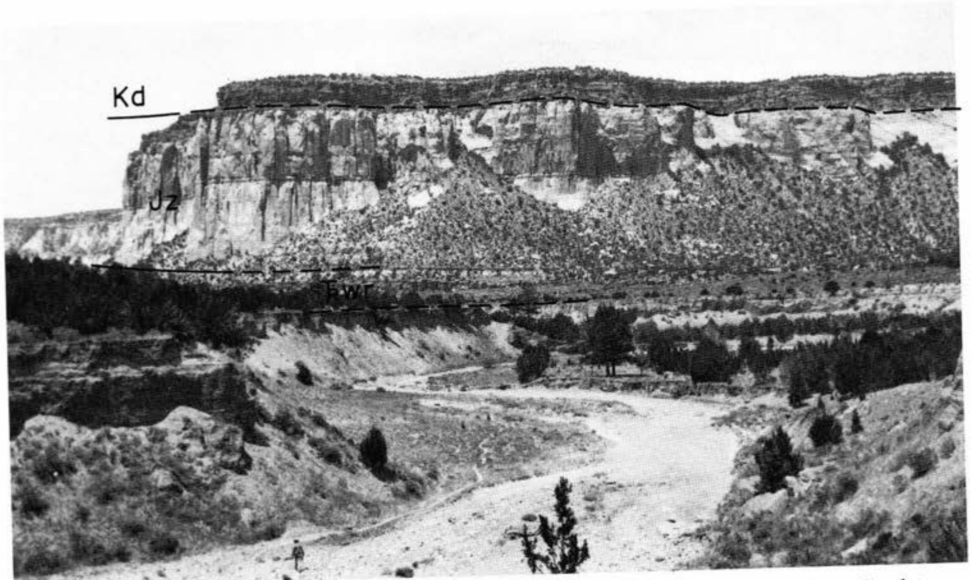
Nutria monocline near Upper Nutria, looking north. K = Dakota Sandstone, Jz = Zuni Sandstone, TRwr = Rock Point Member of Wingate Sandstone, TRc = Chinle Formation, Psa = San Andres Limestone. Photo O. J. Anderson.



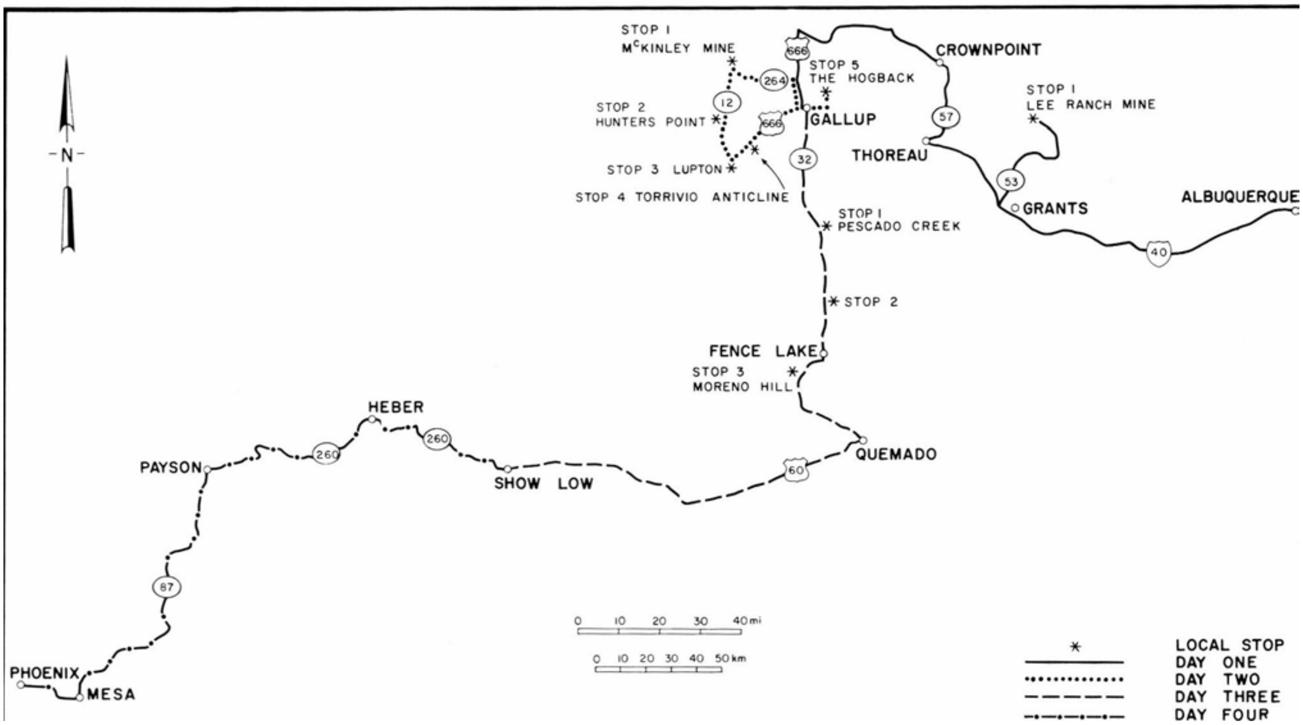
View to northeast of Taaiyalone Mesa (Corn Mountain) near Zuni Pueblo. Kd = Dakota Sandstone, Jz = Zuni Sandstone, TRwr = Rock Point Member of Wingate Sandstone, TRc = Chinle Formation. Photo O. J. Anderson.

Introduction

The idea for this field trip through west-central New Mexico was proposed by Fred Kuelimer (New Mexico Institute of Mining & Technology). The purpose was to look at the recent activity in the coal mining industry and the current geological investigations in this region. The route of the field trip goes through areas with excellent exposures of the lower two-thirds of the Late Cretaceous coal-bearing sequences and their marine counterparts, showing the facies relationships along the transgressive-regressive shoreline in the southern San Juan Basin. Several stops are planned to look at these sequences and discuss their depositional environments. The coal mines that will be visited (Lee Ranch, McKinley, Fence Lake No. 1) are different in both size and method of operation, a reflection of the extent of the coal resource and the quality characteristics of the coal.

The invited papers included in this guidebook cover the geology of west-central New Mexico, the hydrogeology of the area (a factor in coal mining), and the individual coal mines to be visited. Most of these articles represent recent work of the authors in areas which had not previously been looked at in such detail. It is hoped that the contributions are representative of the present knowledge of the Late Cretaceous in the southern San Juan Basin and outlying areas.

Many people have helped put this field trip and guidebook together, besides those specifically mentioned in the text. Frank E. Kottlowski (Director, New Mexico Bureau of Mines & Mineral Resources-NMBMMR) actively encouraged the participation of staff members and allowed many of us the time and support to work on this project. Ben Donagan (Leonard Resources) provided reference material for much of the Arizona part of the road log. Jiri Zidek (NMBMMR) edited this guidebook for publication. Kevin Cook (NMBMMR) helped with various phases of road logging and guidebook preparation. Lynne McNeil and Norma Baca (NMBMMR) did much of the typing. NMBMMR drafting section did several of the figures in the road log and articles.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STOP 1
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STOP 3 LUPTON
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STOP 5
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GALLUP
CROWNPOINT
STOP 1
LEE RANCH MINE
THOREAU
GRANTS
ALBUQUERQUE
STOP 1
PESCADO CREEK
STOP 2
FENCE LAKE
STOP 3
MORENO HILL
QUEMADO
SHOW LOW
HEBER
PAYSON
PHOENIX
MESA
666
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260
87
0 10 20 30 40 mi
0 10 20 30 40 50 km
LOCAL STOP
DAY ONE
DAY TWO
DAY THREE
DAY FOUR

FIRST DAY

Road log from Albuquerque to Gallup, New Mexico

(modified from Shomaker, 1981)

Edward C. Beaumont

3236 Candelaria NE, Albuquerque, New Mexico 87107

Mileage

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

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

1.50 At 2:30 is view of Albuquerque volcanoes and associated basalt flows. Volcanoes are aligned approximately north-south, probably indicting feeders along a fault. 5.5

7.00 Top of second terrace, the Llano de Albuquerque surface, cut in Santa Fe Group and capped by caliche having an average thickness of about 10 ft. At 10:00 in far distance is Sierra Ladrones, a large fault block of Precambrian rocks on the western margin of the Rio Grande trough. 7.2

14.20 Mesa de la Negra at 12:30-2:00, a localized basalt flow in the Santa Fe Group. **1.4**

15.60 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. **0.6**

16.20 Roadcuts in shale and sandstone of the Mesaverde group: Gibson Coal Member or higher beds of the Crevasse Canyon Formation. The Rio Puerco Mesaverde coal area is an irregular belt of outcrops of Upper Cretaceous Mesaverde Group rocks in the Rio Puerco valley, beginning about 25 mi west of Albuquerque and trending north-northeastward for a distance of about 40 mi. The Dilco and Gibson Members of the Crevasse Canyon Formation, both coal-bearing units of economic importance elsewhere in the southern San Juan Basin, are present in the area and both contain coal. The outcrops of the coal-bearing units occur, for the most part, within the Rio Puerco fault zone, a north-northeast-trending swarm of high-angle faults. As a result, the outcrops appear in narrow, steeply dipping blocks. The eastern part of the area is covered by thick sand and gravel deposits of the Cenozoic Santa Fe Formation, which in some places obscure coal-bearing rocks. **5.5**

21.70 Cretaceous sandstone in roadcut (Dakota); Mancos Shale crops out below the road in valley to left. **2.5**

24.20 Dakota Sandstone in cuesta at 2:30. **0.6**

24.80 Canoncito exit. **0.8**

25.60 East end of a long roadcut in Gallup Sandstone at base of Mesaverde Group. **3.85**

29.45 Underpass. **1.85**

31.30 Correo Sandstone Member of upper Chinle Formation in cliffs on right. **3.1**

34.40 Overpass. Cross tracks of AT&SF (Atchison, Topeka, and Santa Fe) Railroad. **1.6**

36.00 Bridge over Rio San Jose. Valley cut in Chinle Formation. **3.6**

39.60 Note slump features at 11:00. Todilto gypsum-anhydrite beds are 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. **0.4**

40.00 Sandstone dikes at 11:30 and 12:30. 0.9

40.90 Deep roadcut in Bluff Sandstone. 0.9

41.80 Basalt dike in Bluff Sandstone, both sides of roadcut. **1.4**

43.20 Laguna Pueblo at 3:00. Now within area covered by geologic map in Fig. 1. **5.0**

48.20 Exit to Acoma, Paraje, and Casa Blanca. **2.3**

50.50 Cross AT&SF railroad tracks. **1.6**

52.10 In next few tenths of a mile area a series of roadcuts in Brushy Basin Member of the Morrison Formation overlain by Dakota Sandstone. **0.4**

52.50 We have now climbed through the Morrison and Dakota sections and are riding on the dip slope of the Dakota Sandstone. 7.5

60.50 Between 9:00 and 3:00 exposures of uppermost Twowells Tongue of the Dakota. **2.2**

62.70 Now proceeding through McCartys basalt flow, no more than 2,000 yrs old. Fragments of Indian pottery have been found enclosed in basalt. Source is not Mount Taylor but small vents near eastern edge of Zuni Mountains 10-12 mi southwest of highway. **1.0**

63.70 Note pressure ridges in basalt and perched-water ponds. **6.6**

70.30 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. **0.8**

71.10 Grants exit. 5.5

76.60 Milan exit. Exit here and continue on to stop light. 0.5

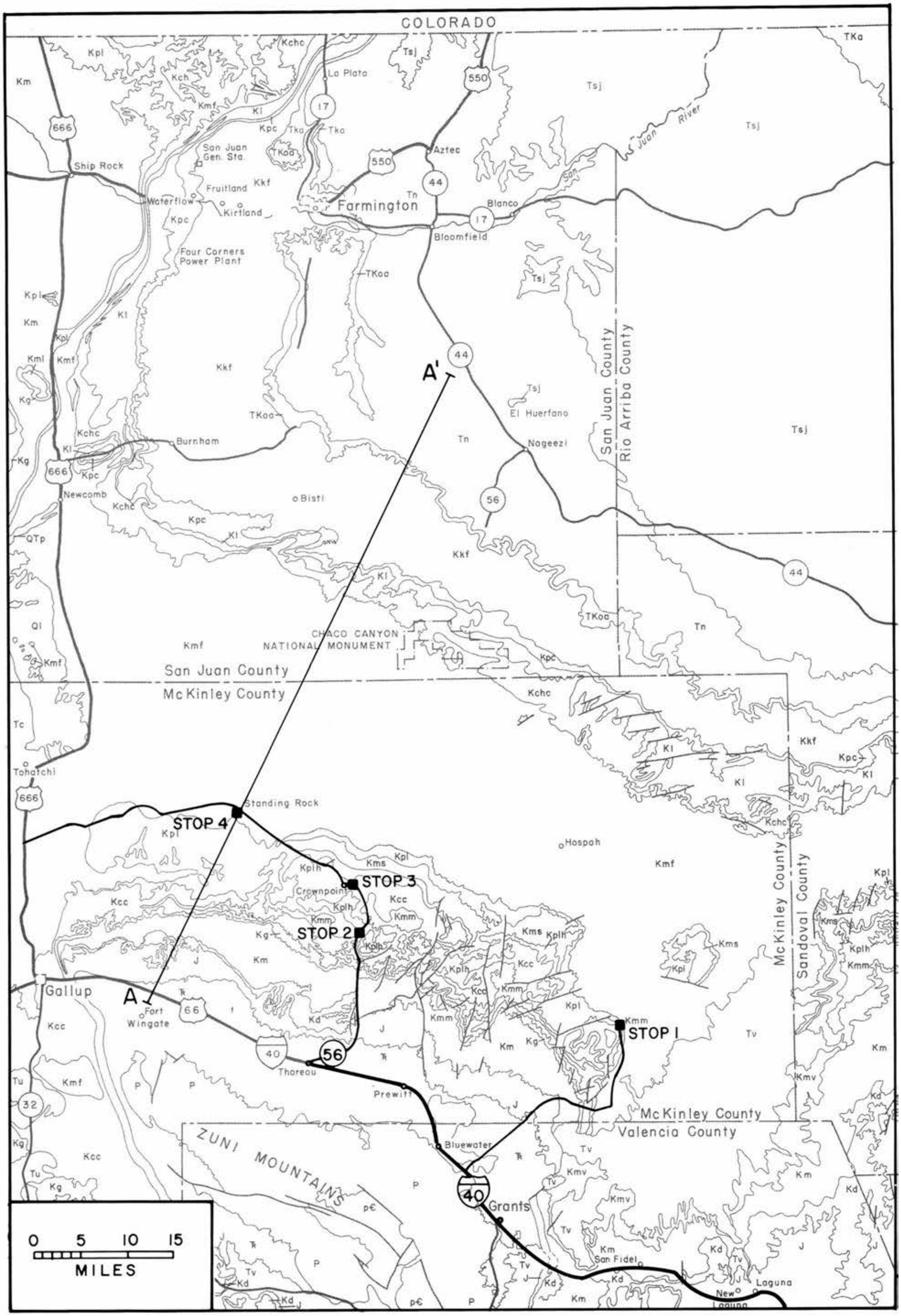

FIGURE 1—Geologic map of San Juan Basin with trip route and stops. Modified from Dane and Bachman (1965).

77.10 Turn left at stop light. **0.1**

77.20 Turn right at stop light, onto NM-53 to San Mateo. 3.8

81.00 Mill tailings pond at 10:00. Source of ongoing controversy with respect to groundwater pollution due to leaching by precipitation. **0.8**

81.80 Homestake Mining Company's mill. 1.2

83.00 View at 2:00 of Mount Taylor flanked by apron of extrusive basalt capping the mesa. Basalt underlain by Dakota and Morrison Formations. The Morrison contains, in descending order, the Brushy Basin, Westwater Canyon, and Recapture Members. 0.1

83.10 Old AEC (NRC) test pit on left side of highway. **0.9**

84.00 Low black knob at 3:00 is El Tintero, a volcanic plug. The high mesa to the right of this feature is Haystack Mountain. This is the site of the first uranium discovery in the Grants uranium district. **2.75**

86.75 McKinley County line. Salmon-pink sandstone cliffs to the west are Entrada Sandstone overlain by gray limestone beds of the Todilto Limestone, both Upper Jurassic in age. The thick gypsum deposit of the Todilto Formation seen in the vicinity of Canoncito (on I40) is not present here. **1.45**

88.20 Bluff Sandstone of Upper Jurassic age on left. We are going up in the section. **0.4**

88.60 Upper Jurassic Morrison Formation in the cliffs. Red sandstone is the Westwater Canyon Member of the Morrison. This is overlain by the Brushy Basin Member of the Morrison Formation. Note the irregular contact between the Brushy Basin Member and the overlying Cretaceous Dakota Sandstone, which represents a major unconformity 1.3

89.90 Dakota Sandstone cliffs on both sides of highway. **0.6**

90.50 Crossing valley developed on non-resistant Mancos Shale. Ambrosia Lake turnoff to left. Follow NM-53 straight ahead to San Mateo. **0.9**

91.40 Cuesta at 3:00 composed of limy siltstones in the Juana Lopez Member of the Mancos Shale. 1.3

92.70 Cliffs and knolls overlying Mancos Shale at 10:30-11:00 are Gallup Sandstone. The lowest sandstone visible below the cap rock is assigned to the lower part of the Gallup Sandstone. The shales exposed in the cliff wall are assigned the D-Cross Tongue of the Mancos Shale which intertongues with the Gallup sandstones. The sandstone cap is the main body of the Gallup Sandstone which has been referred to as the Gallegos Sandstone Member of the Gallup (Hunt, 1936). **0.6**

93.30 Cibola County line. Main body of the Gallup Sandstone capping cliffs on left side of highway. Highway is in Mancos Shale. Good view of Mount Taylor at 12:00-1:00. 1.0

94.30 Note transition zone of the shale of the D-Cross Tongue of the Mancos to the Gallup Sandstone at 3:00. The Gallup Sandstone is the first major regressive unit in Late Cretaceous time in the San Juan Basin after the sea had transgressed into southeastern Arizona. **0.8**

95.10 The covered valley we are traveling through is underlain by Dilco Coal Member of the Crevasse Canyon Formation and the Mulatto Tongue of the Mancos Shale. Outcrops on the left are of Dalton Sandstone Member of the Crevasse Canyon Formation. **0.5**

95.60 Cuesta at 3:00 is held up by the Hosta Tongue of the Point Lookout Sandstone. The carbonaceous to coaly streaks underneath the sandstone are part of the Gibson Coal Member of the Crevasse Canyon Formation. 0.3

95.90 Sandstones at bend in road are Point Lookout. Roadcut is in carbonaceous nonmarine Cleary Coal Member of the Menefee Formation which overlies the Point Lookout. The E-NE dip of the beds in the roadcut shows the regional dip associated with the San Mateo dome. **0.4**

96.30 Cliffs at 9:00 are capped by Point Lookout Sandstone with Gibson Coal and Dalton Sandstone Members of the Crevasse Canyon Formation in the underlying slopes. 1.0

97.30 Entrance to the Lee Ranch headquarters. **0.55**

97.85 Sandstone beds on the right are in the Cleary Coal Member of the Menefee Formation. **0.15**

98.00 Turn off to the village of San Mateo. **0.45** 98.45 Village of San Mateo at 3:00. Chevron's Mount Taylor Uranium mine at 2:30. Note giant head

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
		Ћ	Triassic, undifferentiated
		P	Permian, undifferentiated
		p€	Precambrian, undifferentiated

frame designed to operate at depths below 3,000 ft. 0.6

99.05 Cattleguard. 0.1

99.15 Turn off on Lee Ranch mine road to left. **0.2** 99.35 High cliffs at 12:00 are capped by Point Lookout Sandstone. **0.95**

100.30 Forest Service boundary at cattleguard. Pipeline on right of highway carries water from the Mount Taylor mine to Laguna Polvadera on the Lee Ranch. Water is from the Jurassic Morrison Formation, Westwater Canyon Member. **0.65**

100.95 Lee Ranch Mine road to left. Forest Service road to the right allows access to the top of Mount Taylor. **0.3**

101.25 Roadcuts in barren Menefee Formation (Allison). **1.10**

102.35 East-dipping beds on left side of highway are Point Lookout Sandstone. The dip of these beds shows the influence of the San Mateo dome. **0.6**

102.95 Crossing San Lucas Dam. The carbonaceous sediments exposed in the roadcut at the bend in the road are in the upper part of the Cleary Coal Member of the Menefee Formation. **0.9**

103.85 Sandstone on the left is Point Lookout, overlain by Cleary Coal Member in the roadcut to the right and above the road. **0.2**

104.05 Cleary Coal Member in roadcuts. The steep dip in this area precludes surface mining of coals in the Cleary Coal Member. These coals also tend to be thin (see Beaumont on Lee Ranch mine, this volume, for further explanation). **1.3**

105.35 Prominent feature at 2:00 is Cerro Alesna and associated volcanic plugs. **0.2**

105.55 Causeway across Leopoldo diversion dam. **0.3**

105.85 Note dip (18-24°) of massive Point Lookout sandstones at 12:00. **1.0**

106.85 The steep dip of the beds on the left side of the highway dissipates rapidly to the east-northeast, away from the San Mateo dome that is evident in the Cleary Coal Member outcrops on the right. **0.25**

107.10 Roadcuts in the Cleary Coal Member of the Menefee Formation. View to the north is essentially of Menefee outcrops. The Menefee Formation outcrop belt is approximately 25 mi wide, due to the generally low-angle dip of the beds. **2.85**

109.95 Entrance to Lee Ranch mine operated by Santa Fe Pacific Coal Corporation, a subsidiary of Santa Fe Industries. This mine has been in production since 1984, with the first shipment of coal in October 1984. Coal from the Lee Ranch mine is shipped by rail to the Springerville Generating Station in Arizona and the Escalante Generating Station near Prewitt, New Mexico. The coal is mined by truck and shovel method, with several seams being mined. The coal averages 9,200 Btu/lb, with variable sulfur content (see Beaumont, this volume).

STOP 1. Tour of the Lee Ranch mine.

Return to Milan. **32.85**

142.80 AT&SF Railroad tracks; turn left at light. **0.15**

142.95 Turn right at light. **0.20**

143.15 Turn right onto 1-40 access road. **0.20**

143.35 Enter 1-40 West. **2.9**

146.25 San Andres Limestone prominently displayed in bluffs at 10:00; north slope of Zuni Mountains visible to left of road. This ancient uplift marking the southern boundary of the San Juan Basin would appear to have been positive to some extent throughout most of Paleozoic and Mesozoic time. 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 roadcuts ahead. **1.3**

147.55 Vertical-walled roadcuts exposing wavy-bedded arenaceous limestone of the San Andres. 2.2

149.75 Haystack Mountain at 2:00, site of the initial discovery of uranium (in the Todilto Limestone) in the Grants uranium district. Manufacturing plant in 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**

151.35 Mouth of Bluewater Canyon at 9:00, with village of Bluewater in foreground. **2.4**

153.75 Chinle Formation (Triassic) resting on San Andres Limestone (Permian) from 10:00 to 11:00. 1.1

154.85 Highway rises into resistant area held up by the Sonsela Sandstone Bed, which occurs within the Petrified Forest Member of the Chinle Formation. **0.5**

155.35 McKinley County line. **3.2**

158.55 Highway passing through low hills held up principally by the Sonsela Sandstone Bed. **0.9**

159.45 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 are 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 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. **4.8**

164.25 Roadcuts in the Sonsela Sandstone Bed for next 0.4 mi. **1.2**

165.45 Roadcuts in the Petrified Forest Member of the Chinle. **1.3**

166.75 Panoramic view across valley to northwest of the upper part of Triassic sequence and the entire Jurassic. **4.0**

170.75 Thoreau exit. Turn off to right. **0.2**

170.95 Stop sign. Intersection with frontage road; turn left; El Paso Natural Gas Company pumping station on south side of 1-40. 0.3

171.25 Stop sign; turn right on NM-57; cross over AT&SF railroad tracks. **0.3**

171.55 Bear right on NM-57. **2.8**

174.35 Entrada and Todilto in cliff at left. **2.2**

176.55 Plains Electric Power Coop Escalante Station at 3:00. With an initial capacity of 233 megawatts, this generating station receives its fuel supply from the Lee Ranch mine in 42-car unit train deliveries. It is anticipated that this operation will eventually be expanded to a 1,000 MW maximum capacity. Plains Electric is a wholesaler that supplies electric power to 13 rural electric cooperatives in the region. **0.5**

177.05 Todilto Limestone at 10:00 is quarried for road material. **2.4**

179.45 Remnant of coal in the Dakota Sandstone in roadcut, both sides of road. The coal is just above rocks of the Morrison Formation (Jurassic) and thus is probably the oldest 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. **0.2**

179.65 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. **3.5**

179.65 Smith Lake Mercantile and Rod's Indian Jewelry on right side of highway. Cuesta behind stores is held up by Juana Lopez Sandstone Member (sometimes referred to as Sanostee) of Mancos Shale. This unit is about 100 ft thick and is composed of very fine-grained sandstone, siltstone, and calcarenite. It is interpreted as representing accumulation and reworking of sediments in a shallow sea during the Carlile cycle of sedimentation. 1.3

180.95 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 one to three thin seams from 1.5 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 coarsest material. An interesting aspect of this layer of quartzite clast 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 felt on the surfaces of the clasts. Stresses sufficient to fracture rock fragments that had already survived the trials of transport would appear unlikely in this area of relatively minor tectonic activity. 0.3

181.25 Road is in the upper part of the Dilco Coal Member, close to the contact with the overlying Mulatto Tongue. **0.8**

182.05 Bend in the road; good view of the Mesa de los Lobos region. We are close to the DiIco-Mulatto contact; sandstones to the right of the highway are in the Dilco Coal 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 are two or three beds ranging in thickness from 2.5 to 4 ft (Sears, 1936). 1.3

183.35 Lower scalloped sandstone cliffs to right of highway formed on Dalton Sandstone Member. **0.7**

184.05 Entrance to Satan Pass. Relatively steep dip to the east in this area is associated with a north-trending minor monoclinal fold compounded by a series of normal faults. Faulting, generally not prominent in the San Juan Basin, occurs more frequently 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. **0.6**

184.65 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 gully immediately to the right of the highway. The Mulatto-Dilco contact is exposed in this gully. Coal beds visible on the left side of the highway as we approach this point are in the Dilco Coal 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 them over 2.5 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 right-hand (east) end of the Mesa de los Lobos, on the west side of Satan Pass, the thickened Point Lookout Sandstone is interrupted in the middle by a narrow bench. This bench marks the position of the southwest-thinning Satan Tongue of the Mancos Shale, 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° 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**

185.05 Excellent exposure of the contact between the gray shales of the Mulatto Tongue and the Dalton Sandstone at 3:00. **0.8**

185.85 **STOP 2.** 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 drag-folding. From 10:00 to 11:00 to the right of the fault, the lower slopes are in the Gibson Coal Member within which is visible a prominent medial sandstone. 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 Member. **0.8**

186.65 Low cliffs on both sides of highway formed by Dalton Sandstone. **0.4**

187.05 Descending the north side of Satan Pass; highway in Mulatto Tongue. **1.5**

188.55 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 dip gently to the north and northeast on the Chaco Slope sector of the San Juan Basin, as described by Kelley (1950). **0.8**

189.35 Highway ascends from Mulatto Tongue into the Dalton Sandstone. **1.9**

191.25 Small bluff at 10:00 exposing shale and coal in the lower part of the Gibson Coal Member. **0.4**

191.65 Intersection. Turn left on road to Crown-point. **0.7**

192.35 STOP 3. Crownpoint. Shales and coal beds in the upper part of the Gibson exposed beneath the Hosta Tongue in low mesas on both sides of road. Studies have been conducted on the Crevasse Canyon Formation because of its fossil-pollen content. **0.1**

192.45 Enter Crownpoint, New Mexico. Bluffs capped by light-colored Hosta Sandstone Tongue rim the village. **0.15**

192.60 Stop sign; continue straight ahead.
0.15 192.75 Stop sign; turn right. **0.2** 192.95
Stop sign; turn left. **0.2** 193.15 Coals and
shales in the Gibson Coal Member
exposed to the left of the highway and in the gully on the right side. 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 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**

193.75 Church; outcrops of coal to right of road. **0.2**

193.95 Coal in the Gibson Member **0.2**

194.15 End of pavement; turn half-right on dirt road (Navajo 104). **0.6**

194.75 Thin Gibson coal bed forms persistent pothole in road. **0.15**

194.90 Intersection with paved road (Navajo Highway **9); turn left. 0.35**

195.25 Panorama of Mesa de los Lobos at 9:00. Cap is Point Lookout Sandstone, with the prominent break below it representing the Satan Tongue of the Mancos and the ledge below that formed by the Hosta Tongue of the Point Lookout. The lower slopes are Gibson Member, including several thin coals near the top. Route lies on, and along strike of, gently north-dipping Chaco Slope that represents the transition between the Zuni uplift to the south and the San Juan Basin to the north. **4.7**

199.95 Top of rise; Dalton Pass at 8:30. Road is on the Satan Tongue of the Mancos, with the Hosta Tongue of the Point Lookout just below. The Point Lookout, and above it all the way to the skyline the Menefee Formation, can be seen on the right. 1.9

201.85 Roadcuts on the left are in the Point Lookout. 0.7

202.55 Long, low ridge on left and parallel with road is Satan Tongue overlain by Point Lookout. The Point Lookout here consists of two rusty-brown ledges, with anomalous radioactivity due to high concentrations of titanium (Chenoweth, 1975). **1.0**

203.55 Panorama of the eastern end of Navajo Tribal Utility Authority's (NTUA) coal mine to-be on the right. A tract about 10 mi long, generally paralleling the highway on the north, has been drilled at fairly close spacing. A resource of somewhat above 200 million tons has been estimated, with heating value averaging around 9,500 Btu/lb, ash averaging approximately 13%, and sulfur on the order of 0.7%. **1.45**

205.00 Sandstones in basal Menefee Formation, termed the Cleary Coal Member, in bluffs at 3:00. The principal coal zone in the NTUA project area lies below these sandstones. At this point, the zone includes about 18 ft of coal; its projected outcrop is between the road and the hogans at the foot of the bluff. **0.15**

205.15 Evidence of burned coal in low roadcuts. The stratigraphic position is at the top of the principal coal zone. **0.4**

205.55 Coal in roadcuts. **0.2**

205.75 Exploratory water well for NTUA project, 250 yards from road at left. The well is 2,657 ft deep and is completed in the Jurassic West-water Canyon Member of the Morrison Formation. **1.4**

207.15 **STOP 4.** Standing Rock. The principal coal zone of the Cleary Coal Member, the basal Menefee Formation, crops out here and is partly burned. In a drill hole about 0.5 mi to the north, on top of the hill east of the water tower, the zone consists of two beds totaling 13 ft. At this location though, and in drill holes in a trend northeastward from here and about 0.5 mi wide, the coal is much thinner or absent. The "want" seems to represent a channel through the swamp, subsequently filled with sandstone. **1.2**

208.35 Clinker hill at 9:00. The coal burned here was an outlier of the principal coal zone. **1.7**

210.05 The Chuska Mountains, a dissected plateau capped by Tertiary Chuska Sandstone and volcanics, on the skyline from 1:00 to 2:30. The Chuskas lie more or less on the Arizona state line. 0.8

210.85 Long roadcut in sandstone bed near the base of the Menefee Formation. A very thin coal can be seen near the bottom of the cut at left. 1.3

212.15 Clinkered coal, black shale, and sandstone from 3:00 to 4:00 are at the base of the Menefee. The coal is part of the principal zone, which in this area contains one bed 7-10 ft thick. 0.2

212.35 Highway crosses the easternmost of at least three northeast-trending faults which control the valley of Soft Water Wash and mark the western end of the NTUA project area as presently envisioned. The faults offset the coal-bearing rocks by as much as 100 ft near the highway, but die out northeastward so that there seems to be no displacement beyond about 3 mi down the valley. The displacement is downward to the east. The faults coincide with a northeast-trending "want," apparently similar to the one that intersects the highway near Standing Rock. 3.1

215.45 Curve, Point Lookout dip slope along left side of highway. 1.1

216.55 Good Look at the Point Lookout in Wild Berry Canyon and other canyons on left. The Menefee-Point Lookout contact is not far from the road on the left. The axis of a broad north-trending syncline crossed the road about here. 1.5

218.05 Crossing Menefee-Point Lookout contact, climbing the east limb of the north-plunging Coyote Canyon anticline. **0.5**

218.55 Excellent exposures of Point Lookout Sandstone on both sides of road. **1.0**

219.55 Crest of Coyote Canyon anticline. The Chuska Mountains are from 1:30 to 2:30, with the Chuska Valley at their foot. Ford Butte and Bennett Peak, two exhumed plugs, at 3:00. Shiprock, "one of the world's most impressive exhumed intrusive plugs" (according to the 1967 New Mexico Geological Society Guidebook) is about 65 mi away at 3:30. **2.4**

221.95 Coyote Canyon Trading Post and day-school. Note the flat dips in the Point Lookout, in contrast with the textbook form of the anticline just behind us. 1.6

223.55 Crossing Point Lookout-Menefee contact again. The road is now descending into the Gallup sag-a structural feature that is also marked by a topographic low. Dips are now to the west. 1.9

225.45 Crossing under powerlines. The Point Lookout is at about 200 ft here, and the Menefee Formation includes several coals, up to about 4 ft thick, just above this. **0.3**

225.75 Cuts in Menefee Formation. **4.5**

230.25 Panorama of the southern Chuskas from 12:00 to 4:00, Menefee Formation capped by Chuska Sandstone. **0.8**

231.05 Intersection with U.S. 666; turn left. The shoreward pinchout of the Point Lookout is beneath us near this position, as can be deduced from a careful examination of Fig. 1, and from here southwestward the Menefee lies directly upon the Crevasse Canyon and the distinction between the two is lost. **0.5**

231.55 Hills in Menefee on right; bluffs across the Menefee Valley to left exposes the Gibson Coal Member, the Bartlett Barren Member, the Dalton Sandstone Member, and the Dilco Coal Member of the Crevasse Canyon Formation in the westward-dipping Nutria monocline. The Nutria monocline is the steep western boundary of the Zuni uplift; the Coyote Canyon anticline, which the route crossed between miles 218.05 and 219.55, is about at the nose of the uplift, where the Nutria structure merges into the gently north-dipping Chaco slopes. **1.5**

233.05 Twin Lakes School. **3.0**

236.05 Menefee Formation in roadcut and bluffs. **0.2**

236.25 Leaving the Navajo Reservation. **0.6**

236.85 Road climbs Menefee Formation bluff. The highway is more or less on the axis of the Gallup sag, which is almost V-shaped, with fairly uniform dips of about 300 ft/mi on both sides. Most of the water supply for the City of Gallup is drawn from wells in the Gallup Sandstone in this vicinity, which at this point is at a depth of about 1,700 ft. The Point Lookout is of course absent here, so the basal Menefee, or Clearly Member, is indistinguishable from the Gibson Coal Member of the Crevasse Canyon (see Fig. 2) and the two form a single coal zone. In a hill just to the left of the road and about 0.8 mi beyond the top of the climb, the Gibson–Cleary zone lies between 955 and 1,060 ft and includes a coal bed about 9 ft thick, two beds about 4 ft thick, and several thinner ones. **1.8**

238.65 Intersection with NM-264. **0.2**

238.85 Top of overpass. 0.75

239.60 Roadcuts in Allison Barren Member. **1.95**

241.55 Houses on left are at China Springs, a contact spring draining the small sandstone cap—part of the Allison Barren Member. **1.5**

243.05 Community of Gamerco on right. Tall stack and abandoned headframes mark, respectively, the ruins of the Gallup Electric Company power plant and the No. 5 mine of the Gallup American Coal Company. The mine was opened in 1922 through a 785 ft shaft and was equipped to produce 4,000 tons/day from the No. 5 bed of the Gibson Member. The mine served the power plant until the mid-1940's, at which time the plant was converted to natural gas. Gamerco, whose name derives from that of the coal company, was the company town associated with the No. 5 mine and several others in the vicinity. **1.6**

244.65 Beds of the Gibson (in reality the merged Gibson and Cleary, of course) dip northwest toward the road and under the Allison Barren Member. **0.9**

245.55 Entering Gallup. Gallup is situated on a sharply asymmetrical anticline within the Gallup sag; its eastern limit is the Nutria

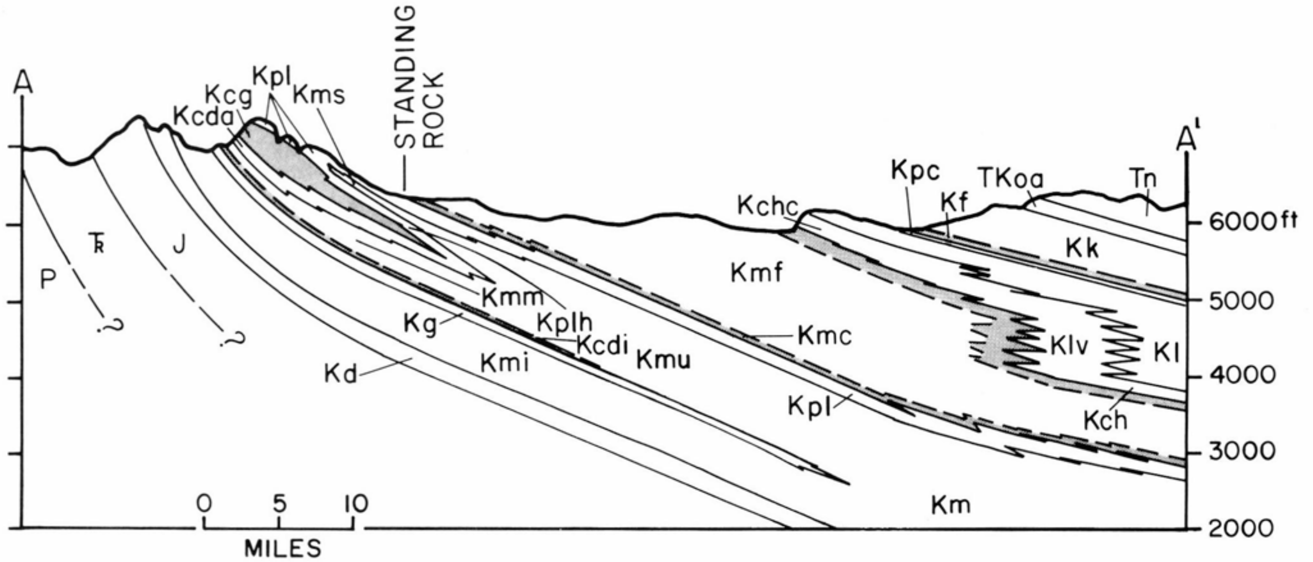

FIGURE 2—Diagrammatic cross section of western San Juan Basin showing relationship of Cretaceous units. Coal-bearing units shown in shaded pattern. See Fig. 1 for line of section. Tn = Nacimiento Formation, TKoa = Ojo Alamo Sandstone, Kk = Kirtland Formation, Kf = Fruitland Formation, Kpc = Pictured Cliffs Sandstone, Kl = Lewis Shale, Kchc = Chacra Tongue of Cliff House Formation, Klv = La Ventana Tongue of Cliff House Sandstone, Kch = Cliff House Sandstone, Kmf = Menefee Formation, Kmc = Cleary Coal Member of Menefee Formation, Kpl = Point Lookout Sandstone, Kms = Satan Tongue of Mancos Shale, Kplh or Kh = Hosta Tongue of Point Lookout Sandstone, Kmcg = combined Gibson Member of Crevasse Canyon Formation and Cleary Member of Menefee Formation, Kcg = Gibson Coal Member of Crevasse Canyon Formation, Kcb = Bartlett Barren Member of Crevasse Canyon Formation, Kcda = Dalton Sandstone Member of Crevasse Canyon Formation, Kmm = Mulatto Tongue of Mancos Shale, Kmu = upper part of Mancos Shale, Kcdi or Kcd = Dilco Coal Member of Crevasse Canyon Formation, Kg = Gallup Sandstone, Km = Mancos Shale, Kml = lower part of Mancos Shale, Kd = Dakota Sandstone, J = Jurassic undifferentiated, Ŧ = Triassic undifferentiated, P = Permian undifferentiated.

monocline, the steep west-dipping face of which is visible on the skyline beyond the town, reaching the crest of the anticline about 1 mi east of our present position. The western limb of the anticline, just east of the road, is a steep monoclinal flexure. 0.3

245.85 Stop light, continue ahead. 0.15

246.00 Stop light, continue ahead. 0.35

246.35 1-40 overpass. 0.15

246.50 AT&SF overpass. 0.15

246.65 Intersection; turn right. 0.15

246.80 Intersection; turn right. 0.15

246.95 Stop light; turn left on U.S. 66. 2.35

249.30 The Inn of Gallup on left.

SECOND DAY
Road log from Gallup, New Mexico, to Window Rock, Arizona

(modified from Shomaker, 1981)

Edward C. Beaumont
3^{2}36 Candelaria NE, Albuquerque, New Mexico 87107

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0.0 Depart from the Inn. Retrace log of first day to intersection with NM-264. 10.65

10.65 Ya-Ta-Hey, turn left on NM-264. 0.55

11.20 Roadcut in shales of Allison Barren Member of Menefee Formation, which is exposed over a large area in central part of the Gallup sag. "Allison" is properly used only in the Gallup area; northward, it has not been applied to stratigraphically equivalent beds in the Menefee Formation. 2.1

13.30 Road junction left to Rock Springs, Rock Springs Ranch. Principal distinction between Allison Barren Member and underlying Cleary-Gibson Members is the absence of minable coal in the Allison. 2.2

15.50 Roadcut in Allison. In the last major revision of stratigraphic nomenclature of the Upper Cretaceous in this region (Beaumont, Dane, and Sears, 1956), the Lower Gibson Coal Member was placed within the Crevasse Canyon Formation and the Upper Gibson Coal Member was changed to the Cleary Coal Member and placed in the basal part of the Menefee Formation. In the absence of the Point Lookout Sandstone which over a large area separates these units but pinches out a few miles north of this position, the two coal-bearing members of the two formations are indistinguishable from one another in a sequence that originally was, quite simply, the Gibson Coal Member of the Mesaverde Formation. Thus, under the present stratigraphic terminology, the formational boundary lies somewhere within the undivided Gibson-Cleary Coal Member. Sandstone bluffs ahead and to the right are lenticular fluvial deposits within the Allison Barren Member. 4.0

19.50 Sandstone-capped mesas at 3:00 are an indication of the predominantly sandy character of the lower part of the Allison Barren Member. Some thin coal becomes visible in lower slopes as we descend stratigraphically into the Cleary Coal Member of the Menefee Formation. 0.9

20.40 Tse Bonito School on right. Road is following a broad syncline that plunges eastward to join the Gallup sag, and as a result we are moving down in the section as we go westward. 1.2

21.60 Roadcut in the Gibson-Cleary. 0.2

21.80 Bottom of Defiance Draw. Turnoff to left leads to old facilities of McKinley mine. Hills on both sides are in the uppermost Gibson-Cleary section, which usually is less sandy than the overlying Allison Barren Member. 0.5

22.30 Crossing railroad tracks. Coal near top of Gibson-Cleary can be seen beneath sandstone lens on left. 0.2

22.50 Reclaimed mined lands of the McKinley mine on both sides; good grass cover has been established. If mining continues, the whole neighborhood will resemble a park. The mine operations lie on both sides of the road. 1.7

24.20 Backslope of Gallup Sandstone at 10:00-2:00. The Gallup and older rocks are caught up in the sinuous east-dipping Defiance monocline that lies just west of the McKinley mine and represents the boundary between the Defiance uplift to the west and the Gallup sag to the east. **0.8**

25.00 Intersection with road to McKinley mine facilities; turn right. Note abrupt change of dip, from steep monoclinal structure on the left to nearly flat dips on the right. 0.2

25.20 Bartlett Barren and Dilco Coal Members of the Crevasse Canyon Formation on the right, Gallup Sandstone on the left. 2.3

27.50 Crossing under railroad tracks. **0.2**

27.70 **STOP** 1. Gate at mine office. The road log will resume at this point on the return trip, after a short tour of the mine. **0.2**

27.90 Good view of Defiance monocline at 10:00-11:00. **2.35**

30.25 Intersection with NM-264; turn right toward Window Rock. **0.2**

30.45 Going through Coal Mine Wash and under powerlines. 0.5

30.95 Road follows Tse Bonito Wash and goes through gap in Defiance monocline. **1.6**

32.55 Window Rock. Intersection of Navajo Highway 12 and NM-264.

Road log from Window Rock, Arizona, at intersection of Navajo Highways 12 and 264, to Lupton, Arizona, via Navajo Highway 12

(modified from Huffman, Condon, and Thaden, 1984)

Orin J. Anderson

New Mexico Bureau of Mines & Mineral Resources, Socorro, New Mexico 87801

Mileage

32.55 At intersection of Navajo Highways 12 and 264, at traffic light; proceed west on 12 and 264. 1.9

34.45 Routes divide at intersection; turn left and proceed south on Navajo Highway 12 toward Lupton. Roadbed is on the Upper Triassic Chinle Formation or alluvium-covered Chinle for approximately next 7 mi. **1.0**

35.45 St. Michael's School on right. 1.6

37.05 At 9:00 some spoil piles of the Pittsburg and Midway Company's McKinley mine developed in the Gibson Coal Member of the Crevasse Canyon Formation and the Cleary Coal Member of the Menefee Formation. Mine was opened in 1961; much of the coal goes to the APS Cholla Generating Station, Joseph City, Arizona. 2.0

39.05 Hunter's Point School and water tank on right. 0.6

39.65 On left at 8:30, note Upper Jurassic Morrison Formation exposed in section with steep southward dips; the Morrison is progressively beveled off to the south by pre-Dakota erosion. 1.4

41.05 Hunter's Point, a salient along the east-facing Defiance monocline on right; good view of a dip slope developed on the Permian DeChelly Sandstone, the equivalent of the Glorieta in New Mexico. **1.1**

42.15 Turn right (west) onto dirt road and bear left. 0.35

42.50 **STOP 2.** Our location is about 3 mi west of the Arizona—New Mexico state line (Fig. 1) and we are on the Hunter's Point quadrangle mapped by Condon (1986). Condon described Hunter's Point as the faulted anticlinal core of the Defiance uplift (Fig. 2) with approximately 4,000 ft of structural relief. As we are nowhere near the center of the uplift, perhaps the term core is not entirely appropriate; our view here is of the anticlinal bend of the east-facing Defiance monocline which forms the eastern margin of the Defiance uplift. The monocline is characterized by short, diagonal cross folds giving it a "wrinkled" outline in plan view. Kelley (1955) thought that this wrinkling or "right lateral buckling" indicated some right-lateral shift during compression and upthrusting, but gave no specific example of thrusting along the Defiance structure. Condon (1986) showed a normal fault truncating the eastern edge of the monocline, but this normal faulting may be younger than the Laramide compression which produced the uplift. One considera-

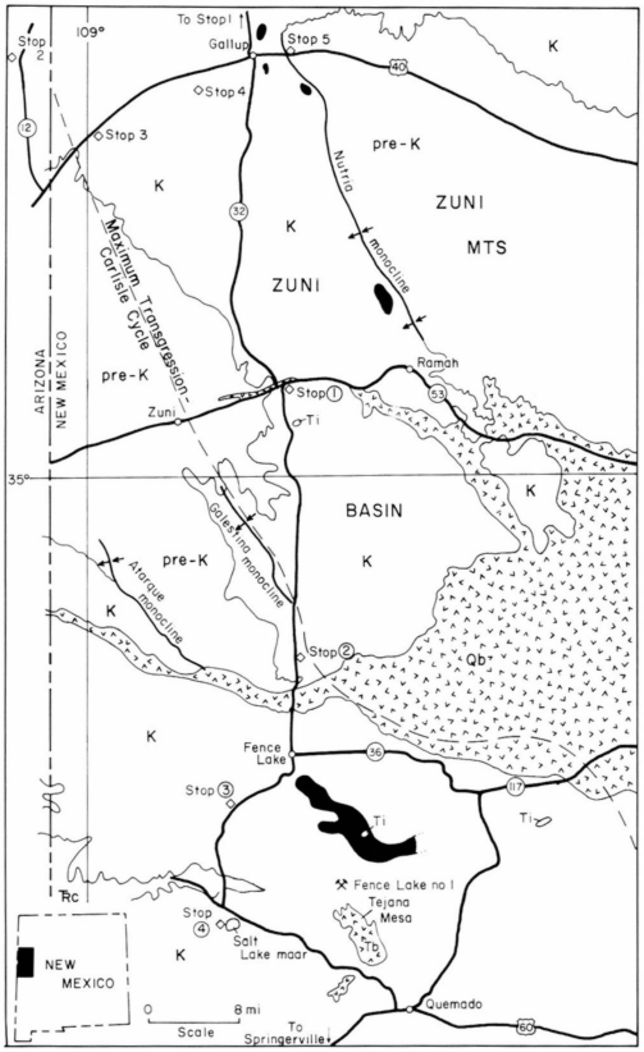

FIGURE 1—Index map of the Zuni Basin and the area covered by second- and third-day road logs. Stops are indicated by diamonds and third-day stops are circled. Qb = Quaternary basalt flows (pattern), Ti = Tertiary intrusives, Tb = Tertiary basalt, Trc = Chinle Formation, K = Cretaceous rocks. Blackened areas indicate thicker coal occurrences or previously mined area. Coal data from Sears (1925), industry sources, and Roybal and Campbell (1981).

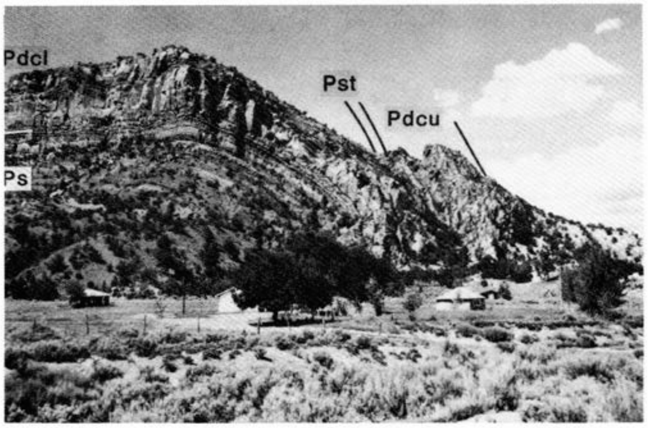

FIGURE 2—Defiance monocline at Hunter's Point, at Stop 2. Ps = Supai Formation, Pst = Tongue of Supai, Pdcl = lower part of DeChelly Sandstone, Pdcu = upper member of DeChelly Sandstone. View is to the north.

tion is that this is a zone of transpression along a right-lateral strike-slip fault, with the fault plane dipping to the west at a high angle. Extrusion of material and vertical movement within a zone of transpression would result in high-angle reverse faults. A high-angle reverse fault in the crystalline basement could account for the abrupt flexure in the Permian and Triassic sedimentary sequence exposed here.

Turn around and return to pavement. **0.35**

42.85 At intersection with Navajo Highway 12 turn right and proceed southward. **0.50**

43.35 Obliquely crossing the anticlinal limb of the Defiance monocline. **1.70**

45.05 At 9:00 view of the northern portion of the Zuni uplift, about 25 mi east of us; in between is northern portion of the Zuni Basin. **0.30**

45.35 Road descends through light pinkish-gray outcrops of the eolian Cow Springs Sandstone, Middle Jurassic. **1.0**

46.35 At 9:00 note the series of light-colored knobs developed on moderately eastward-dipping Cow Springs Sandstone. **1.2**

47.55 At 11:00 note the slightly darker-colored, even-bedded Dakota Sandstone overlying the Recapture Member of the Morrison Formation; road now descends into a strike valley developed on the Chinle Formation. **2.2**

49.75 The Dakota (tan) and Recapture (light pinkish gray) contact is visible on the skyline at 10:00-11:00. 0.3

50.05 Crossing Black Creek; at 1:00 the east-facing Defiance monocline is well exposed. 1.1

51.15 Canyon at 3:00 has cut through the DeChelly Sandstone and exposed in the red beds of the underlying Supai Formation. **0.5**

51.65 Cliffs on left of road expose the entire Jurassic section-the Entrada Sandstone at base, the Cow Springs Sandstone, and the Recapture Member. **2.1**

53.75 Chinle exposed in roadcuts. 0.7

54.45 The northward pinchout of the "beds at Lupton" in the hogback on left. The "beds at Lupton" are conglomeratic fluvial channel sandstones thought to be in the upper part of the Chinle or in the Rock Point Member of the Wingate Sandstone. **0.6**

55.05 Roadcuts on left expose the dark reddish-brown and purple mudstones and sandstones of the Rock Point Member. **1.1**

56.15 The "teapot" formed in an eolian facies of the Recapture is visible at 9:00 **.0.4**

56.55 The reddish-brown ridge along east side of road is developed on the "beds at Lupton." **1.1**

57.65 At 9:00 the east-dipping "beds at Lupton" form the hogback in the middle distance. In distance note the natural amphitheaters in the rounded-cliff-forming Cow Springs, overlain by talus covered Recapture Member 1.0

58.65 Ridge on east side of road is on part of the Petrified Forest Member of the Chinle Formation. **0.6**

59.25 Cross under 1-40. 0.1

59.35 Stop sign at intersection with south frontage road; bear left (east) and proceed toward Lupton, Arizona, and Gallup, New Mexico. **0.2**

Road log from Lupton, Arizona, to Gallup, New Mexico

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Mileage

59.55 Santa Fe Railroad tracks parallel frontage road on the right. 0.7

60.25 At about 9:00 and 11:00 note a horizontal notch in the lower portion of the rounded cliffs; this perhaps is the "Todilto notch" with the Entrada below and the Cow Springs above. But is this a mappable contact? To the south this Entrada-Cow Springs eolian interval has been mapped as the Zuni Sandstone (Anderson, 1983, 1987). 0.2

60.45 Intersection with paved road to the south; straight ahead 0.25 mi is Lupton, Arizona, elevation 6,183 ft, *but* turn right here and cross Santa Fe Railroad tracks. After crossing tracks note the 600 ft of section straight ahead in which the Entrada and Cow Springs are exposed overlain by the Recapture. The Recapture is largely eolian at this point, but most of the USGS investigators have in this area differentiated it from the underlying eolian units on the basis of (1) the thin reddish-brown mudstone, siltstone, or very fine-grained silty sandstone beds in the Recapture-much better seen on the north side of 1-40; and (2) the assumed presence of the J5 unconformity at the base of the Recapture, which is the break between Middle and Upper Jurassic rocks. If the J-5 is present here, it is a disconformity; but a close look at the section locally reveals that, if anything, perhaps only a diastem exists. Maxwell (1976) indicated that in the Acoma Pueblo area the Morrison Formation consists only of the Brushy Basin Member. Maxwell (oral comm. 1987) further believes that the major unconformity at the base of the Brushy Basin represents the break between Middle and Upper Jurassic rocks; as no major unconformity in the Jurassic section is evident here, Maxwell would have no portion of the Morrison Formation present. The lack of age-diagnostic fauna in these continental rocks makes regional correlations very difficult; therefore, tracing unconformities has become an important method. 0.7

61.15 Crossing Arizona-New Mexico state line. **0.1**

61.25 Road crosses the Rio Puerco (of the west) and continues on a very old floodplain of the Rio Puerco. Watch for rough stretches of road and grazing animals for next 10 mi. **0.5**

61.75 On right in light-colored cliffs note planar crossbed set visible in Cow Springs Sandstone. Flat-bedded intervals are also common and suggest some reworking periodically during deposition of eolian sediments. The "hollows" or natural amphitheaters are a characteristic of the Cow Springs. **0.6**

62.35 Dirt road to right; continue straight ahead. The mesa at 12:30-2:30 is capped by the coarser-grained, darker-colored Dakota Sandstone; the Dakota here ranges from 95 to 120 ft in thickness and unconformably overlies the Recapture Member. This K/J unconformity has up to 20 ft of relief on it locally, and represents a ±35 my gap. **0.4**

62.75 Variegated color of Cow Springs Sandstone (very light-red or pink lenses) noticeable at 2:30. **0.8**

63.55 Just to right of the notch in the mesa top, at about 2:00 and about midway up, large-scale, planar, southwest-dipping crossbeds are visible in the Cow Springs (below the talus-covered bench). As we proceed, also note the natural amphitheaters and flying buttresses which are typical weathering features of the Cow Springs. **0.7**

64.25 At 10:00, the "Todilto notch" marks a color change with the light colors below; these colors, however, may be very superficial. **0.4**

64.65 Rest area for eastbound 1-40 traffic on left; slow and proceed straight ahead, and watch for pedestrians. Excellent exposures of cross-bedded sandstone may be seen in rounded cliffs of Cow Springs on right. **0.5**

65.15 Box canyon on right at 2:00; at this point we are passing the boundary between the Surrender Canyon quadrangle on the west and the Manuelito Canyon quadrangle on the east; the latter has been mapped by Anderson (in prep.). **0.6**

65.75 At 1:30 note the K/J unconformity; a very thin carbonaceous shale may be seen preserved on the unconformity at this point; normally the basal Dakota is conglomeratic, with chert and quartzite pebbles. The Dakota is the basal unit of the Upper Cretaceous section (see Fig. 3). **0.3**

66.05 Dirt road to right leads into Manuelito Canyon with excellent exposures of the K/J unconformity; proceed straight ahead. **0.1**

66.15 Road crosses Manuelito Creek; at 11:30 note massive Dakota outcrop. **0.2**

66.35 At 9:00 to 11:00 a deltaic (?) sequence in the upper part of the Dakota. Dips here are 2-4° NE. **0.3**

66.65 At 2:00 note talus-covered, slope-forming Mancos Shale that overlies the Dakota and is overlain by the Gallup Sandstone-a shoreface- and wave-dominated deltaic sequence. **30.4**

67.05 **STOP 3.** Pull off to right-hand side of road and watch for traffic! The light-colored (tan) sandstone exposed in the lower roadcuts ahead is the Twowells Tongue of the Dakota Sandstone (see Fig. 3).

The Twowells Tongue in the Zuni Basin off to the south (Fig. 1) generally lies 50-70 ft above the main body of the Dakota and is the uppermost of the intertongued DakotaMancos sequence so well displayed in the Paguate area we passed on the first day. The interval here, however, is much less than the typical 50-70 ft, perhaps as little as 20 ft. The top of the Twowells Tongue is commonly marked by the presence of an oyster bed containing almost exclusively *Pycnodonte kellumi* and forms transitional between *P. kellumi* and *P. newberryi*. The oysters are present here weathering out of the shale immediately above the Twowells Tongue. Also note the burrowed and bioturbated nature of the Twowells Tongue here.

Approximately 40 ft above the Twowells Tongue, thin beds of the Bridge Creek Limestone Member of the Greenhorn Formation can be found locally. Although no good outcrops of the Bridge Creek beds are found here, it does occur as float above the Twowells Tongue; look for slabs of limestone or calcarenite 2-4 in. thick, lying on the shale above the Twowells Tongue. The slabs contain dark-

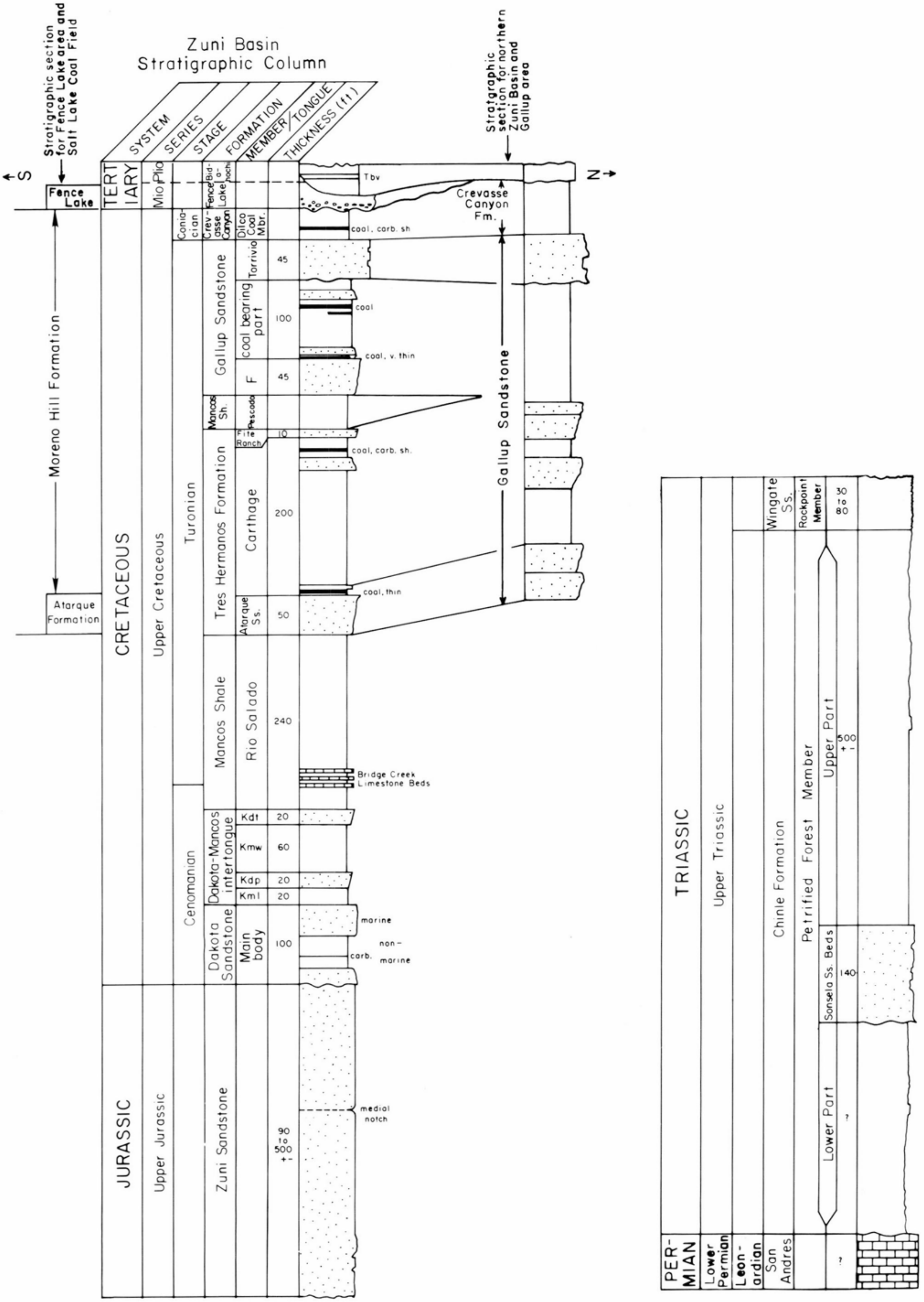

FIGURE 3—Composite stratigraphic column for the Zuni Basin; also shown are the relationships to the stratigraphic sequences at the southern and northern ends of the basin. Not shown are remnants of the Morrison Formation (Jurassic) present in the northern part of the basin. After Anderson (1987).

colored inoceramid debris. The oyster *P. newberryi* generally occurs in or just above the Bridge Creek Limestone beds throughout the Zuni and Acoma Basins; careful examination of the float here may produce specimens of *P. newberryi.*

The white- to orange-weathering zones in the shale above the Twowells are bentonite beds, the alteration product of thin ash falls. Selenite crystals are found in association with, and weathering out of, these bentonite beds. This portion of the Mancos Shale between the Twowells and the Gallup Sandstone is the Rio Salado Tongue. The name Rio Salado is generally restricted to the portion of the Mancos between the Twowells Tongue and the Tres Hermanos Formation; although the Tres Hermanos and the Gallup cannot be recognized as separate units in this area, the basal Gallup is genetically and lithologically (and probably temporally) equivalent to the Tres Hermanos, so the name Rio Salado is used for the underlying unit to avoid name proliferation.

Further eastward in the roadcut, especially on the north side, are good outcrops of the Rio Salado; dips are about 3°NE.

Return to vehicles, watch for traffic, and proceed on pavement. **0.2**

67.25 Road descends to older floodplain of Rio Puerco; at 11:00-12:00 note Gallup Sandstone capping the mesa; dips on mesa are 2-3°NE, toward the axis of the Gallup sag which is the northern part of the Zuni Basin. 1.1

67.35 Dirt road to right leads into Burned Out Canyon; proceed straight ahead. At 1:00 (also 9:00) massive, grayish-orange sandstone three-fourths the way up is the marine Gallup overlain by the slope-forming, coal-bearing Gallup (140 ft thick), which is in turn overlain by the normally reddish-brown (or "pink," as Sears, 1925, called it) Torrivio Member of the Gallup. We will discuss the Gallup in some detail at Stop 4; the Torrivio is a medium- to coarse-grained feldspathic sandstone widely considered to be a braided-stream deposit. The finer-grained, light-colored sandstones within the coal-bearing part contrast with the "pink" Torrivio. 0.8

69.15 On mesa at 9:30-11:30 note the evenbedded marine Gallup forming the persistent ledge overlain by the talus-covered coal-bearing part of the Gallup. Minor reentrant in ledge above overpass at 11:00 is formed in the marine Gallup, which is here 160-180 ft thick. **0.4**

69.55 Bridge over Rio Puerco. **0.4**

69.95 Stop sign at entrance to New Mexico Transportation Department inspection and weigh station; bear right and stay on frontage road. 0.1

70.05 Hunting Canyon to right; to the left, on the north side of 1-40, the marine part of the Gallup Sandstone forms the lower half of the section exposed at 9:00; this is overlain by the slope-forming, coal-bearing part of the Gallup, which in turn is overlain by the reddish-brown or pink Torrivio. 0.4

70.45 Big Rock Canyon on left at 9:00 is tributary to the Rio Puerco; the lower portion of the canyon walls cut in marine Gallup, and the Torrivio forms the mesa top on both sides. Paleoflow directions in the Torrivio, based on measurements of planar crossbed sets, are generally east to northeast; in this area, however, some northwest paleoflow directions have been recorded (Anderson, in prep.) in the Manuelito quadrangle. 0.3

70.75 Crossing bridge over Rio Puerco; immediately past the bridge on the right note the top of the marine Gallup. This represents the last marine depositional event in the Zuni Basin. These marine sandstones locally contain a late Turonian fauna that is characteristic of the Juana Lopez Member of the Mancos Shale; inasmuch as the calcareous Juana Lopez Member marks a transgressive maximum during the Carlile cycle of sedimentation, we are at this locality very near the landward extent of the marine Gallup. **0.5**

71.25 Note carbonaceous shales in Gallup in road-cut on right. Dips are 1-4°NE, so as we proceed we continue to go up section. **0.6**

71.85 Slow down and note thick carbonaceous shale with a thin coal bed in the Gallup on right; this is overlain by a fluvial-channel sandstone. **0.6**

72.45 Gently northeastward dipping Torrivio passes into subsurface under Crevasse Canyon Formation, at 9:30 and 2:00. 0.3

72.75 Bridge over Salt Water Wash; at 11:00 and also from 1:00 to 2:30 on the skyline is the Torrivio anticline, an intrabasinal fold about 9 mi long. The Federal Aviation Agency VORTAC facility on top (a white cone at about 2:00) is our lunch stop. For next 1.3 mi we will be in the nonmarine Crevasse Canyon Formation, covered by alluvium along our route. **1.3**

74.05 Stop sign, turn left; before turning note the light-colored Gallup Sandstone forming the dip slope on the west flank of the Torrivio anticline dead ahead; also note the excellent exposures of the entire marine section in the 1-40 roadcut. Proceed northward through I-40 underpass. 0.3

74.35 Yield sign, bear right and continue east on north frontage road. 0.1

74.45 Roadcut exposes carbonaceous shale and channel sandstones in the coal-bearing Gallup Sandstone. 0.2

74.65 Crossing axis of the asymmetric Torrivio anticline; dips on west limb approach 30° locally; dips on east limb generally do not exceed 6°. **0.6**

75.25 Entering village of Williams Acres. At 11:00 note recent slump on south wall of mesa, which exposes multiple shoreface sandstones in the Gallup Sandstone, interbedded with arenaceous shales of the transitional zone, restricted bays, or lagoons. Four separate sandstones representing four transgressive-regressive events are displayed here; some of the sandstones are doublets. 0.6

75.85 Road passes under the Tucson Electric Power high-voltage transmission line from San Juan Generating Plant to Tucson. **0.1**

75.95 At 9:00 note flat-bedded marine Gallup dipping eastward under alluvium. 0.4

76.35 Spoil piles at 10:00 from Carbon Coal Company's Mentmore mine (inactive); at this site, which was the secs. 16-21 operation, they produced from the Dilco Coal Member of the Crevasse Canyon Formation; further north was their sec. 33 operation, which produced from the Gibson Coal Member of the Crevasse Canyon. 0.6

76.95 Turn right (south) onto dirt road for side trip to top of Torrivio Mesa. 0.3

77.25 Road passes under 1-40; continue straight ahead. 0.2

77.45 At 9:30 is the eroded stump of a volcanic vent; the wall rock is Crevasse Canyon Formation; compositionally, the volcanic rock is a minette. The feature is called Twin Buttes, but quarrying for aggregate has drastically changed its profile during past 25 years. 0.2

77.65 Intersection, bear right (west); road is on alluvial surface which conceals the Crevasse Canyon. 0.6

78.25 Road passing approximate contact of Crevasse Canyon and underlying Torrivio Member; stay to right and go through gate. Road will generally be on the coal-bearing part of Gallup for next 1 mi. 0.6

78.85 Torrivio Member caps small mesa on left. 0.2

79.05 Road passes under TEP high-voltage line. 0.4

79.45 Road has now ascended to top of the Torrivio Member. 0.3

79.75 **STOP** 4-FAA VORTAC facility. Lunch stop and discussion of local structures. From a vantage point 150 ft north of the VORTAC radar we will be able to view, from east to west, the following structures: (1) the north end of the Nutria monocline which defines the Zuni uplift, (2) the Gallup sag-Zuni Basin, and (3) the Torrivio anticline (which we are on) and the east-facing Defiance monodine at Hunter's Point. The Chuska Mountains may also be seen-the flat-topped feature at 1:00 in the distance. The McKinley mine is visible with the aid of field glasses, and the Carbon Coal Mentmore mine is in the foreground at about 11:00.

If time permits after lunch, we will walk westward through the Torrivio down onto the bench formed in coal-bearing part of the Gallup to see extensive burrowing in nonmarine sandstone.

Retrace route back to road log mileage 76.95. 0.9

80.65 Note carbonaceous shale at 2:00 in coal-bearing part of Gallup. **1.6**

82.25 Pass under 1-40 on return route. 0.3

82.55 Intersection with north frontage road at stop sign; turn right and proceed toward Gallup. 0.4

82.95 Road to left is McKinley County No. 1 which leads to the Mentmore mine 1.3 mi to the north. 0.3

83.25 Pass 1-40 on ramp on right; continue straight ahead. 0.3

83.55 Road passes under 1-40; we are now on Business 40 (old route 66) which will lead us through downtown Gallup; we will also be paralleling the Santa Fe Railroad tracks for next 7 mi (look for coal in transport on unit trains). 1.3

84.85 At 9:30 the sandstones and mudstones of the Bartlett Barren Member of the Crevasse Canyon are exposed in a small butte. 1.6

86.45 Gallup Municipal Airport on right; elevation 6,468 ft. Gallup was founded in 1881, named after David Gallup, paymaster and auditor for the A&P Railroad, later to become the AT&SF (referred to now as the "Santa Fe Railroad"). 1.3

87.75 Junction with NM-666 north to Shiprock and NM-32 south to Zuni at traffic light; proceed straight ahead. **1.0**

88.75 Downtown area of Gallup. 0.2

88.95 Old depot of the Santa Fe Railroad on left. 0.7

89.65 Famous El Rancho Inn on right; the New Mexico Geological Society 10th Fall Field Conference (1959) banquet was held here. 0.7

90.35 The northern end of the Nutria monocline, locally called the hogback, visible from 9:00 to 12:00. 0.5

90.85 At 11:00 note the 1-40 roadcut through the hogback exposing the Gallup and Mancos dipping at high angles to the west. **0.8**

91.65 Road crosses the hogback, here formed on the Torrivio Member; slow down and prepare to turn. 0.2

91.85 Intersection with dirt road to left; turn left and pass under the Santa Fe Railroad tracks. **0.1**

91.95 Cross bridge over Rio Puerco and immediately bear to left into parking area at toe of hogback for **STOP 5.** Park and walk around south edge of hogback formed on Dakota Sandstone and then westward along north bank of Rio Puerco to the hogback formed on the Gallup Sandstone. Discussion of structure and of the Gallup Sandstone which was named for these exposures by Sears (1925). The nonmarine, or coal-bearing, part of the Gallup thins from 150 ft to the south and west in the Zuni Basin to about 45 ft or less here, invoking speculation that movement along this structure may have begun as early as in late Turonian time, or pre-classic Laramide. View northward at top of hogback gives an excellent chance to see the abrupt nature of the synclinal bend of the monocline, which is generally sharper than the anticlinal bend.

Return to vehicles and retrace route across the Rio Puerco to Business Route 40 and back to the Inn for the evening, or make optional side trip to Zuni Pueblo.

THIRD DAY

Road log from Gallup, New Mexico, to Show Low, Arizona Road log from Gallup to Fence Lake, New Mexico

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Mileage

0.0 Traffic light at intersection of Business Route 40 and Ford Drive on east side of Gallup (1.6 mi east of junction with NM-666). Continue straight ahead. 1.4

1.4 Intersection with South Boardman at traffic light; turn right (south). **0.5**

1.9 J. E Kennedy mid-school on right. **0.4**

2.3 Gallup High School on right; we are traveling through the lower part of Crevasse Canyon Formation. **0.7**

3.0 Roadcuts expose thin coal beds in the Dilco Coal Member of the Crevasse Canyon; view of Carbon Coal Company No. 2 mine at about 9:00. **0.6**

3.6 Carbonaceous shales on right in roadcuts are in the upper part of the Dilco Coal Member. **0.3**

3.9 Gallup Indian Hospital (BIA) at 3:00. **0.1**

4.0 Intersection with College Road at stop sign; the Gallup Branch of University of New Mexico is on the left; proceed straight ahead. **0.7**

4.7 Intersection with NM-32 at traffic light; turn left and proceed south on 32. 0.7

5.4 Road to left leads to Carbon Coal Company No. 2 mine (inactive) 1.5 mi to the east, near the site of the old Catalpa mine operated in the 1920's. **(OPTIONAL STOP) 0.8**

6.2 Roadcuts in Crevasse Canyon Formation; we will be in Crevasse Canyon Formation, locally covered with the Bidahochi Formation (Pliocene) for approximately the next 16 mi. **0.3**

6.5 Milepost marker 144; road begins descent to a tributary of Bread Springs Wash. **1.0**

7.5 Milepost marker 143; note the local topography developed on continental rocks and how it contrasts with that developed on marine sandstones. **0.3**

7.8 Road to right leads to Red Rock Chapter House. 0.7

8.5 Bread Springs Wash parallels road on the right. **2.6**

11.1 Roadcut on right exposes a 30 ft section of carbonaceous shales, coal, and splay sandstones. The coals are terminated upward in each case by a sandstone; sequence is repeated three times. 1.4

12.5 Milepost marker 138. **1.5**

14.0 Bidahochi Formation, upper part exposed on both sides of road in cuts; it is a pale reddish-brown, argillaceous sandstone. We are entering the northeast corner of the Vanderwagen 7^1/2 min quadrangle at this point, mapped by New Mexico Bureau of Mines & Mineral Resources, that will soon be available as a GM series map. The mapping revealed minimal coal resources-beds 14 in. or more thick-in the Gallup, and also the presence of coal down in the middle part of the marine Gallup. The equivalent part of the section at the 1-40 roadcut through Torrivio Mesa is composed of restricted bay or even the transitional-zone sediments. Thus, an embayment or restricted bay existed there while a peninsular land mass developed on a prograding deltaic-sand body here; a highly embayed or digitate shoreline is indicated. 1.1

15.1 Paved road to left goes to Bread Springs and to excellent exposures of the Nutria monocline at Stinking Springs, where structural dips are 80-88°; continue straight ahead. 0.5

15.6 To the right just ahead the Crevasse Canyon Formation is exposed in bottom of drainage; the overlying Bidahochi gets up to 125 ft thick locally. 0.5

16.1 On the right Crevasse Canyon is exposed in drainage; upland covered by Bidahochi. 0.4

16.5 In low roadcut on the right note a white rhyolitic ash bed (12 in. thick) in the Bidahochi. 0.4

16.9 White ash bed exposed in roadcut to left, the light-gray to white wispy streaks. 1.3

18.2 Paved road to right is Indian Highway 7046 and leads to Chichiltah and Jones Ranch BIA schools; also to a nice exposure of the Piñon Springs anticline. 0.2

18.4 Roadcuts in Bidahochi. 0.8

19.2 Crevasse Canyon outcrops to both east and west. **0.4**

20.2 Cross bridge over Whitewater Arroyo; the light-colored sandstone ahead at 1:00 is a typical upper fine- to medium-grained Crevasse Canyon fluvial-channel sandstone overlying the medium- to coarse-grained Torrivio Member of the Gallup; contact is frequently very hard to pick, as basically there is no contact but rather a facies development; lithogenetically, the Torrivio belongs in the Crevasse Canyon Formation. The Torrivio "fades" dips into the subsurface just west of the highway. **1.1**

21.3 Bidahochi exposed in roadcuts on both sides of road. **0.2**

21.5 The village of Vanderwagen and the Whitewater Trading Post on the right. 0.2

21.7 Road crosses Nelson Wash; Torrivio is exposed on north side of wash at 4:00. 0.5

22.2 Roadcuts ahead in Bidahochi. 0.9

23.1 McKinley County Road 6 to the right leads to Chichiltah and closely follows the southern boundary of the Vanderwagen quadrangle. **0.9**

24.0 Zuni Trading Company on the left; continue straight ahead. 1.3

25.3 Roadcut in Bidahochi; **entering Zuni Indian Reservation.** The Bidahochi-Mancos Shale contact is on left side of road just ahead and is marked by a 6 in. thick altered ash (bentonitic) bed. This is not the same ash bed we saw about 12 mi back. Road now descends into strike valley developed on the Rio Salado Tongue of Mancos Shale. 0.6

25.9 At 9:30-11:00 the skyline is formed by the Atarque Member of the Tres Hermanos Formation **1.6**

27.5 Dip slope on right is developed on Dakota. **1.2**

28.7 Milepost marker 122. 0.3

29.0 Road to right leads to Zuni Pueblo, 9.5 mi; continue straight ahead on NM-32. **1.3**

30.3 Dirt road to left leads to Nutria and the reservoirs on Nutria Creek. **0.4**

30.7 Mesa at 10:30 is capped by Gallup Sandstone overlying a 40 ft thick section of Pescado Tongue of Mancos Shale. The presence of the marine Pescado Tongue permits the division of this Turonian section into the Tres Hermanos Formation below and the Gallup Sandstone above (see Fig. 3 of second-day road log). The Pescado Tongue thins rapidly northward from this locality, thus bringing the Tres Hermanos-Gallup together as one marine and marginal-marine lithogenetic unit. The northward pinchout of the Pescado indicates a "pivot point" in the Turonian shoreline just south of Gallup, New Mexico-more discussion of this at Stop 1. 1.2

31.9 Crossing bridge over Rio Nutria. **1.0**

32.9 At about 2:00 note the water gap cut by the Zuni River through the east flank of the Piñon Springs anticline. The Zuni River begins here at the confluence of the Pescado and Nutria Creeks. Dip-slopes are developed on the Dakota which overlies a multicolored, largely eolian, Zuni Sandstone. **0.7**

33.6 Junction with NM-53 at stop sign; turn left. **0.1**

33.7 Dakota Sandstone exposed on right. 0.3

34.0 Junction, NM-53 and 32 divide; turn right (south) and immediately pull off pavement to left side and park for **STOP 1-discussion** of the reference section of the Tres Hermanos Formation for Zuni Basin area (Fig. 1); also discussion of the Gallup Sandstone and Turonian shoreline configurations.

Proceed south on NM-32 toward Fence Lake. This segment of the valley is called Horsehead Canyon. **0.6**

FIGURE 1—Pescado Creek reference section of Tres Hermanos Formation; looking northwest from junction of U.S. 53 and Nutria Road. Dotted lines indicate where each section was measured. From cover of New Mexico Bureau of Mines & Mineral Resources Circular 185 (1983).

34.6 Roadcut exposes the Twowells Tongue of Dakota interbedded with Mancos Shale. The road now follows a strike valley developed on the Mancos Shale for next 15 mi; the Tres Hermanos Formation caps the section and forms the skyline on the east for next several miles. **0.8**

35.4 Dakota-Zuni contact at 2:00; note the sharp color contrast; the top of the Zuni is commonly bleached and kaolinized due perhaps to organic acids moving down from the swamp-laden environment in which the Dakota was deposited. **1.1**

36.5 Milepost marker 114; thin alluvial cover blanketing Rio Salado Tongue of Mancos Shale in this area, with Twowells Tongue exposed in patches. **0.4**

36.9 At 9:00 good exposures of the Atarque Member of the Tres Hermanos Formation in sharp basal contact with the Rio Salado Tongue of the Mancos. 0.8

37.7 Twowells exposed in roadcut on the left side. 0.6

38.3 Road now descends to drainage of Knife Hill Creek. 0.1

38.4 Dirt road to left leads to Knife Hill Quarry, 0.4 mi off the highway. The quarry was developed in a minette intrusive (alkali feldspar with biotite phenocrysts). The intrusion (shown as Ti just south of Stop 1 in Fig. 1) was an isolated one, but is of great interest because it falls on a northeast-trending line that passes through the end points of a number of monoclines locally and thus supports the case for compartmental deformation in the Zuni Basin (Anderson, 1986). **0.4**

38.8 On left side of road note the Dakota dipping very steeply to the west on the flanks of the intrusive minette. 0.4

39.2 Road has now climbed to an alluvium-covered surface developed on the Whitewater Arroyo Tongue of the Mancos Shale and the

Twowells Tongue of the Dakota. 0.3

39.5 At 9:00 is a good view of the south end of the elongate dome created by the minette intrusive. **1.0**

40.5 Milepost marker 110; to the left ahead is a good example of strike-valley development. **0.6**

41.1 Roadcuts in the dark-gray marine shale of the Whitewater Arroyo Tongue. 0.4

41.5 Milepost marker 109. **0.4**

41.9 Surface locally developed on Whitewater Arroyo Tongue of the Mancos Shale. 1.0

42.9 Dirt road to left leads to Galestina ponds, 1.2 mi; continue straight ahead. We have now entered the area covered by the 1:50,000 Atarque Lake Geologic map (Anderson, 1987). Coal resources of this eight-quadrangle area are discussed in the map text. 0.3

43.2 Road descends through thin beds of Two-wells Tongue; the Twowells offers good oyster collecting *(Pycnodonte kellumi)* on left side of road. In the panorama ahead note the decrease in northeast regional dips as compared with the Zuni-Pescado Creek area. 0.3

43.5 Milepost marker 107; surface is locally developed on the Paguate Tongue of the Dakota Sandstone. **0.8**

44.3 Crossing bridge over headwaters of Galestina Canyon; Dakota exposed in arroyo to right and in reclaimed quarry immediately to the south. 0.8

45.1 McKinley-Catron County line. **0.4**

45.5 Milepost marker 105; surface in vicinity developed on Whitewater Arroyo Tongue of Mancos. **0.4**

45.9 Twowells exposed along both sides of road. **1.3**

47.2 Road descends through excellent exposures of Paguate Tongue of Dakota which here rims the canyon walls. 0.3

47.5 Milepost marker 103; at 10:00 is a small mesa capped by Twowells. **0.4**

47.9 Road to right is NM-36 and provides southern access to Zuni Pueblo; continue straight ahead. 0.9

48.8 **Leaving Zuni Indian Reservation;** roadcuts just ahead are in the Whitewater Arroyo Tongue. 0.7

49.5 Road climbs to top of the Twowells Tongue. **0.5**

50.0 Defunct Billy Crockett Bar on right, just outside the Reservation; Twowells Tongue caps the mesa 0.5 mi to the left. **0.5**

50.5 Road descends through Paguate Tongue outcrops at milepost marker 100. **0.4**

50.9 Guillermo Canyon leads off to southeast with good exposures of all facies of Dakota; now entering the Mesita de Yeso $7^1/2$ min quadrangle mapped by Anderson (1982). Coal occurs locally in the Dakota and Tres Hermanos Formations, but does not constitute a resource. This quadrangle is the southwesternmost area in which the Tres Hermanos nomenclature is used. **0.6**

51.5 Milepost marker 99; road on Dakota-stripped surface. **1.4**

52.9 On skyline at 10:00 are the landwardmost outcrops of the transgressive upper part of the Tres Hermanos Formation (the Fite Ranch Sandstone Member); we thus are in the turnaround area for the Carlile cycle of sedimentation (Fig. 1). Stated another way, the Upper Cretaceous rocks to the west and southwest were influenced by only one marine transgressive-regressive cycle, whereas the rocks to the east show the influence of two such cycles. **0.4**

53.3 At 2:00 the Twowells, dipping 2-5°SW, caps a small mesa at the southeast terminus of the Galestina monocline. End points of local monoclines form northeast-trending line that coincides with Pinitos Draw which is just ahead. **1.0**

54.3 In this area NM-32 is taken as the line for the change in nomenclature of Turonian age rocks, from Tres Hermanos on the east to Atarque Formation and the overlying Moreno Hill Formation on the west and south (i.e., the Atarque is raised in rank from Member to Formation). 0.3

54.6 Road descends through the upper part of the Dakota to the floor of Pinitos Wash. 0.9

55.5 Dirt road to left leads to Pine Hill (BIA) school and to Mountain View on the Ramah Navajo Reservation; stock loading pens of Atarque Ranch on right. **0.1**

55.6 Milepost marker 95. 0.3

55.9 Dirt road to right leads to Atarque Ranch, 5.5 mi, and ultimately to St. Johns, Arizona; continue straight ahead. **1.2**

57.1 Twowells overlying Whitewater Arroyo Tongue of Mancos Shale exposed in roadcut on right; road now begins to ascend Mesita de Yeso, the topographic feature which lends its name to this quadrangle. 0.3

57.4 At 1:00 note mounds of light-colored gravel from an aggregate pit developed in the Bidahochi Formation (coarser facies at base of Bidahochi represent reworked Fence Lake Formation). 0.5

57.9 At base of slope about 400 ft west of road is a good exposure of Bridge Creek Limestone beds of Greenhorn Formation, containing inoceramid debris. Along road locally the oysters *Pycnodonte kellumi* and *P. aff. kellumi* (meaning forms transitional between *P. kellumi* and *P. newberryi)* weather out of the base of the Rio Salado Tongue of the Mancos and the top of the Twowells. Slow down for Stop 2. 0.3

58.2 **STOP 2.** Pull off pavement to right onto aggregate storage area for discussion of panorama and review of stratigraphy.

The view straight ahead at 12:00 is of the upper surface of Santa Rita Mesa capped by the conglomeratic Fence Lake Formation (Miocene?). At 11:00 is Allegros Mountain composed of Oligocene volcanics and interbedded sediments, elevation 9,850 ft. At 10:00 is Veteado Mountain held up by a local basalt flow capping the Fence Lake Formation, elevation 8,525 ft. At 9:30 are numerous vents in the North Plains lava field.

At 9:00 is the mesa containing the southwesternmost extent of the Tres Hermanos Formation; it also defines the southern end of the Gallup-Zuni coal field. The overlying Pescado Tongue thins to 28 ft at the last outcrop about 8 mi east of here. Of interest is the fact that the stratigraphic interval between the top of the Atarque Sandstone and the base of the Pescado is about 210 ft. The importance of this in relation to the coal deposits in the Salt Lake coal field just south of here is that the thickest coal beds, those of the Cerro Prieto zone, lie in a sequence that is 200-270 ft above the Atarque Sandstone and that they trend northwest (Roybal and Campbell, 1981). This correlation suggests that the Cerro Prieto coal beds accumulated in a coastal-plain environment that developed just landward of the maximum extent of the seaway during the Carlile cycle of sedimentation (Fig. 1).

About 500 ft down the road on the right is good oyster collecting *(Pycnodonte kellumi)* from the top of the Twowells.

Return to vehicles and proceed south on NM-32. 0.4

58.6 Milepost marker 92; road descends through surface developed on the Whitewater Arroyo with the Paguate Tongue exposed in isolated patches. 0.5

59.1 Flat skyline ahead is the Jaralosa Draw lobe of the North Plains lava field. 0.7

60.3 The Dakota-Zuni contact is visible in slope below road level, at 3:00. Just ahead on the left is the base of the basalt flow; this flow has been dated by Laughlin et al. (1979) at 1.41 my. The flow followed a paleochannel around the southern end of an area slightly elevated along two northwest-trending monoclines formed by Laramide compression. 0.7

61.0 At 3:00 is the abandoned village of Atarque (Spanish for diversion dam)-red adobe buildings about 1 mi away. Immediately north of the village are south-facing cliffs in an area called Los Pilares. The cliffs expose the southernmost outcrops of the Zuni Sandstone locally; the Zuni thins to 90 ft here, from 500 ft near Zuni Pueblo 20 mi north.

We have now entered the Fence Lake 7$^1/2$ min quadrangle which was mapped by the USGS in 1980-81 as part of the national coal-resource-evaluation program. The New Mexico Bureau of Mines & Mineral Resources participated in this joint effort, called the Fence Lake Project, and another 1:50,000 scale map, adjoining the Atarque Lake map to the north, will incorporate all the detailed mapping and coal resource data. **1.6**

62.6 Milepost marker 88. **0.8**

63.4 Road descends from basalt flow to surface of thin alluvium masking the Atarque and Moreno Hill Formations (see Fig. 3 of second-day road log). **2.1**

65.5 Intersection with dirt road which leads to local farms and ranches; dry-land farming has been attempted in this area, but has met with limited success as annual precipitation is only about 13 in. Continue straight ahead to Fence Lake. **0.9**

66.4 Village of Fence Lake, New Mexico, and intersection of NM-32 and 36. Store and Post Office only. **0.3**

Road log from Fence Lake, New Mexico, to Springerville, Arizona

Orin J. Anderson, Richard Chamberlin, and Gretchen H. Roybal

New Mexico Bureau of Mines & Mineral Resources, Socorro, New Mexico 87801

Mileage

66.4 Proceed south from Fence Lake on NM-32, an all-weather gravel road. **0.3**

66.7 Road on thin alluvial cover containing coarse clastics derived from Fence Lake Formation. Beneath the alluvium is the coal-bearing lower part of the Moreno Hill Formation. 0.7

67.4 Dirt road to left at section line; continue straight ahead. **1.0**

68.4 Road bears right at cattleguard; proceed west. We are now on a thin residuum of the Fence Lake Formation. **1.0**

69.4 Road bears left (south); note the cobbles and boulders of vesicular basalt that have weathered out of the Fence Lake for next 1 mi. **1.0**

70.4 Road bears right (west); caliche-covered basaltic cobbles and boulders along road. **0.5**

70.9 Road bears left (south); extensive meadow on right may be due to very poor (caliche-rich) soil unable to support a piñon-juniper cover. **1.0**

71.9 Road bears right (west). 0.3

72.2 Escarpment dead ahead has been shown as a fault by Landis et al. (1985). **0.6**

72.8 Outcrop of bouldery facies of Fence Lake Formation in roadcut on left. **1.6**

74.4 Small mesa at 12:30 is capped by Fence Lake Formation. **0.6**

75.0 Aggregate pit in Fence Lake on left; slow down and prepare to stop. **0.3**

75.3 **STOP 3.** Pull off to left side of road and park. This vantage point is Moreno Hill.

Walk 100 ft downhill to examine the basal conglomerate of the Fence Lake Formation in contact with the underlying Moreno Hill Formation. The source area for the basalts and basaltic andesites that dominate the cobble and boulder fraction is 35 mi to the south and east in the Gallo and Mangas Mountains. This Oligocene volcanic pile stood at elevations in excess of 10,000 ft (present elevations approach 10,000 ft). Our elevation here is 7,320 ft, thus we probably had gradients of 60-70 ft/mi to transport material of the size we see here.

The plain to the southwest is largely developed on the Dakota Sandstone and is at an elevation of about 6,500 ft. Further in the distance at the center of the valley is the west-flowing Carrizo Creek, a tributary to the Little Colorado River.

A 1 mi optional walk down the hill gives an excellent opportunity for a close-up view of the mudstone, fluvial-channel sandstones, and carbonaceous mudstone and coal that make up the Moreno Hill Formation. For those who choose to do so, the bus will be at the bottom near the contact with the Atarque Sandstone. Up to 45 minutes will be allowed for the walk. Those who choose to ride down can examine a coal bed near the base of the Moreno Hill Formation and the top of the Atarque-a regressive shoreface sandstone.

A palynologic investigation of the Moreno Hill Formation recently completed as an M.S. thesis by K. C. Kelley (1987) of Michigan State University indicated a "marine flora" below the middle sandstone (see Campbell, this volume) of the Moreno Hill Formation. Kelley also reported finding marine algal grains just below the middle sandstone in the Rabbit coal zone, which can be as much as 300 ft above the Atarque. (Remember, the marine Pescado Tongue was found 210 ft above the Atarque just to northeast of here.). **1.0**

76.3 Parking and pick-up area for those who have walked down through the Moreno Hill. At the parking area we are very near the top of the Atarque, here about 45 ft thick.

Regather and proceed southward on NM-32. **0.1**

76.4 To the right is a good view of the entire Atarque Sandstone; note the thinly bedded deposits of the transition zone at the base; underlying shale is the Rio Salado Tongue. **0.4**

76.8 Crossing Cibola-Catron County line. **2.3**

79.1 Crossing cattleguard; view in distance to left at 8:00-9:00 of 600 ft of Moreno Hill Formation on south face of Santa Rita Mesa. **1.1** 80.2 Milepost marker 66. **1.1**

81.3 Road descends through subdued outcrops of Twowells Tongue of Dakota; several hundred feet down the road are small outcrops of Whitewater Arroyo Tongue of Mancos Shale-look for more of these in roadcuts for next 0.5 mi. **1.2**

82.5 Low knob at 3:00 is Dakota Sandstone. At 3:30 note contact of the tan and grayish-orange Dakota Sandstone resting unconformably on the purplish Chinle Formation; Jurassic is absent here. View to rear of the unconformity gets better as we proceed. **1.1**

83.6 Caliche-encrusted basalt boulders and cobbles are Fence Lake Formation lag deposits. **0.9**

84.5 Note dark-gray cinders coloring the local landscape; the cinders are from the eruption at Zuni Salt Lake maar approximately 1 mi to the south. **0.9**

85.4 T intersection; bear left and follow NM-32. Immediately after turning left, watch for a dirt road to the right that leads 0.5 mi to Zuni Salt Lake maar lookout point. **0.5**

85.9 Photo stop on west rim of maar, Stop 4; the limnology and paleolimnology of Zuni Salt Lake was the subject of a University of New Mexico Ph.D. dissertation by J. Platt Bradbury (1967). There will be a short discussion on the maar by Robert G. Myers, Hydrogeologist, USGS, Las Cruces. If the optional side trip at milege 90.4 is not feasible (weather, time) Marcie Greenburg of the Salt River Project will discuss the Fence Lake No. 1 mine at this stop.

Zuni Salt Lake (Fig. 2) is located about 18 mi northwest of Quemado, New Mexico, on the floor of a maar about 175 ft below land surface. The Cretaceous Mancos Shale and Mesaverde Group equivalents are exposed in the maar wall. The regional direction of ground-water flow of the aquifers in the Mancos Shale and Mesaverde Group in the

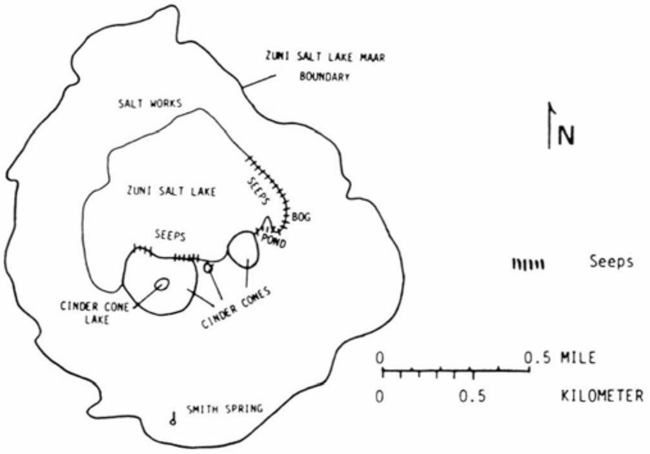

FIGURE 2—Generalized map of Zuni Salt Lake maar.

southern part of the Carrizo Wash basin is toward Zuni Salt Lake and Carrizo Wash. A smaller brine lake of about 4.7 acres occurs in a crater about 84 ft deep in the largest of three cinder cones at the southern edge of Zuni Salt Lake. The maar is about 1.4 mi across at the widest point and covers about 1 mil. Zuni Salt Lake has long been a source of salt for prehistoric and historic people. The maar, Zuni Salt Lake, Smith Spring at the southern edge of the maar, and the cinder-cone lake have religious significance for the Zuni Indians and some other Pueblo Indians in New Mexico.

Zuni Salt Lake varies in size, but generally is less than 0.7 by 0.5 mi across. The depth of water is usually less than 4 ft. There are 5 major sources of water in Zuni Salt Lake: (1) surface-water runoff from the surrounding basin; (2) brackish ground water from seeps and springs along the northeastern to eastern edge of the lake; (3) brine springs on the southern edge of the lake from the northern edge of the large cinder cone; (4) fresh water from the Quaternary alluvium and volcaniclastics south of the maar from Smith Spring; and (5) direct precipitation on the surface of the lake. The water in Zuni Salt Lake has a concentration of dissolved solids up to 370,000 mg/1, with dominant ions of sodium and chloride.

The cinder-cone lake is up to 23 ft deep. The major sources of water are precipitation within the crater and brine springs in the cinder cone. The water has a concentration of dissolved solids up to 150,000 mg/1, with dominant ions of sodium and chloride.

Ground water in the upper Quaternary alluvium of the Zuni Salt Lake Maar is brackish. The concentration of dissolved solids is about 1,200 mg/l. The ground-water quality at depth is unknown. There are four sources of the brackish ground water in the maar: (1) Smith Spring in the south wall of the maar; (2) surface-water runoff from outside the maar; (3) ground water from the Cretaceous sedimentary rocks; and (4) direct precipitation on the alluvium in the floor of the maar. Most of the water entering the alluvium of the maar floor is fresh (less than 1,000 mg/1 dissolved solids).

Return to NM-32. 0.5

86.4 Rejoin NM-32; at 10:00 note Cerro Prieto, a mid-Tertiary intrusive; proceed eastward. 0.6

87.0 At 12:00 note dark band capping south slope of hill; dark band composed of cinders erupted from the maar. Cinders are used as road metal locally. 0.9

87.9 At 3:00 the two prominent mesas are composed of Moreno Hill Formation; they are not named but straddle the Zuni Salt Lake-Lake Armijo 7 1/2 min quadrangle boundary. 0.4

88.3 Atarque Sandstone exposed in knob at 2:00; it is also present in low ridges to left from 9:00 to 10:30. 0.3

88.6 Milepost marker 58; at 10:00 note fluvial channel sandstone and mudstone sequence in Moreno Hill Formation; sequence dips 23°E or ESE here. 1.3

89.9 At 10:30-12:30 on skyline is basalt-capped Tejana Mesa, a 6-9 my old flow overlying Eocene and Miocene sedimentary units; elevation reaches 7,635 ft; base of flow rises gently to northwest, away from the source, indicating slight southeastward tilting following the eruption. 0.5

90.4 Dirt road to left (north) leads to Nations Draw and Hubbell ranch road; cross cattleguard and continue straight ahead. Optional side trip to Fence Lake No. 1 mine will leave main road log at this point. 1.2

91.6 Milepost marker 55; tan-colored sandstones at 11:00-12:00 and 1:00-2:30 have been designated as the middle sandstone of Moreno Hill. **1.2,**

92.8 Passing upward through middle sandstone of Moreno Hill; good outcrops to right ahead. This sandstone has upper medium-grained to lower coarse-grained feldspathic facies that are similar to the Torrivio Member of the Gallup Sandstone. **0.6**

93.4 From notch in skyline at 9:30 and eastward along south side of Tejana Mesa note the presence of dark reddish-brown Baca Formation (Eocene) in Recent landslide scars. The Baca is overlain by lighter-colored conglomerate and sandstone of the Fence Lake Formation (Miocene). 0.35

93.7 At 12:00, just before descending hill, note dark reddish-brown Baca Formation in hills above the tan Cretaceous rocks; descend into valley developed on lower Moreno Hill Formation. 2.0

95.7 As we pass under the utility line, at about 10:00 note triangular patch of fresh rock exposed by recent landslide, revealing the reddish-brown Baca Formation near base of scar, and at the top, just below the basalt, the tan and light grayish-brown Fence Lake Formation; in addition, the Fence Lake has white, pedogenic, carbonate beds; field glasses helpful at this point. 0.7

96.4 Baca Formation exposed at 12:00 in a slide area on the northwest face of the mesa; at 1:00, immediately underlying the basalt, are pedogenic carbonate beds of the Fence Lake Formation. 0.8

97.2 Excellent exposures of upper part of Moreno Hill Formation on left side of road. At top note residual lag of quartzite gravels from the Baca Formation. 0.3

97.5 Crossing bridge over tributary to Largo Creek. **0.9**

98.4 At 9:00 is the last good outcrop of Cretaceous rocks we will see for a while!. 0.4

98.8 From 9:30 to 11:00 note abrupt thickening of basalt toward the fissure vent for Tejana Mesa basalt flows; at 1:00 is southwestward extension of fissure system. 0.9

99.7 At 9:00 note good view of the southeast wall of fissure-vent. 0.8

100.5 Baca Formation exposed in roadcuts. **0.6**

101.1 Southeast end of Tejana Mesa at 9:00. Note thinning of the basalt as the flow extended up the paleochannel from the source. **0.2**

101.3 A small horst block of Cretaceous rocks (Moreno Hill Formation) in fault contact with the Baca Formation. Normal fault strikes N10°E, dips 70-80°, N80°W. 1.7

103.0 Pavement begins, but very narrow. 1.3

104.3 Junction with U.S. 60; turn right (west) toward Springerville (Quemado is 1 mi to the left). 0.3

104.6 Baca Formation exposed in gentle cuts on north side of road. 1.0

105.6 Rest area and picnic table on right. Baca Formation exposed in roadcuts for next 1.1 mi. 1.1

106.7 Road crosses poorly exposed contact between Baca and Spears Formations. Light grayish-brown sandstone of Spears Formation in roadcut on left. Fence Lake Formation caps hill at 11:00. Entering Armstrong Canyon. **0.8**

107.5 Note Spears-Fence Lake contact on right side of road. Slow down for view of roadcut on left just ahead. 0.1

107.6 About three-quarters of way up the roadcut on left note the scoured contact between the light brownish-gray sandstones of the Spears and the overlying basal bouldery facies of the Fence Lake; also note the low-angle, west-dipping, normal fault in Spears, marked by white secondary carbonate zone. **0.5**

108.1 In roadcut on right note fine-grained, light-gray, lithic sandstone of Spears Formation. 1.0

109.1 Thick pedogenic carbonate horizon developed on Fence Lake Formation. Milepost marker 28. **0.1**

109.2 Microwave tower on right; road now on surface developed on Fence Lake Formation, for next 0.7 mi at least. **2.2**

111.4 Pedogenic carbonate on fine-grained Fence Lake Formation in roadcut. **1.1**

112.5 The prominent mesa at 11:00, with south-sloping upper surface and frequently snow-covered flanks, is Escudilla Mountain, southeast of Springerville, Arizona. 0.7

113.2 Milepost marker 24. 2.4

115.6 Upper Fence Lake Formation masked by blown sand in roadcut. **1.2**

116.8 Highway descends across west edge of Quaternary basalt flow. 0.5

117.3 Note brownish Fence Lake Formation overlying reddish Baca in roadcut on right. **0.9**

118.2 Roadcuts expose conglomeratic sandstones of Baca Formation, containing quartzite clasts and greenish sandstone clasts (Late Cretaceous); capped by basaltic cinder deposits. 1.7

119.9 At 1:30-2:00 note outcrops of reddish-orange Baca sandstones in low hills along west side of drainage. 1.1

121.0 Tertiary flows on Cimarron Mesa from 12:30 to 2:30. 1.4

122.4 Quaternary sands and bedded cinders in roadcut on left. 0.4

122.8 Dirt road to left leads to Luna, 32 mi; continue straight ahead. 1.9

124.7 Fence Lake Formation exposed in low road-cuts. **1.0**

125.7 Baca Formation(?) in low roadcuts, with carbonate soil horizon developed at top. 0.6

126.3 Red Hill, elevation 7,261 ft; abandoned store on left. Springerville 25 mi ahead. 1.1

127.4 Road ascends to top of basalt flow; red color at basal contact is Baca Formation, locally with remnants of carbonate soil under basalt flow. 1.6

129.0 Rest area on left. 0.4

129.4 At 11:00 in the distance is Escudilla Mountain just inside Arizona; the highest point is 10,912 ft. 0.8

130.2 Passing under Tucson Electric Power high-voltage line. **1.4**

131.6 Microwave tower on left; Tertiary basalt flows cap high mesas on right and at 12:00; road descends to Quaternary flow in the valley. **2.8**

134.4 At 12:00 is Tertiary basalt-capped mesa. We are traveling on a Quaternary(?) flow exposed in low roadcuts. **1.0**

135.4 Dirt road to right leads to local ranches and to the Rincon $7^1/2$ min quadrangle with excellent exposures of Twowells Tongue of Dakota Sandstone. 0.1

135.5 Road descends through cuts in Quaternary basalt flows which rest on light-colored Baca sandstone. **0.3**

135.8 In roadcut on right note fluvial-channel sandstone and the mudstones of the Baca Formation. The low-angle crossbeds are probably lateral-accretion sets and may be a point-bar deposit. Milepost marker 1 on left tells us we are 1 mi from Arizona state line. **1.0**

136.8 Arizona state line; note hoodoo developed in Baca Formation at 11:00. 0.7

137.5 Roadcut exposes red and pink coarse-grained conglomeratic sandstone and red mudstone of the Baca Formation unconformably overlying the variably oxidized Upper Cretaceous mudstones and thin overbank deposits of the Moreno Hill Formation. Chamberlin (1981) was among first to notice deeply weathered, abnormally colored Cretaceous rocks at the K/T boundary. 0.2

137.7 Road descends to valley of Coyote Wash. Abnormally colored Cretaceous rocks are exposed on both sides of road for next 0.9 mi. **0.4**

138.1 On left note the red (oxidized during early Tertiary) massive channel sandstones of the Moreno Hill Formation; crossbedding indicates a northeast transport direction. **0.3**

Road log from Springerville to Show Low, Arizona

Edward C. Beaumont[1] and Gretchen H. Roybal[2]

[1]3236 Candelaria NE, Albuquerque, New Mexico 87107; [2]New Mexico Bureau of Mines & Mineral Resources, Socorro, New Mexico 87801

Mileage

150.9 Junction with U.S. 260 on left; continue ahead on U.S. 60, 180, and 666. **1.2**

152.1 Lava flows on either side of highway belong to extensive White Mountain volcanic complex that had its origin in middle Tertiary time. The basaltic flows are late Tertiary to early Quaternary in age. There are more than 200 small volcanoes and cinder cones associated with this flow which covers an area of more than 1,200 mil. **0.8**

152.9 Red sediments at base of hill at 3:00 belong to the Eagar Formation of Eocene age—equivalent to part of Baca Formation in New Mexico. **1.2**

154.1 Junction with U.S. 666 (to St. Johns); continue ahead on U.S. 60. Route will continue in volcanic terrain the entire way to Show Low (with one small exception). This rolling, nearly treeless plain is poorly drained and contains many small lakes and ponds. Cinders (more appropriately called scoria) have been or are being mined in several locations on the flanks of several of the cones. Scoria, both black and red, is used for building blocks, surfacing material, road metal, and landscaping. **13.5**

167.6 Note black scoria pit on flank of cinder cone. The White Moutnians to the south of the highway reach nearly 11,000 ft and were the site of at least four episodes of glaciation during the Quaternary. **9.1**

176.7 Tan sandstone ledge to south of highway is Cretaceous. This is the only window in the lava along our route according to the geologic map of the county. **9.0**

185.7 Junction with U.S. 61, continue ahead on U.S. 60 to Show Low. 8.7

194.4 White Mountain Lake at 3:00. **0.5**

194.9 Show Low city limits. **1.6**

196.5 Junction with U.S. 77; continue on U.S. 60. 0.7

197.2 Junction with AZ-260 West; continue straight ahead on AZ-260/U.S. 60. **1.2**

198.4 Maxwell House Motel.

Road log for optional side trip to Fence Lake No. 1 mine north of Quemado, New Mexico

Gretchen H. Roybal

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Mileage

0.0 Intersection with road to Nations Draw. Turn north off NM-32. Outcrops at 11:00 are sandstones in the lower member of the Moreno Hill Formation. Small butte to right of flat-topped mesa at 10:00 is Cerro Prieto, a volcanic plug. Tejana Mesa on skyline at 2:00-3:00. 0.8

0.8 Sandstones of middle member of Moreno Hill Formation at 3:00. 0.4

1.2 High, long mesa on skyline ahead is Santa Rita Mesa capped by Tertiary Fence Lake Formation gravels, underlain by the sandstone and shale sequence of the Moreno Hill Formation. 1.4

2.6 Sandstone ledges in the flank of hill to right of road are part of marine Atarque Sandstone which is underlain by the Rio Salado Tongue of the Mancos Shale. Atarque-Mancos contact well exposed across Nations Draw. The top of the hill to the right is capped by sandstone in the lower member of the Moreno Hill Formation. 1.1

3.7 Sandstones in hill at 1:00 are in lower member of the Moreno Hill Formation. 0.4

4.1 Road is now in Nations Draw, a major drainage system for the area. On the skyline to the northeast is a very flat mesa, appropriately named Flat Top Mesa, which is capped by the Fence Lake Formation. This is underlain by the upper member of the Moreno Hill Formation. Thick sandstone ledges near the base are the middle member of Moreno Hill. 2.3

6.4 Massive sandstone capping small butte at 2:00 is middle member of the Moreno Hill Formation. 2.3

8.7 Cerro Prieto at 11:00, northeast end of Tejana Mesa at 3:00. 0.5

9.2 Road to right leads to Fence Lake No. 1 mine. Turn right. 0.2

9.4 Sandstones in hill on the left are in the lower member of Moreno Hill. Road follows Tejana Draw to the southeast. **1.1**

10.5 Tejana Windmill and northern permit boundary of Fence Lake No. 1 mine. 0.4

10.9 Intersection with haul road. Turn right for better view of mine. A short discussion by Marcie Greenburg of Salt River Project of the mine operation will take place here. Return to intersection and head south (to the right) on haul road. The road (which used to be a ranch road) parallels Tejana Mesa. We will be going up section as we head south. 0.2

11.1 Leaving permit area. 0.6

11.7 Low knolls to left and right are capped by middle member of Moreno Hill. 0.7

12.4 The road is now, and will be for the next 0.6 mi, on top of the middle member of Moreno Hill. The slopes of Tejana Mesa (to the right) are composed mostly of the siltstone-shale sequence of the upper member of Moreno Hill, with a few thin sandstones. The mesa is capped by lava flows which are underlain by Fence Lake Formation and Spears Formation. The red sediments are Baca Formation that are between the Moreno Hill and Spears Formations. **1.0**

13.4 The last 0.5 mi the exposures on the right have been of the upper member of Moreno Hill. Mesa at 10:00 is Mesa Tenaja, a volcanic plug. 1.3

14.7 Contact between Cretaceous Moreno Hill and Tertiary Baca Formations. Note the contrast in color. There is often a basal conglomerate (in the Baca Formation) at or near the contact. **0.25**

14.95 Contact between Baca and Spears Formations. This contact is difficult to see and for the next 0.5 mi it is difficult to say whether the rocks are Baca or Spears. 0.5

15.45 We are back in the Baca Formation. Good view to right of flows on Tejana Mesa. for the next 7.2 mi into Quemado the outcrops are Baca Formation, except on the skyline to the east where some Spears outcrops are visible. 2.2

17.65 Intersection with county road, turn right. 2.5

20.15 Entering small valley. In the lower part of this valley are a few outcrops of the upper member of Moreno Hill. 2.0

22.15 Rodeo grounds on left. 0.5

22.65 Road turns to the left. On the outskirts of Quemado. 0.15

22.80 Turn right and continue to junction with U.S. 60. **1.35**

24.15 Intersection of U.S. 32 and 60. Return to main road log at this point.

FOURTH DAY
Road log from Show Low to Phoenix, Arizona, via Payson

(modified from Burt and Péwé, 1978)

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Road log begins 0.8 mi south of Maxwell House Motel at Junction of U.S. Highway 60 and Arizona State Highway 260. Area is set in undivided, slightly coaliferous Upper Cretaceous sediments. Although undivided, the Cretaceous strata are low in the Upper Cretaceous-probably Dakota Sandstone, Lower Mancos Shale, and the Atarque Member of the Gallup Sandstone. These strata belong to the preserved remnant comprising the Pinedale coal field, a rather narrow and thin band of strata, elongate in an east-west direction, on the margin of the Mogollon Rim. Beneath the pre-Cretaceous unconformity, strata belonging to the earliest Triassic unit in the area, the Moenkopi Formation, are found in the vicinity of Show Low. Farther west, toward Heber, the Moenkopi is absent and the Cretaceous rests directly on the white, arenaceous, cliff-forming limestone of the Permian Kaibab Limestone. The field trip route between Show Low and Heber skirts the Cretaceous strata of the Pinedale coal field and is alternately in lowermost Upper Cretaceous, lowermost Triassic, Upper Permian, or Quaternary/Tertiary sand and gravel or alluvium. West of Heber, we will traverse in a southwesterly direction poorly exposed Cretaceous strata until very near the Mogollon Rim. As we approach the Rim, we will begin to descend in the section passing first through a thin section of the Kaibab and then into a massive, crossbedded, yellowish-tan sandstone belonging to the Coconino Sandstone (also Permian).

Below the Coconino, we pass through a thick sequence of Permo-Pennsylvanian red siltstone, shales, and marls belonging to the Supai Formation. The Supai grades downward into the Naco Formation, which consists predominantly of limestone. Beneath a pre-Pennsylvanian unconformity, the route passes through a relatively thin sequence of Mississippian Redwall Limestone, Devonian sandstone and limestone, and the Cambrian Tapeats Sandstone. About 12 mi before Payson, we enter a complex of Precambrian rocks-altered sediments and volcanics, and igneous intrusives (Fig. 1). The route remains largely in Precambrian terrain much of the way between Payson and Phoenix, although rather broad areas of Quaternary-Tertiary gravel and lake deposits are traversed in the upper Tonto Basin and the Verde and Salt River Valleys.

Mileage

0.0 (0.8 mi south of Maxwell House Motel) Junction of U.S. 60 and AZ-260; turn right (west) on 260. Tan sandstone is roadcut is Upper Cretaceous. 2.3

2.3 Triassic Moenkopi Formation underlying Upper Cretaceous rocks in roadcut. 1.2

3.5 Permian Kaibab Limestone in roadcut. 0.8 4.3 Moenkopi red beds in roadcut. **1.0**

5.3 Moenkopi red beds preserved in channels cut in top of Kaibab. 2.8

8.1 Kaibab Limestone in roadcuts. 10.6

18.7 Cretaceous sandstone in roadcut. 0.2

18.9 Cottonwood Wash flowing over Permian Coconino Sandstone which is overlain by Upper Cretaceous sandstone. 5.2

24.1 Red beds in roadcut appear to be Moenkopi, although the geologic map of the region would indicate this area to be several miles southwest of truncated margin of the Moenkopi. 0.4

24.5 Coarse-grained, crossbedded, tan channel sandstones both overlying and underlying reddish-brown mudstones and shales (Moenkopi?). 1.1

25.6 Red beds in roadcut are Moenkopi(?). **6.6**

32.2 Village of Overgaard set in Kaibab Limestone. 2.3

34.5 Stop sign. Junction of AZ-260 and 277; turn left and continue on 260 West. Outcrops of massively bedded Kaibab visible in hillsides and roadcuts. **1.9**

36.4 Crossing Black Creek in heart of Heber, Arizona. **0.1**

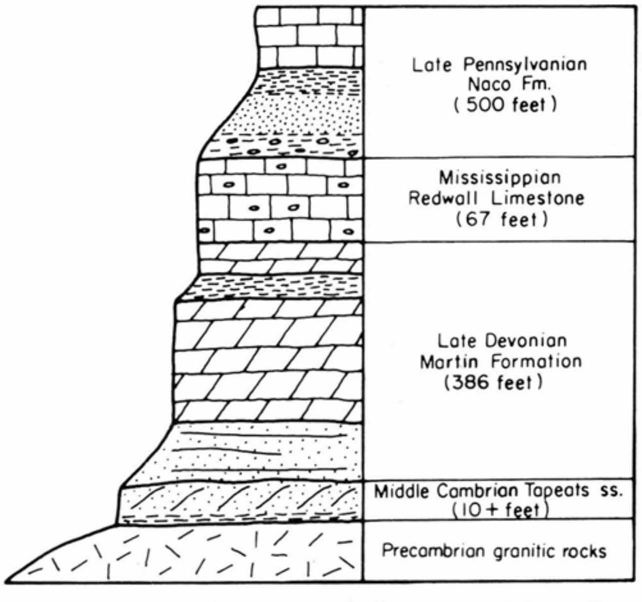

FIGURE 1—Stratigraphic section in the Payson area, Arizona. From Burt and Péwé (1978, p. 148).

36.5 Ascending stratigraphic section through Kaibab; small Cretaceous-filled channel at 37.2 mi, with principal contact between Kaibab and Cretaceous sandstone at 37.9 mi. The irregularity of this disconformable contact is clearly visible. 5.0
41.5 Road to left to Young, Arizona. 7.0
48.5 Navajo/Coconino County line. Road to left is the Mogollon Rim road which can be followed to the vicinity of Show Low. In this area the highway is traversing yellowish-tan and orangish-brown Upper Cretaceous sandstone. 5.3
53.8 Outcrops of massive, crossbedded, orangishtan Coconino Sandstone. **4.5**
58.3 Coconino/Gila County line. Excellent exposures of Coconino underlain by Supai Formation. **1.1**
59.4 Limestone exposed in hillside belongs to Ft. Apache Member of the Supai. A few miles north of the Mogollon Rim the Supai contains a thick section of evaporites which were the subject of extensive potash exploration in the 60's. An isopach map suggests very strongly that the southern terminus of the salt sequence is controlled by ground-water movement along a front more or less parallel to the Mogollon Rim. The present position of their solution front seems to be the Holbrook anticline. The axis of this structure trends very irregularly northwestward, and the northwest limb is presumed to be largely the result of salt withdrawal. 3.1
62.5 Base of Supai Formation. 2.3
64.8 Promontory Butte capped by Coconino Sandstone at 12:00. 2.0
66.8 Abundant purplish-gray limestone in Paleozoic sequence; may be Naco Formation of Pennsylvanian age. **6.1**
72.9 Junction with AZ-160; keep left. Highway descends through rather thin interval of Tapeats Sandstone before entering Precambrian granite. **4.9**
77.8 Tapeats Sandstone capping mesa at 2:00. **10.1**
87.9 Payson, Arizona; junction with AZ-87; turn left at stop light. Payson is located in a large area of Precambrian metavolcanic greenstone. 4.3
92.2 Dark reddish-brown sandstone belonging to Tapeats in roadcuts. **2.2**
94.4 Mazatzal Mountains composed largely of Precambrian greenstone, quartzite, and schist, but also containing Laramide-related granitic intrusives near Jakes Corner. **1.1**
95.5 Highway descends through Precambrian metasediments into Tonto Basin. **2.2**
97.9 Red beds in Tonto Basin Tertiary fill. Numerous lake terrace levels in the fine silts and coarse gravels of the Tonto Basin. The coarser, locally derived gravels interfinger with the finer lake sediments. 3.6
101.5 Rye, Arizona. 1.6
103.1 Rye Creek; good exposures of Quaternary/ Tertiary gravels in banks of creek at 3:00. 4.0
107.1 Roadcut in calichefied terrace material. 3.0
110.1 Tonto Basin at 9:00. 0.5
110.6 Small outcrop of greenstone in midst of younger material as highway passes through south end of Mazatzal Mountains. 2.8
113.4 High peaks from 2:00 to 3:00 are part of Mt. Ord (7,128 ft). **13.4**
126.8 Saguaro cacti at 11:00. **4.7**
131.5 Sycamore Valley-an intermontane valley downfaulted and partly filled with Quaternary gravel, sand, and lava flows. **5.0**
136.5 Mazatzal Quartzite exposed in roadcuts. **1.1**
137.6 Precambrian granite everywhere! **0.9**
138.5 Sugarloaf Mountain at 3:00. 2.3
140.8 Weavers Needle; this prominent, sharp peak is an erosional remnant of ash-flow tuffs in the Superstition Mountains at 9:00. The Superstitions are a volcanic range and are part of a larger lava and tuff complex that includes several calderas. 2.4
143.2 Saguaro Lake to left of highway. 7.9
151.1 Verde River. **3.8**
154.9 Central Arizona Project canal. 9.6
164.5 McDowell Road; end of road log; turn right for Phoenix.

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Coal mining and production in New Mexico*

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Abstract—New Mexico has two major coal areas, the San Juan Basin and the Raton area. There are a few minor coal fields outside of these areas, but most of the state's coal mining has taken place within the two. Early production in New Mexico was limited to small operations for home heating fuel until the early 1860's when a mine was opened by the U.S. Army. The introduction of railroads and the development of smelters in the state in the late 1880's and early 1900's brought the total production of coal in the state to over a million tons. World War I placed further demands on the coal-powered industries in New Mexico and production reached over four million tons in 1918. The first major slump in recorded production came in the mid- to late 1950's with the introduction of diesel-engine trains and the increased usage of natural gas. The present coal industry in New Mexico began in the early 1960's with opening of two large strip mines in the San Juan Basin. Several strip mines were opened in the late 1970's and early 1980's in the San Juan Basin. Production reached a record high in 1985, with 21.6 million tons produced. At present, New Mexico is the 13th largest producer of coal in the U.S. with 11 producing mines, two of which are underground operations. The majority of New Mexico coal produced in the last 25 years has been used in coal-fired generating plants supplying electricity to New Mexico, Arizona, and California.

Most of New Mexico's coal (Fig. 1) is in two geographical areas, the San Juan Basin in the northwest corner, and the Raton area in the north-central part of the state. These two areas have had the majority of the past and present coal production in the state. The San Juan Basin contains 96% of the state's strippable reserves, about 6.5 billion tons, all of which is Cretaceous-age coal. Most of the coal in the Raton area is deep coal of Tertiary—Cretaceous age, with an estimated 4.7 billion tons of strippable and deep resources. Most of the other coal fields in the state are relatively small and have had minor amounts of coal production in the past, but few have active operations today. Since the first records in 1882, coal production in New Mexico (Fig. 2) has fluctuated from a historic low of 116,656 tons in 1958, to a high of 21,601,816 tons in 1985. Before that time the Spanish settlers mined small amounts of coal for home use, and anthracite is known to have been mined in the Cerrillos field, near Madrid, as early as 1835. In 1861, the U.S. Army troops at Fort Craig opened a mine in the Carthage field (Gardner, 1910), in south-central New Mexico, marking the first significant production in the state. Demand by railroads and copper smelters in 1889 caused coal production to exceed a million tons for the first time. In 1918 production exceeded 4 million tons due to World War I demands on smelters, factories, and railroads. With the advent of diesel engines and the use of natural gas, the state's coal production fell to under a million tons in 1950, with a record low in 1958.

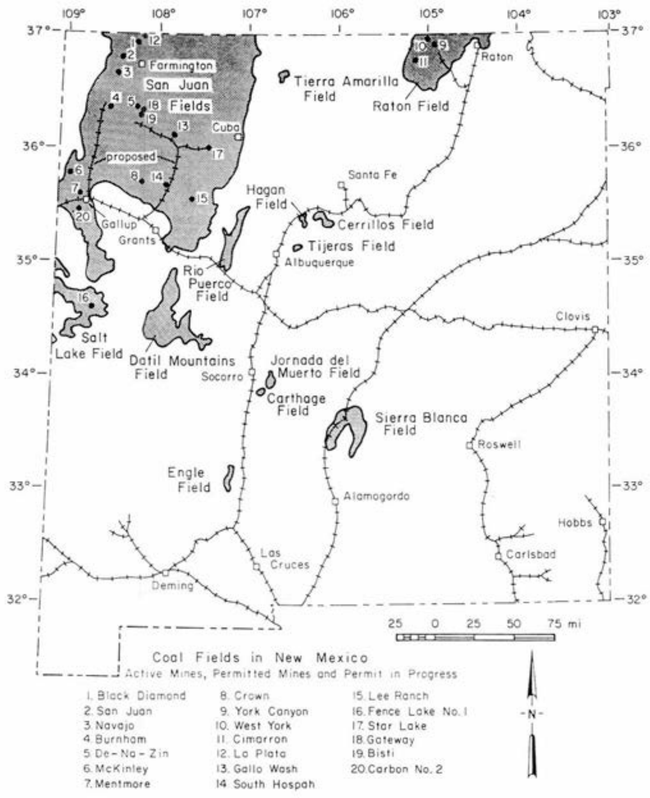

FIGURE 1—Coal fields and coal mines in New Mexico.

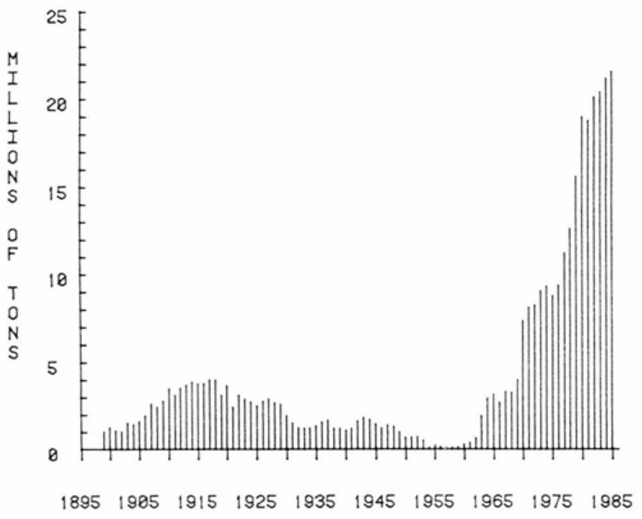

FIGURE 2—New Mexico coal production.

In the early 1960's, coal production in New Mexico began an upward trend with the large-scale strip-mine operations in McKinley and San Juan Counties in northwest New Mexico, and the development of the coking-coal mines in the Raton field by Kaiser Coal Corporation (1966). The increased demand for electrical power in Arizona, New Mexico, and California, and the inexpensive strippable-coal resources in northwestern New Mexico, led to the opening of Pittsburg

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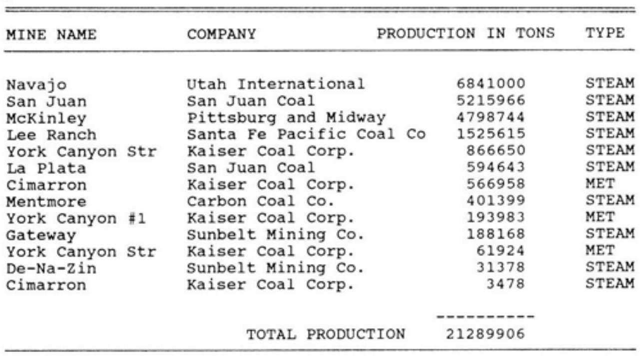
*Compiled from 1987 Keystone Coal Industry Manual article on New Mexico by F. E. Kottlowski, G. H. Roybal, and K. S. Hatton; updates from K. S. Hatton, New Mexico Energy, Minerals and Natural Resources Department.

and Midway's McKinley mine (1962) near Gallup, and Utah International's Navajo mine (1963) west of Farmington. The San Juan mine (San Juan Coal Company, west of Farmington), the second largest strip-mine operation in the state, began mining in late 1972. Kaiser Coal Corporation's York Canyon surface mine near Raton also began operations in 1972. A short hiatus in mine development occurred from the early to late 1970's. Carbon Coal's Mentmore mine near Gallup began production in 1978 with the increased demand in the energy market. The De-Na-Zin and Gateway mines operated by Sunbelt Mining Company started production in 1980 and 1982, to fill the increased needs at the San Juan Generating Station. The Lee Ranch mine owned by Santa Fe Pacific Coal Corporation started operations in 1982, with first production in 1983. Kaiser Coal Corporation's underground Cimarron mine in the Raton area began producing in 1985. The La Plata mine (San Juan Coal Company) north of Farmington was permitted and produced over a half million tons in 1986. The latest mine to be permitted and be on active status is the Salt River Project's Fence Lake No. 1 mine near Quemado (see article by M. Greenburg).

New Mexico ranks 13th in the nation in coal production (1985), with 11 producing mines in the state, two of which are underground operations. Production for 1986 was 21,289,906 tons (Table 1), with a value of $490,546,240. Over half of the coal produced in the state is delivered to two power plants in the northwest corner of the state: the Four Corners power plant receives coal from the Navajo mine; and the San Juan Generating Station from the San Juan, Gateway, De-Na-Zin, and La Plata mines. All of these operations are mining coal from the Fruitland Formation. Recently a third power plant in New Mexico came on line, the Plains Escalante Generating Station near Prewitt, which receives coal from the Lee Ranch mine northwest of Grants. This mine also ships coal to the Alamito Company power plant near Springerville, Arizona. The Lee Ranch operation mines several seams in the Menefee Formation.

Much of the remaining coal produced in New Mexico is shipped to cement plants and other industries in Arizona. Production from several seams in the Menefee and Crevasse Canyon Formations at the McKinley mine is shipped by rail to Arizona Public Service's Cholla plant near Joseph City, Arizona, and to Salt River Project's Coronado Plant near St. Johns, Arizona. Other customers for McKinley mine coal are Flintkote and Southwest Forest Industries in Arizona, and Kaiser Cement and Gypsum Corporation in California. Menefee and Crevasse Canyon coals from the Mentmore mine (Carbon Coal Company) were shipped by unit train to Arizona Electric Power Co-op's power plant at Cochise, Arizona, before market conditions forced a shut-down of the mine.

TABLE 1—New Mexico coal production in 1986. Data from K. S. Hatton, New Mexico Energy, Minerals, and Natural Resources Department.



MINE NAME	COMPANY	PRODUCTION IN TONS	TYPE
Navajo	Utah International	6841000	STEAM
San Juan	San Juan Coal	5215966	STEAM
McKinley	Pittsburg and Midway	4798744	STEAM
Lee Ranch	Santa Fe Pacific Coal Co	1525615	STEAM
York Canyon Str	Kaiser Coal Corp.	866650	STEAM
La Plata	San Juan Coal	594643	STEAM
Cimarron	Kaiser Coal Corp.	566958	MET
Mentmore	Carbon Coal Co.	401399	STEAM
York Canyon #1	Kaiser Coal Corp.	193983	MET
Gateway	Sunbelt Mining Co.	188168	STEAM
York Canyon Str	Kaiser Coal Corp.	61924	MET
De-Na-Zin	Sunbelt Mining Co.	31378	STEAM
Cimarron	Kaiser Coal Corp.	3478	STEAM
	TOTAL PRODUCTION	21289906	

Kaiser Coal Corporation's underground production from Raton is sent to the copper and steel industries and the chemical and utilities industries in Texas. Other markets for this coal are the cement and other industrial plants in the Southwest. Most of Kaiser's York Canyon strip-mine production is shipped to Salt River Project's power plant located near St. Johns, Arizona. All of Kaiser's mines in the Raton area are mining in the Upper Cretaceous Vermejo Formation.

Several proposed and permitted mines have been put on hold due to the poor market conditions that have developed in the past few years. In 1984 Consolidation Coal's Burnham mine suspended operations, and the Carbon No. 2 and Mentmore (Carbon Coal Company) mines went on inactive status in 1986. Marketing factors inhibiting the production and mining activity in New Mexico are 1) the decrease in the demand from coal-fired generating plants due to the low price of fuel oil, and 2) the coming on-line of the Palo Verde nuclear power plant near Phoenix, Arizona. The continued depressed market for coking coal and lower-priced natural gas has hurt production in the Raton area. These factors have had an impact on the production and employment figures in the New Mexico coal industry. In 1987, the effects of the oil slump and introduction of power from Palo Verde continue to be felt with temporary shut-downs at the Navajo, San Juan, and La Plata mines. A short-lived labor dispute with the United Mine Workers of America at the McKinley mine in early 1987 also caused production problems at that mine. With these events in mind, New Mexico's coal production for 1987 is likely to be lower than in 1986.

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Geology and mining activity in the Lee Ranch area, McKinley County, New Mexico

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Abstract—The Lee Ranch area which includes the Lee Ranch coal mine operated by SF Coal Corporation, a subsidiary of Santa Fe Southern Pacific Corporation, is located in southeastern McKinley County, New Mexico. The property lies on the Chaco Slope, a subdivision of the San Juan Basin, and is about 30 mi north of Grants and 70 mi northwest of Albuquerque, New Mexico. The coal deposits which are being exploited belong to the Cleary Coal Member of the Menefee Formation. Bed relationships within the Cleary are so complex as to require extremely closely spaced drilling. Radial changes in bed thicknesses, interbed intervals, and sulfur content require constant monitoring of the coal sequence in the pit. The coal is sub-bituminous in rank, with an average sulfur content of about 0.8%. The writer believes the domal structures in the area are a result of draping over basement highs associated with the much larger positive structure to the south, the Zuni uplift. These structures influenced the distribution of coal deposits in the area. Normal faulting with displacements ranging from 10 to 150 ft is fairly common on and adjacent to these domes.

The Lee Ranch mine is located in sec. 27 of T15N R8W, at the western end of a solid block of coal land which is reported to contain 215 million recoverable tons. In March 1987, the Santa Fe Coal Corporation and the Bureau of Land Management completed an exchange of coal lands that provided both parties with solid blocks of minable coal. The mining method utilized is "shovel and truck," and at present the mine consists of two pits. The production potential of 5 million tons per year has not been achieved since the mine's opening in late 1984 due to depressed economic conditions. To date, the maximum production was 2.167 million tons in 1985. The coal is sold to two power producers: 1) Plains Electric for use at their nearby Escalante Generating Station, and 2) Tucson Electric's Springerville Station, located in northeast Arizona. The mine employs 158, 49 of whom are salaried employees. At maximum production, the mine will employ about 300 people.

Introduction

The Lee Ranch area and the Lee Ranch mine are located in southeastern McKinley County, New Mexico, about 30 mi north of Grants and about 70 mi northwest of Albuquerque. The area lies immediately east of the Continental Divide at elevations ranging from 6,500 to 7,000 ft, and northwest of the 11,000 ft volcano, Mt. Taylor. This region can be characterized as typical central New Mexico grazing land, sparsely vegetated except in the mountains and lowlands (Fig. 1). The mine is accessible by paved public highway to the vicinity of San Mateo and by paved private road for the last several miles. The mine is served by the Lee Ranch spur which extends 43 mi from the main line of the AT&SF Railroad. A shorter spur connects the Lee Ranch spur directly with Plains Electric's Escalante Generating Station.

FIGURE 1—View looking south of Lee Ranch mine with outcrops of Point Lookout Sandstone along north flank of San Mateo dome; Mt. Taylor on skyline.

Previous work

Knowledge of the coal potential in the vicinity of Mt. Taylor dates at least as far back as Schrader (1906). However, the work of Gardner (1909) is the first significant study of the coal in the vicinity of San Mateo. The stratigraphic framework for the southern San Juan Basin was established through the efforts of a team of three U.S. Geological Survey geologists working in the region in the late 1920's and early 1930's (Sears, Hunt, and Dane, 1936). The area concerned is discussed by Hunt (1936).

The U.S. Geological Survey relied entirely on surface exposures as a means of estimating the coal potential. Generally, the coal in the San Juan Basin does not hold up well in outcrop and the main manifestation of its presence is the red clinkered shale produced by near-surface burning of the coal. In the few existing coal outcrops, the thickness is misleading due to thinning effect of weathering. However, suggestions of the kind of coal that has been delineated through drill holes were reported by Hunt (1936, pl. 35) on the flank of San Miguel Creek dome, where approximately 14 ft of coal were measured in a 21 ft interval. Another factor which may play a part in the measured thicknesses of the outcropping coal beds is the suggested possibility that peat accumulations were influenced by local structural anomalies. This would make likely thinning of the coal updip, toward the outcrop. The major effect, by far, must be the almost ubiquitous tendency of the coal in the area to burn, and, where not burned, to be reduced greatly in thickness through weathering.

Stratigraphy

Cleary Coal Member of Menefee Formation

The coal beds that are being mined at the Lee Ranch mine belong to the Cleary Coal Member of the Menefee Formation. This unit had previously been known as the upper part of the Gibson coal member of the Mesaverde Formation (Hunt, 1936, p. 49). The name change is the result of a general reclassification of the Upper Cretaceous stratigraphy in the region (Beaumont, Dane, and Sears, 1956). The Cleary consists of a variable combination of sandstone, siltstone, mudstone, shale, and coal with scattered bands of concretionary siderite (weathers to limonite and goethite). All the lithologic types are considered to be of nonmarine origin, and the coarser clastic units, particularly the sandstone beds, are lenticular and discontinuous. The thickness of the Cleary, the total coal-bearing part of the lower Menefee Formation, is about 150 ft. The coal beds become thinner and less frequent toward the top of the sequence. The exploitable interval of the Cleary, that part in which coal beds of minable thickness are found, ranges in most places between 50 and 70 ft and is in the lower to middle parts of the unit.

The Cleary Coal Member intertongues with the underlying marine nearshore and barrier-beach Point Lookout Sandstone, and, inasmuch as it is a regressive deposit, the base of the Menefee rises stratigraphically northeastward and becomes younger in that direction. The Late Cretaceous depositional strandline is well established in the San Juan Basin as having a northwesterly orientation. The writer has examined several sets of data and feels that N55°W is a good average strandline direction throughout all but the latest Late Cretaceous time. In the area of the Lee Ranch mine the possibility exists that local anomalies in the Cretaceous landscape played some part in the shoreline configuration and in the thickness and distribution of the coal.

Coal deposits

Individual coal beds considered to be in the category of reserves range in thickness from 1.5 to more than 15 ft in the Lee Ranch area. The number of individual beds present at any one locality varies between one and five. The coals that are of significance have been assigned color names, and the complexity of the partings and splits has led to many sub-color designations. The colors have been extended throughout the Lee Ranch area, but the many thin beds, the discontinuous nature of the coal, the presence of sandstone channels, and the generally complex nature of the coals cast doubt on the reliability of such widespread implied correlation. The general grouping of the coal units may be reasonably reliable, but the detailed relationships within these groups may be somewhat questionable.

The Lee Ranch area has been divided into several lesser areas. The present mine is in Area C. In the vicinity of the mine are three coal groups, in descending order Purple, Blue, and Red. The Purple beds consist of one to four relatively thin coals, two of which might be of minable thickness at any given locality (Fig. 2). The maximum thickness of a Purple coal may locally reach 5 ft. In the vicinity of the mine the Purple coal beds are discontinuous, and where two or more beds are present, the interval separating them varies from 1 to ca 10 ft.

As shown in Fig. 2, in the vicinity of the mine the Blue

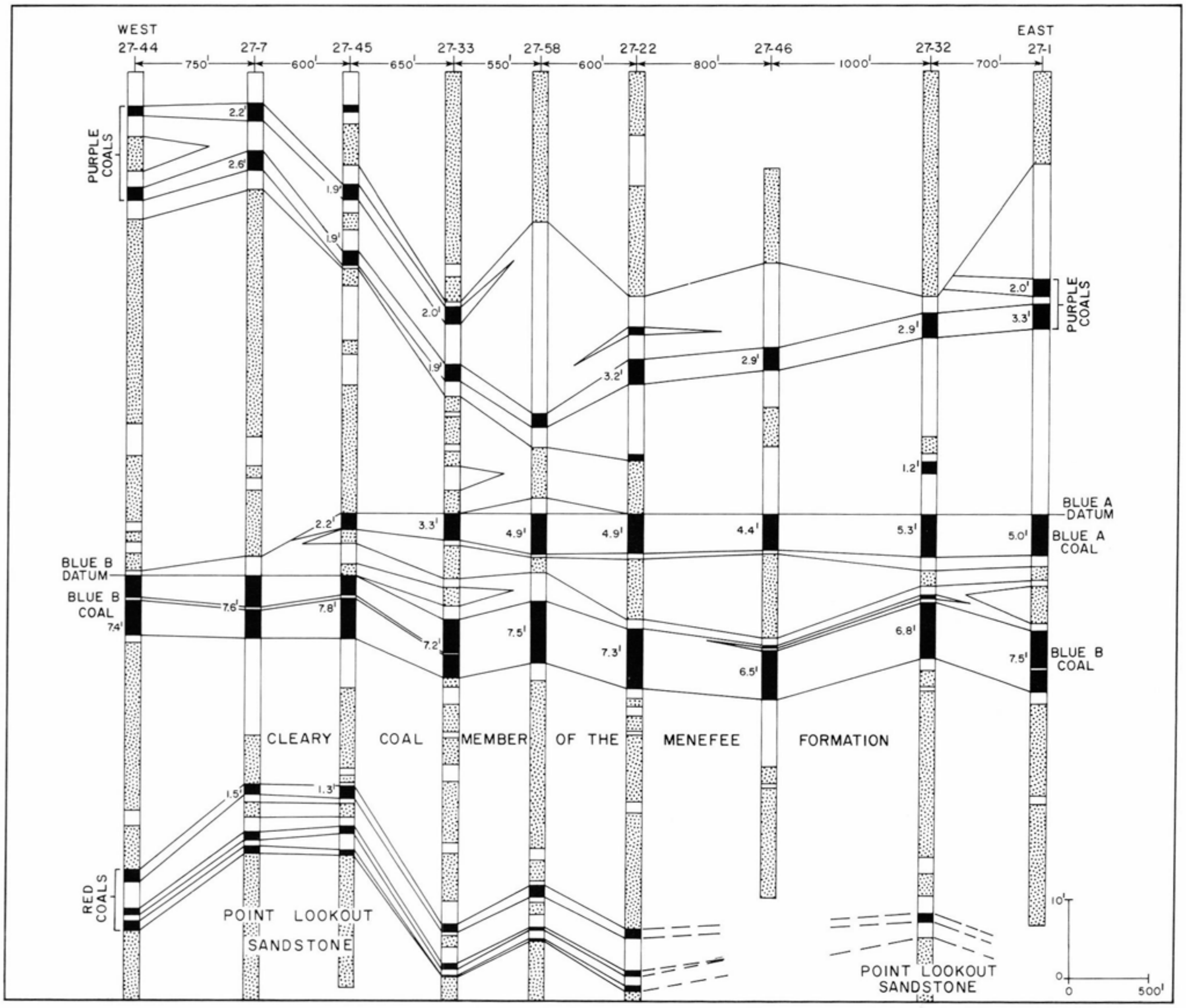

FIGURE 2—Coal correlation diagram across the north end of the Lee Ranch mine.

A coal bed is underlain by the Blue B bed. The Blue A bed, which is locally truncated at the west end of the mine, attains a maximum thickness of slightly more than 5 ft. It lies from about 10 ft to more than 40 ft below the lowermost Purple coal. About 2.5 mi east of the mine the lowermost Purple bed merges with, and becomes indistinguishable from, the Blue A; it is separated from the Blue B coal bed by 5-12 ft in the area covered by Fig. 2, but elsewhere in Area C the Blue A and B beds merge into a single 15 ft unit. The barren interval between A and B varies widely over short distances, from a few feet to nearly 50 ft, as sand bodies come and go in this interval. Especially the Blue B is likely to have partings and splits. East of the mine area, an upper split of Blue B was named the Green bed. The Blue coals are the most persistent and the thickest throughout the Lee Ranch area; because of this, they constitute the principal reserve units.

Several thin, presumably non-economic coals are present in the area of the mine 18-30 ft below the Blue B. These coals are in the Red group. As shown in Fig. 2, these coal beds are quite thin and variable in number. Elsewhere in the Lee Ranch area, Red coal beds have local thicknesses in excess of 5 ft. The Red group lies immediately above the Point Lookout Sandstone. This situation proves to be the exception to the norm, since it is generally true in the San Juan Basin that the coal unit immediately shoreward from the barrier-beach sand (above, in regressive conditions) is the thickest in the sequence. The sandstone-dominated interval separating Blue B and the Red coals may in part be a Point Lookout Tongue.

Coal quality

Coal quality is variable with respect to ash and sulfur content. The distribution of sulfur is probably a function of the depositional environment of the peats, and the distribution of mineral matter is more than likely related to the depositional position within the swamps. Extensive sampling and analysis in the vicinity of the Lee Ranch mine resulted in an average set of as-received values for this coal as follows: ash 18%, moisture 16%, sulfur <1%, Btu/lb 9,200. Application of the Parr formula to these components places this coal in the upper end of the Subbituminous A rank. Comprehensive washability studies indicate that the ash could be reduced by washing to about 10% with a corresponding increase in the Btu's to about 10,200. Sulfur would probably not be significantly affected by washing.

Structure

Chaco **Slope**

The Lee Ranch area is located in the southern part of the San Juan Basin, in a structural subdivision defined by Kelley (1950, p. 102) as the Chaco Slope. This broad, gently dipping part of the San Juan Basin extends from the margin of the Zuni uplift on the south northward to the Central Basin. The regional dip of the beds is northerly, and the average dip across the Chaco Slope is about 1° (Kelley and Clinton, 1960, p. 76). Locally, the dip increases to several degrees, and on the margins of the several domal structures and noses situated on the Chaco Slope the dip locally exceeds 10°. Faulting is not common on the Chaco Slope, but the occurrence of normal faults with displacements in the range of 10-150 ft are not uncommon, particularly on the margins of the positive structures. Small faults are not readily detectable in the Menefee Formation owing to the lenticularity of the sandstone units and crossbedding.

The Lee Ranch coal mine is located on the northeast flank of the Zuni uplift, just south of the nose that separates the north flank of the Zuni uplift from the west flank of the Mt. Taylor syncline. The south-trending, eastward-dipping beds of the Menefee are locally deflected eastward again along the margin of the San Mateo dome. It is just north of this irregularly shaped domal structure that the Lee Ranch mine is located. The prominent, north-dipping outcrops of the Point Lookout Sandstone are clearly visible beyond the mining operations in Fig. 1. Also visible in Fig. 1 and from the road leading into the area are the steeper dips associated with the east flank of the San Mateo dome. Kelley (1955) recognized that the east flank, with dips exceeding 30°, possessed the character of a Colorado Plateau monocline which might imply development above basement faulting. Though the San Mateo dome has a structural relief of more than 1,200 ft on the north and east sides, it merges with the northeast flank of the Zuni uplift to the south and west, and, as a consequence, possesses probably no more than 100 ft of closure.

About 6 mi northeast of the San Mateo structure is a second structurally positive feature, the San Miguel Creek dome. It is irregular in outline and is about 5 mi in average diameter. Though having less maximum structural relief than the San Mateo dome, it has a greater closure, perhaps 600 ft. To the west and southwest of the Lee Ranch area are several other domed areas. The writer believes that San Miguel Creek, San Mateo dome, Walker dome, North Ambrosia Lake anticine, and South Ambrosia Lake anticline are outliers of the much larger Zuni uplift, and that the present nature of these structures is due to draping above Precambrian knobs. If this is true, then these features were probably somewhat positive during Late Cretaceous deposition, and it would seem quite logical that they were factors in the distribution of the accumulations of peat and associated sediments. The argument for these domes being drape structures rather than compressional in origin is enhanced by the relatively flat-bottomed configuration of the structurally low areas separating the positive features.

Faulting

Faulting is not common on the Chaco Slope, but its frequency is greater along the southern margin, adjacent to the Zuni uplift, and especially in the vicinity of, and directly on, the positive areas. The faults all appear to be normal, with displacements ranging from a few feet up to 150 ft. The faults associated with the San Mateo dome have a northerly to northeasterly trend, directions that are frequently associated with faulting along the north flank of the Zuni uplift. San Miguel Creek dome is broken into segments by a series of east-trending faults, which are somewhat anomalous for this area.

Faults, even those of relatively little offset, are rather easily detected and mapped in the areas of outcrop of the Point Lookout and other massive marine sandstone units. Small faults and even those with displacements of 40-50 ft are difficult to see at the surface where the irregularly bedded and lenticular nonmarine units like the Menefee Formation are present. Closely spaced drilling, such as that conducted in the Lee Ranch area, is necessary to define faults which might disrupt mining operations. A north-trending normal fault, downthrown on the east, is present approximately along the east margin of the west pit of the Lee Ranch mine. This fault has a maximum throw of about 30 ft where pinpointed by closely spaced development drilling. A second, somewhat larger fault was delineated in the development drilling stage to the southeast of the present mine area. This fault, also north-trending and downthrown to the east, has a maximum observed displacement of about 75 ft. Over a distance of about 0.5 mi this offset is reduced to less than 20 ft. These faults, and the others associated with the domed areas, are thought to be minor tensional-adjustment features that can be expected to die out quickly away from the positive structures.

Federal coal exchange

The Santa Fe Pacific Railroad Company, through incentive grants from the U.S. Government at the time of the building of the railroad, came to possess vast tracts of minerals in a square-mile checkerboard pattern that encompasses the Lee Ranch area. The alternate sections are in large part federal or state minerals. About five years ago it was proposed that there be an exchange of federal lands for lands of corresponding worth belonging to the Santa Fe. After years of negotiations, on 5 March 1987 the Santa Fe and the Department of the Interior (Bureau of Land Management, BLM) were able to agree on an exchange which gave Santa Fe a block of contiguous coal lands surrounding the Lee Ranch mine.

The addition of 4,890 acres increased Santa Fe's already substantial holdings in the area of the mine by 77.5 million tons to give the company total of 215 million tons of recoverable coal with a 11.97:1 stripping ratio in a single block. The BLM received from the exchange 67.8 million tons of coal with a ratio of 10.45:1 in 6,263 acres. The BLM acreage forms three solid tracts to the north, northeast, and southeast of the Lee Ranch mine. The total recoverable coal in these three areas is calculated at 137.7 million tons. The consolidation of the coal lands is estimated to have enhanced the value of the federal lands by $30 million. In addition, the BLM received 4,893 acres of mineral rights in the Chaco Cultural National Historic Park and various archeological protection sites.

The mine

Background

Exploration began in the summer of 1973 when the writer and W. R. Speer, consulting geologist in Farmington, supervised the drilling of 128 plug holes in the shallow-coal area of the Lee Ranch coal holdings of Santa Fe Mining Corporation. Four core holes were drilled for sampling purposes. This reconnaissance program was completed in late 1973 and the area remained dormant until late 1979 when Santa Fe initiated a detailed exploration and development program on their lands. The drilling and coring program continued until mid-1981 and resulted in the drilling of over 1,100 holes.

Engineering design and geological evaluation were carried on concurrently with the drilling program, and in early 1981 Santa Fe Coal Corporation submitted an application to the New Mexico Mining & Minerals Division. A permit to mine up to 5 million tons per year was issued and construction of the mine facilities began in late 1982. Construction continued through 1983 and 1984, with regular coal shipments commencing on 22 October 1984. The Lee Ranch mine was formally dedicated on 22 April 1985.

Mining and handling technology

The Lee Ranch mine utilizes a "shovel and truck" method of overburden removal and coal extraction. The mine is designed as a multiple-pit operation. The overburden (used in the sense to include "interburden") is drilled on a basic 24 x 24 ft grid with $10^{5}/8$ in. holes and shot with mostly ANFO. The overburden is only drilled for each bench as the mining progresses, i.e. the entire mining sequence is not shot at one time. The coal is ripped but not shot. Each pit is equipped with a large, electric-powered stripping shovel with a 40 ton bucket capacity for overburden removal. The overburden is loaded into 170 and 85 ton haul trucks. The ripped coal is loaded by either a front-end loader or hydraulic shovel into 160 ton haulers for transportation to the crusher where it is reduced to 2 in. top size. The crushed coal is stored in one of three 189 ft high silos which have a combined capacity of about 40,000 tons. The operation of the mine, the scheduling of the mining sequence, is governed largely by a sophisticated computer program.

The minimum thickness of the coal mined is 1.5 ft, but there are circumstances that would dictate that lesser thicknesses might be locally feasible to mine, and other conditions whereby it would be impractical to remove coal thicker than the minimum. In the vicinity of the present mining operation, the Red coal beds are too thin and too deep to be economically recovered.

The coal is moved by a conveyor belt from the silos to the train-loading facility which is capable of loading at the rate of 3,000 tons per hour. A 100 car unit train can thus be loaded in less than four hours. The system is designed so that the train, operating on an automatic throttle, moves at a constant rate of about 2.55 mi per hour. Coal may be taken from one or more of the three silos to achieve a specified quality.

At the time of this writing there are two pits progressing northward in sec. 27 and being backfilled in the southern part. The east side of the west pit is controlled by a fault. There is a strip of unmined land about 500 ft wide between the two pits, which will be mined essentially as an expansion of the east pit. Now that the land exchange has been accomplished, it will presumably enable the mining operation to expand both east and west without the mile-long discontinuity that was caused by the previous checkerboard pattern of mineral ownership.

The Lee Ranch mine was designed with a production level of 5 million tons per year as the ultimate capacity. The mine has not attained even half of the production potential due to the generally soft market conditions. By 1985 the mine had developed two markets and produced 2.167 million tons with 967,000 tons going to Plains Electric's Escalante Generating Station and the remaining 1.2 million tons being delivered to Tucson Electric Power's Springerville plant. In 1986 production dropped to 1.529 million tons, with the major reduction being the approximately 50% decline in Tucson's needs. The decrease in production caused the mine to cut back to a four-day work week, but in March 1987 a spot market contract with Arizona Public Service resulted in a temporary expansion of production and made the return to the five-day work week possible. This unforeseen need for Lee Ranch coal was the result of a lengthy strike at Pittsburg & Midway's McKinley mine. Production during 1987 will probably be 1.8 million tons. If both the Escalante and the Springerville stations were to expand to their designed capacities, it would increase production at the Lee Ranch mine to 3.4 million tons. Hopefully, new markets expected to develop in the Southwest will bring the mine to its 5 million ton a year projected level of production in the early 1990's.

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Characterization of New Mexico coals, Menefee and Crevasse Canyon Formations

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Abstract—For the past two years, the New Mexico Bureau of Mines & Mineral Resources, in conjunction with New Mexico Institute of Mining & Technology, E. C. Beaumont, and A. D. Cohen, has undertaken a project to uniformly sample and analyze the coals of New Mexico. The New Mexico Research & Development Institute has funded this coal-quality-assessment project. This paper presents some of the results for the Gallup, Crownpoint, San Mateo, and Standing Rock coal fields. The drilling from these fields produced a uniformly collected set of geophysical logs, as well as cores for complete combustion analyses. Analyses run were proximate, ultimate, Btu, forms of sulfur, major oxide ($Si0_2$, $Ti0^2$, Fe_20_3, CaO, MgO, Na_20, K_20, P_20_5), and trace element (Be, Cr, Cu, Li, Mn, Ni, Pb, Sr, V, Zn). The drilling aspects of this program have produced information concerning the distribution and thickness of coal seams in these areas. Likewise, the analytical work has provided a complete set of combustion data that allows adequate and detailed comparisons of the coals from these four areas. The best-quality coals appear to be from the Gallup field, while those from the Standing Rock field are lowest in rank.

Introduction

Beginning in 1983, the New Mexico Bureau of Mines & Mineral Resources (NMBMMR), in conjunction with New Mexico Institute of Mining & Technology, E. C. Beaumont and Associates, and A. D. Cohen, has been involved in a quality study of New Mexico coals. This project has been funded by the New Mexico Research & Development Institute (NMRDI) and co-sponsored by several private companies (Anaconda, Consolidation Coal, Pittsburg and Midway, Santa Fe Mining, and others). The purpose of this study is to evaluate the quality of New Mexico coals through a systematic sampling and uniform analytical program. The end product will be a representative data base of the lithologic and quality characteristics of the major coal-bearing sequences and their coals in New Mexico.

Procedure

To acquire a consistent set of samples, a drilling phase was essential to accomplish the goals of the project. Drilling sites were located (by E. C. Beaumont), using existing data, approximately 2 mi apart, along a 200 ft overburden line for the uppermost qualifying coal within the coal-bearing sequence. A pilot hole was drilled with cuttings taken every 5 ft to determine general lithology and when the drill hole had sufficiently penetrated (20-40 ft) the underlying formation. The pilot hole was geophysically logged (gamma, caliper, density, resistivity, neutron) for an accurate record of the lithology and to determine core intervals. A minimum thickness of 1.5 ft was chosen as the qualifying bed thickness for the 1986 drilling, as opposed to the 2.5 ft minimum used as the qualifying thickness in the 1985 drilling season. This change was based on the opinion that the coal-bearing sequences drilled the second year (Menefee and Crevasse Canyon Formations) generally contained thinner coal beds than those drilled the previous year (mainly Fruitland Formation). Coring was done with a 15 ft, 3 in. diameter, split tube core barrel with a Chrisdril diamond carbide core bit, using water or mist. Cores included a minimum of 0.5 ft of rock above and below the coal. The deepest core taken at a drill site included more rock below the coal in order to obtain a complete geophysical log of the coal.

After the core barrel had been brought out of the hole and opened, the core was measured to determine if any loss had occurred. A recovery rate of 90-95% was required of the drilling contractor; therefore, if there was a significant loss within the coal cored, or there appeared to be differential recovery in the coal, the core was rejected and the interval recored. Once the core was accepted, it was marked off in foot intervals for lithologic description. Descriptions were made to the nearest five hundredths of a foot. After the description of the core was completed, the qualifying coal beds were sampled.

Any coals thicker than 5 ft were divided into two or more samples, with a maximum sample interval of 5 ft. Partings greater than 0.8 ft were considered removable and were not included in the coal samples. In the 1985 drilling program, removable partings and 0.5 ft intervals above and below the coals were sampled, but this procedure was discontinued the second year (1986). Coals were double-bagged in six-mil polybags to insure preservation of moisture content. Identification of the sample, such as hole number, sample designation, and depth interval were written on a card placed between the two polybags. This information was also put on an aluminum tag which was attached to the cord used to tie the bag. The top of the bag was folded over and tied to further insure against moisture loss. Samples were then sent back to the NMBMMR coal laboratory in Socorro every fifth day of drilling.

Description of coal fields and coal-bearing sequences

Drilling in 1985 and 1986 for the coal quality project was done in the San Juan Basin (Fig. 1). Most of the first year's drilling was in the Fruitland Formation fields (Fruitland, Bisti, Star Lake), with a few sites in the Menefee Formation fields (San Mateo, Standing Rock). The second drilling season concentrated on completing the Menefee Formation drilling (San Mateo, La Ventana, Chacra Mesa), with some drilling in the Crevasse Canyon Formation fields (Crownpoint, Gallup). Results of the drilling in the Cleary Coal Member of the Menefee Formation and Crevasse Canyon Formation are the focus of this paper.

Cleary Coal Member of Menefee Formation

This is a paludal sequence that lies above the regressive barrier-beach sandstones of the Point Lookout Sandstone. The Cleary consists of a sequence of sandstone, siltstone, shale, carbonaceous shale, and coal. Overlying this coal-bearing sequence is the barren nonmarine sequence of the Allison Member of the Menefee Formation (Fig. 2). A total of 39 drill sites were completed in the Cleary Coal Member in the La Ventana, Chacra Mesa, San Mateo, and Standing Rock fields. In the following discussion, the San Mateo-Chacra Mesa area and Standing Rock field are considered.

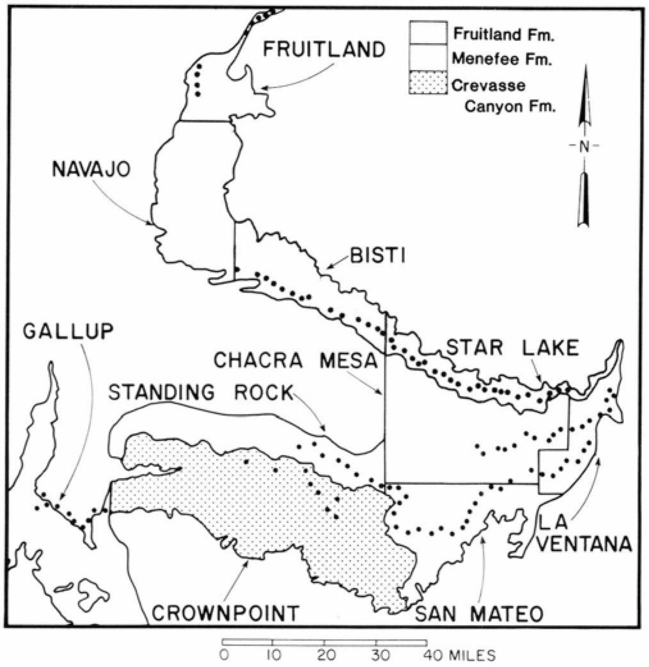


FIGURE 1—Generalized map of drill-site locations, San Juan Basin coal fields.

San Mateo-Chacra Mesa area—The San Mateo field is in the southeast corner of the San Juan Basin, north of Grants, New Mexico. This field covers an area of 370 mil, extending westward from the La Ventana field, southwest of Cuba, from T13-16N R4-8W. The southern boundary of the field is defined by outcrops of the Point Lookout Sandstone. Low-angle dips are the rule in the San Mateo field, but there is some normal faulting throughout the area. The San Miguel Creek dome and San Mateo dome in the southeastern part of this field (see first-day road log, mi 106.85) are prominent structural features, which influence the coal-bearing sequence.

The Cleary Coal Member in the Chacra Mesa field is confined to the southeast corner (T17N R3W and T18N R4W). The drilling done in this area will be discussed under the San Mateo locations.

In the San Mateo-Chacra Mesa area, the Cleary Coal Member is 88-290 ft thick (Fig. 3). The sequence is composed of sandstone, siltstone, shale, carbonaceous shale, and coal. Sandstone is more predominant in the western part of the San Mateo field. The sandstone/shale ratio in-

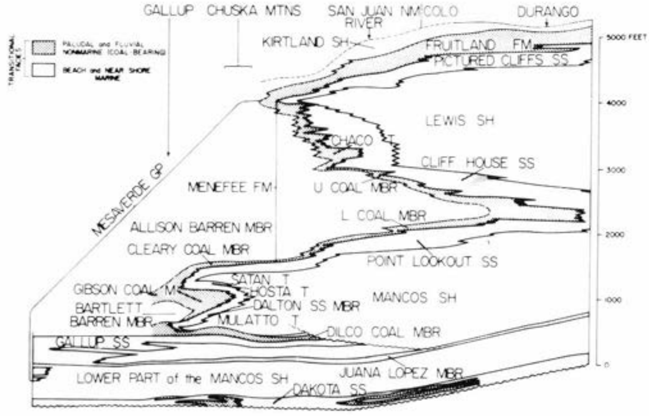


FIGURE 2—Stratigraphic diagram showing sequence, thickness, and nomenclature of Cretaceous rocks in the San Juan Basin, New Mexico and Colorado. From Beaumont (1986).

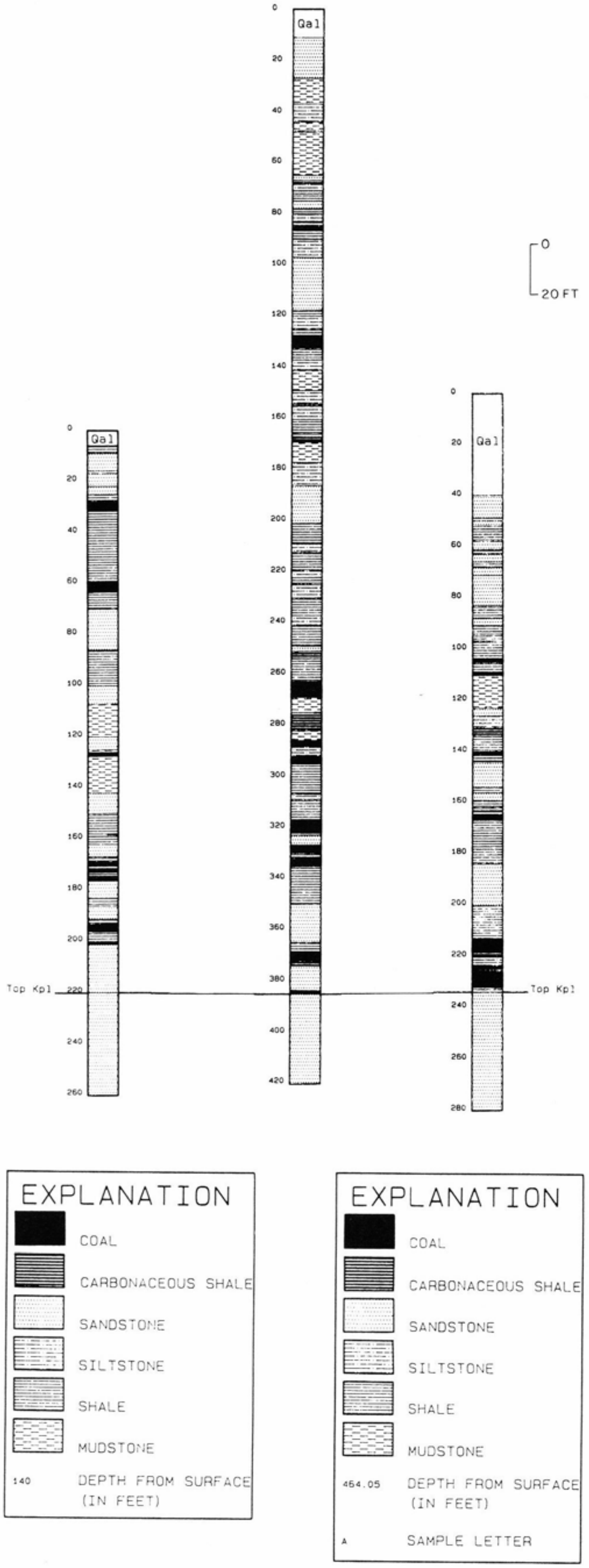


FIGURE 3—Graphic presentation of selected pilot holes in the Cleary Coal Member of the Menefee Formation, and explanation of graphic presentations of pilot and core holes.

creases from the east half of the area (average 0.93) to the west (average 1.22). In the western sections the sandstones are cleaner and medium-grained instead of the fine-grained and silty sandstones in the east sections. Many of these cleaner sandstones may be indicative of intertonguing with the Point Lookout Sandstone.

Cleary Member coals in the San Mateo-Chacra Mesa area are typically associated with shale. A few coals are overlain or underlain by a combination of sandstone and shale or siltstone and shale. The average coal-bed thickness at these locations varies from 1.6 to 5.9 ft, with an average of six seams in each section. The thickest coals are in the area southwest of the San Miguel Creek dome, in the south-central part of the San Mateo field. To the northeast and northwest of this area the coal beds thin, but the number of beds within the sequence shows little variation. The thickest coals within a section are within 20 ft of the Point Lookout Sandstone contact, in a nearshore setting.

The San Mateo-Chacra Mesa coals area are hard, moderately bright to bright, with poor to good cleat. These coals have fine to medium banding and often exhibit hackly fracture. The most notable characteristic of the coals in the San Mateo field is the abundance of pyrite and resin in the samples. Approximately 39% of the total-coal samples taken (56) had nonremovable partings that constituted about 9% of the total-coal sample. This is the largest percentage of partings in all of the coals drilled in the Cleary Coal Member fields.

Standing Rock field—The field covers an area of 350 mil in portions of T16-19N R9-17W in the southwest part of the San Juan Basin (Fig. 1). The southern edge of the field is the cropline of the Point Lookout Sandstone. The northern boundary is the northernmost outcrop of the Cleary Coal Member. This field is dominated by low relief with beds dipping less than 5° to the north. There is some faulting in the area, but none of major consequence.

Eight drill sites were completed in the eastern half of the field. The Cleary Coal Member is 93-290 ft thick in this area. The coal-bearing sequence consists of sandstone, siltstone, shale, carbonaceous shale, and coal (Fig. 4). Sandstone is the dominant lithology in the sequence, with five of the eight locations having a sandstone/shale ratio greater than 1.0. The sandstones are typically fine- to medium-grained and show a fining-upward pattern. Siltstones and shales are secondary lithologies in this sequence.

Coals in the Standing Rock sections are generally associated with shale, but several are overlain or underlain by siltstone or sandstone. In a majority of these sections coal is directly above, or within a few feet of, the Point Lookout Sandstone contact, and most of the coals in the sequence are within 75 ft of the Point Lookout Sandstone. There are three to seven coal beds within each section drilled, but most of these coals are thin and generally only two beds were sampled. Some of the coals sampled were less than the 2.5 ft minimum (of the 1985 drilling); these coals ranged in thickness from 2.0 to 5.7 ft, an average of 4.0 ft.

Coals in the Standing Rock field are dull to bright, with poor to good cleat, and have fine to medium banding. These coals are commonly shaly and contain some pyrite and resin. Fourteen coal samples were taken from this field, and six of them had nonremovable partings averaging 5% of the total sample. This was the smallest percentage of partings in all the Cleary Coal Member samples.

Summary—The total thickness of the Cleary Coal Member of the Menefee Formation does not change significantly within the geographical area sampled, but there is a change from shale-dominated to sandstone-dominated sequence from east to west. The Cleary coal-bearing sequence contains multiple coal beds throughout the San Mateo-Chacra Mesa area and Standing Rock field. These coal beds, although not correlable due to their lenticularity, show a general thinning northeast and northwest of the area between the San Mateo and San Miguel Creek domes. The thicker coals in any of the sections were near the base of the Cleary Coal Member, typically within 20 ft of the Point Lookout Sandstone contact. This may be indicative of a relatively more stable nearshore-swamp environment. Coals higher in the section seem to have developed in a short-lived fluvial-swamp environment. The coals sampled generally are moderately bright and pyritic, although the San Mateo coals tend to have more visible pyrite, resin, and more partings than those in the Standing Rock and Chacra Mesa areas.

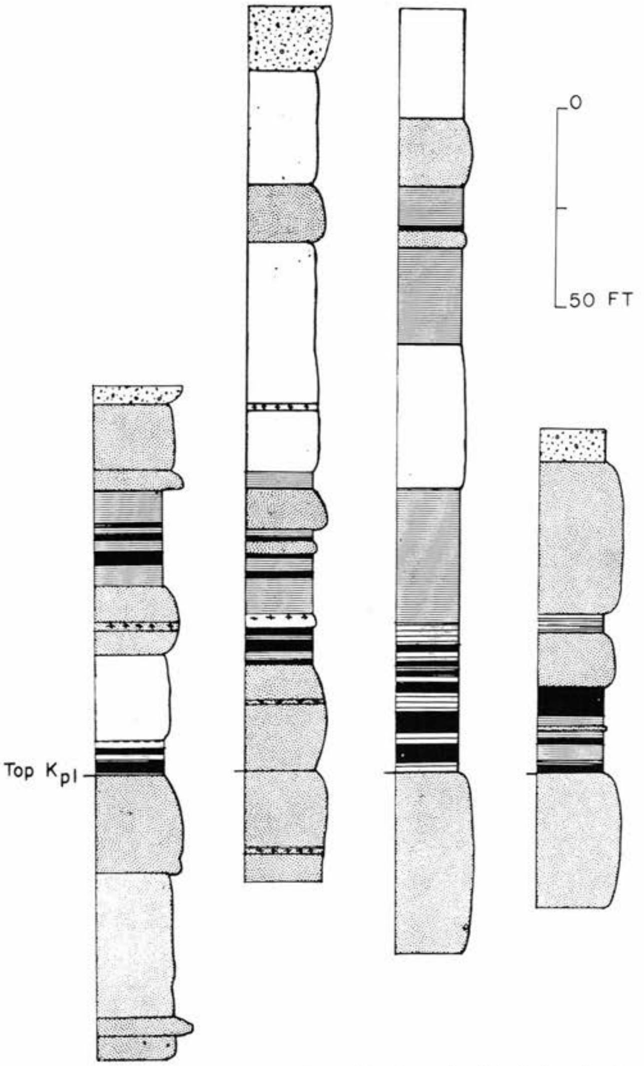


FIGURE 4—Graphic presentation of selected pilot holes in the Standing Rock field.

Crevasse Canyon Formation

The Crevasse Canyon Formation consists of (ascending) the Dilco Coal Member, Dalton Sandstone Member, Bartlett Barren Member, and Gibson Coal Menber (Fig. 2). These units overlie the Gallup Sandstone and, where present, are beneath the Hosta Tongue of the Point Lookout Sandstone. The Crevasse Canyon Formation is predominantly a nonmarine unit, although the Dalton Sandstone Member is a regressive coastal-barrier sandstone (Molenaar, 1977). The Dilco Coal Member is a regressive coal-bearing sequence overlying the marine Gallup Sandstone. Above the Dalton Sandstone Member, and in places the landward equivalent, is the Bartlett Barren Member, considered to be of local significance in the Gallup area, but merging with the Gibson in other areas (Molenaar, 1977). The overlying nonmarine Gibson Coal Member is a component of the Dalton regression in the lower part of the sequence and an element of the Hosta transgression in the upper part. This unit is overlain in the Crownpoint area by the transgressive Hosta Tongue of the Point Lookout, but, as is seen in Fig. 2, the Point Lookout is not present in the Gallup area landward of the pinchout. In the Gallup field, the Cleary Coal Member of the Menefee Formation directly overlies the Gibson Coal Member, and, therefore, these two coal-bearing sequences are grouped together as the Gibson-Cleary Member.

Crownpoint field—The field is located in the south-central San Juan Basin (T12-18N R8-17W) and is the largest coal field in the basin (930 mi^2). The northern and eastern boundaries are defined by exposures of the Hosta Tongue of the Point Lookout Sandstone. The southern boundary is the southern extension of the Crevasse Canyon Formation in the San Juan Basin proper. The structure is simple, with beds dipping gently to the north.

Eight drill sites were completed in the Gibson Coal Member of the Crevasse Canyon Formation in the Borrego Pass-Crownpoint area (Fig. 1). The Gibson sequence is 150-240 ft thick, thinning toward the town of Crownpoint. This unit is composed of sandstone, shale, coal, and a few siltstone beds, with shale being the predominant lithology (Fig. 5). The sandstone/shale ratio average is 0.95 for the eight sections. The sandstones in the Gibson Coal Member are thicker in the sections near the town of Crownpoint. These sandstones are relatively clean, well sorted, and have a log signature suggestive of channel deposits.

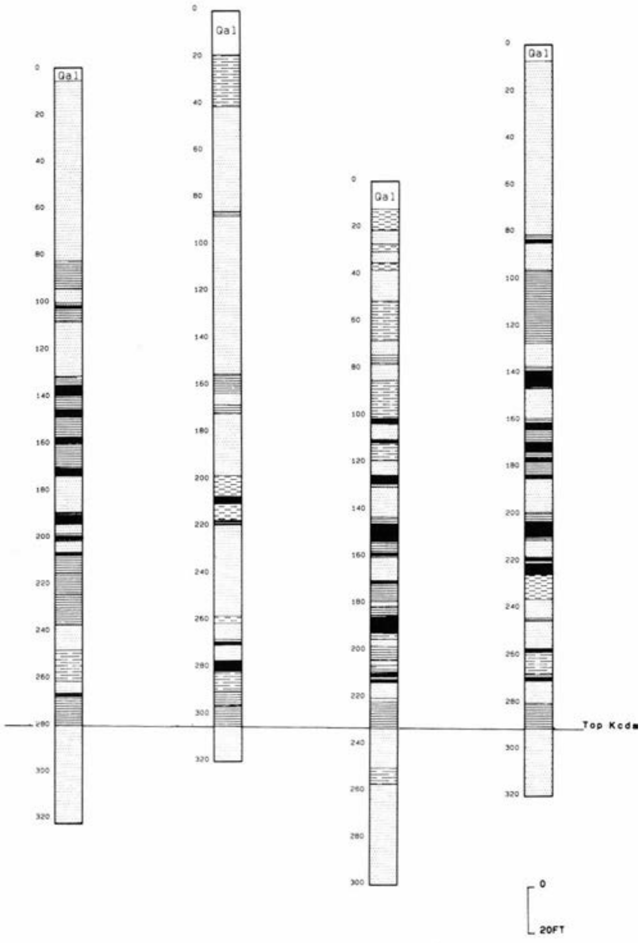


FIGURE 5—Graphic presentation of selected pilot holes in the Gibson Coal Member of the Crevasse Canyon Formation, Crownpoint field.

Many of the coals in the Gibson are associated with sandstones. Coals near the town of Crownpoint area are associated with blocky sandstones, or sandstones that show a coarsening-upward sequence. The frequency of coals associated with sandstones lessens toward the Borrego Pass area where more coals are within a shale sequence. The few coals that are underlain or overlain by sandstone in this area tend to be associated with finer-grained, fining-upward sandstones. The Gibson Coal Member sequence has multiple thin coal beds, 3-13 per section, that have an average thickness of 2.0 ft. The thicker coals are in the Borrego Pass area; the thickest coal encountered was 6 ft.

The Gibson coals sampled in the Crownpoint field were hard, moderately bright, with fair to moderate cleat. These coals contained variable amounts of pyrite and resin. Forty coal samples were taken from this field; 10 of them had nonremovable partings ranging from 1.4 to 28% of the total-coal sample.

Correlation of coals in the Gibson Coal Member is not possible given the geographical spread of the locations done for this study and the lenticularity of the beds. Some trends were evident from characteristic geophysical-log signatures within the coal-bearing sequence. Typically there appeared to be two zones of coal development in the Gibson. The upper zone is near the top of the section, 20-50 ft below the Hosta Tongue of the Point Lookout, and the lower zone is near the base of the section, 10-25 ft above the Dalton Sandstone. The distance between the two zones varies from 30 to 60 ft. Three coal zones are present in the Borrego Pass area. The stratigraphic location of these zones with relationship to the underlying and overlying coastal-barrier sandstone indicates that the lower zone was deposited shoreward of the regressive Dalton Sandstone and the upper zone is the shoreward counterpart of the transgressive Hosta Tongue. The third zone seen in the Borrego Pass area may indicate there was a short standstill in the area, allowing for more peat development before the Hosta Tongue transgression.

Gallup field—This field is in the southwestern part of the San Juan Basin and includes coal-bearing units of the Gallup Sandstone, Crevasse Canyon Formation, and Menefee Formation (Figs. 1, 2). The Gallup field is defined by the steeply dipping outcrops along the Nutria monocline on the east side and the steeply dipping beds associated with the north-trending Defiance uplift on the western edge of the Gallup sag (see discussion in second-day road log). Within the Gallup field the attitude of the rocks is controlled by the Gallup and Torrivio anticlines.

The Gibson-Cleary Member is a sequence of mudstone, sandstone, siltstone, carbonaceous shale, and coal, ranging from 129 to 204 ft at the locations drilled (Fig. 6). The sandstone/shale ratio averages 1.45 for these sections, but varies greatly (0.35-3.3). The sections with the largest amount of sandstone are in the eastern part of the area drilled (northeast of Gallup and just west of highway 666). The sandstones in the Gibson-Cleary are medium- to fine-grained and show a sharp basal contact with a fining-upward resistivity-log signature.

Gibson-Cleary coals are typically associated with shales, except in the easternmost locations that have coals in sandstone-dominated sequences. The thickest coals in the eastern Gallup field are associated with sandstones or siltstones, and those in the west are associated with shales. The thickest coal in a section varies from 2.15 to 6.6 ft in the nine locations. The average coal thickness in a sequence is 1-3 ft, with 3-16 coals within a section. The average bed thickness is greater in the sections that contain nine or more coals. Most of these sections are shale-dominated, while the sections with less than nine seams and thinner coals are sandstone-dominated.

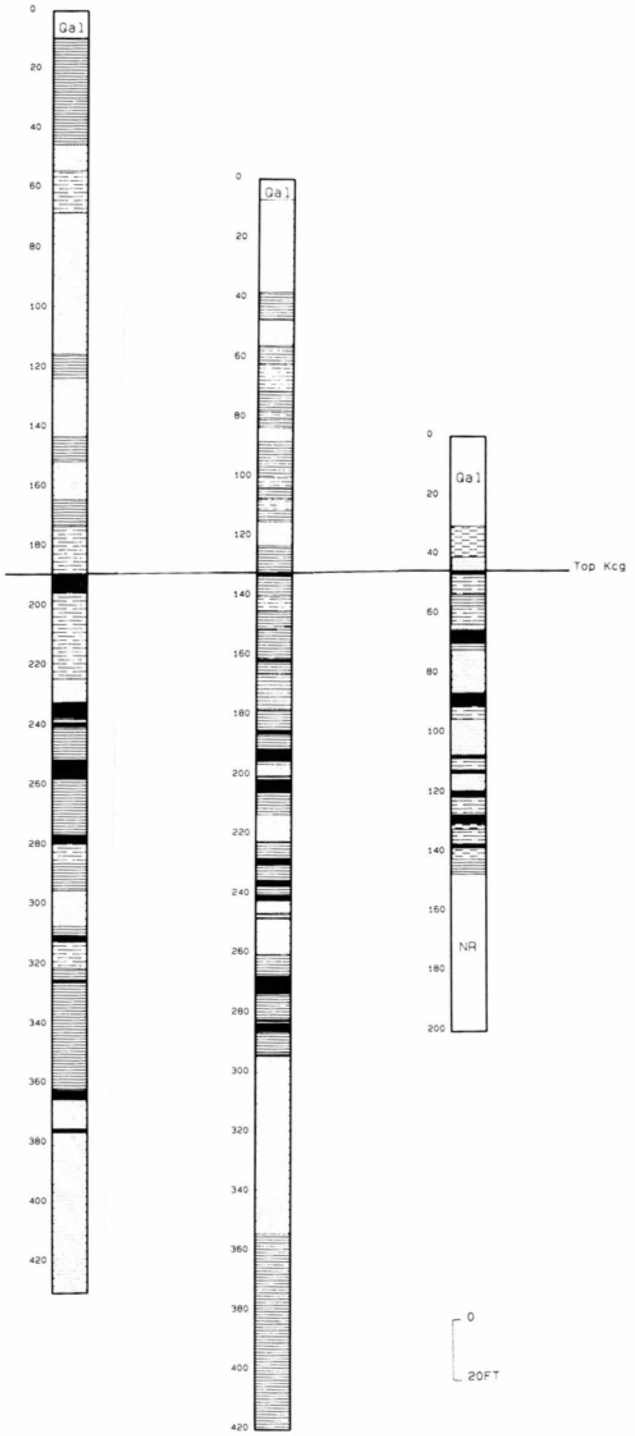


FIGURE 6—Graphic presentation of selected pilot holes in the Gibson-Cleary, Gallup field.

Coals sampled in the Gibson—Cleary are hard, bright to moderately bright, and have a good cleat. Some resin and pyrite were present in these coals and very few were shaly. Forty-one coal samples were taken with nonremovable partings averaging 8.3% of the total sample.

The Gibson—Cleary coal-bearing sequence thins from west of highway 66 to the westernmost drill site, obliquely in the direction of the pinchout of the entire sequence. Toward the northwest (McKinley mine area), the coals in the sequence are thicker and do not fit into this east—west trend. The Gibson—Cleary sequence has multiple seams, most of which are thin, indicative of an unstable environment for peat development. The frequency of coal beds in the sequence also indicates that conditions conducive to peat deposition existed many times during the deposition of the Gibson—Cleary.

Description of combustion analyses

Coals from the San Mateo, Standing Rock, Crownpoint, and Gallup fields were analyzed for combustion as well as chemical parameters as part of the NMBMMR coal-quality project. This report summarizes the coal-quality information gathered from these four fields. All coals were analyzed according to ASTM procedures. The analyses reflect ash contents of 33.3% or less, which is the U.S. Geological Survey cut-off for coal (Wood et al., 1983). Samples with ash contents greater than 33.3% but less than 50% had proximate and forms of sulfur run on them. Those samples with greater than 50% but less than 75% ash were not analyzed for volatile-matter content. When a sample contained more than 75% ash, analyses were run only for moisture and forms of sulfur. The hydrogen and oxygen reported in the NMRDI samples do not include the amounts present in the moisture of the sample. All samples, regardless of ash content, were analyzed for major-oxide content (SiO_2, Fe_2O_3, $A1_20_3$, TiO_2, CaO, MgO, Na_2O, K_20, P_20_5) and trace-element content (Be, Co, Cu, Cr, Li, Mn, Nb, Ni, Pb, Sr, V, Zn).

Comparison to previously sampled coals

The data from this project can be compared to what is already available in the literature. Most of the previous data do not represent uniform geographic sampling throughout the various fields. Previously, not all coal-quality parameters were run on all samples collected. In general, equilibrium moisture was not run by earlier workers. Likewise, major oxides or trace elements were not commonly analyzed for, due to the expense involved. The following comparisons, therefore, do not include equilibrium-moisture, major-oxide, or trace-element analyses. Data from previous investigations are what has been collected in the New Mexico Bureau of Mines & Mineral Resources coal database.

When the analyses for the Standing Rock field, as represented by the NMRDI sampling project, are compared with the previously collected data (Table 1), it can be seen that this project produced fewer samples than what was already available. In general, most parameters agree with the larger previous population. The exceptions are sulfur, which is somewhat higher in the NMRDI samples, and the pyritic and organic fractions. The heating value of the NMRDI samples averages less than that for the previously collected data population.

The sampling performed during the NMRDI drilling has doubled the number of samples known for the San Mateo field (Table 2). The NMRDI data indicate that a lower av-

TABLE 1—Standing Rock field, comparison of NMRDI data with previous data (as-received basis, all but heating values in percent).

	NMRDI Data			Previous Data		
	No.	Mean	S.D.	No.	Mean	S.D.
Eq. Moist.	14	15.39	1.25	N/A		
Moisture	14	16.93	2.59	52	16.28	2.88
Ash	14	13.00	5.18	52	12.90	3.70
V.M.	14	34.31	2.56	52	34.12	1.96
F.C.	14	35.77	4.38	52	36.83	3.40
BTU	14	9300	886	52	9684	663
MMFBTU	14	10918	570	52	11265	585
Carbon	14	54.61	4.70	50	52.62	6.50
Hydrogen	14	4.32	0.30	50	4.30	0.84
Nitrogen	14	0.97	0.19	50	0.93	0.46
Oxygen	14	10.96	1.04	50	13.02	3.61
Sulfur	14	1.07	0.49	52	0.94	0.53
Sulfide	14	0.43	0.36	43	0.38	0.41
Sulfate	3	0.07	0.02	33	0.04	0.09
Org. Sulfur	14	0.71	0.22	43	0.61	0.24

TABLE 2—San Mateo field, comparison of NMRDI data with previous data (as-received basis, all but heating values in percent).

	NMRDI Data			Previous Data		
	No.	Mean	S.D.	No.	Mean	S.D.
Eq. Moist.	51	14.57	1.32	N/A		
Moisture	51	12.47	2.03	44	15.77	1.33
Ash	51	13.44	4.94	44	10.40	4.40
V.M.	51	36.94	2.44	23	34.77	2.25
F.C.	51	37.04	3.81	23	37.36	3.06
BTU	51	10192	837	44	10021	672
MMFBTU	51	12077	628	44	11511	218
Carbon	51	58.78	4.40	33	57.71	4.06
Hydrogen	51	4.43	0.28	33	4.34	0.31
Nitrogen	51	1.06	0.15	33	1.00	0.04
Oxygen	51	9.82	1.74	33	9.81	0.55
Sulfur	51	0.90	0.45	23	0.71	0.27
Sulfide	51	0.31	0.26	23	0.25	0.18
Sulfate	15	0.05	0.04	3	0.01	0.01
Org. Sulfur	51	0.62	0.33	23	0.53	0.17

erage moisture content (12.47+/-2.03%) occurs in coals of this field than the average obtained from previous investigations (15.94+/0.99%). The ash content of the NMRDI samples is substantially higher, at 13.44+/-4.94%, than it is for the previously collected population, which averages 11.90+ /-4.80%. The volatile matter and fixed carbon in both sample populations are similar. The total sulfur content for the NMRDI samples is somewhat higher (.90+ /—.45%) than that previously known (0.71+1-0.27%) for this field. The range in values is notable in that the NMRDI drilling produced samples that had a maximum sulfur content of 2.60%, much higher than the previous 1.53% maximum, indicating a greater variability in this parameter than previously indicated.

Ultimate analyses show several notable differences, besides that noted for sulfur. The total carbon in the NMRDI samples is higher (58.78+1-4.40%), compared to the 57.71+/ —4.06% average of previous work. Hydrogen does not show any significant difference between the NMRDI data and what was previously known for this field. Previous data indicate a 1.00+1-0.04% nitrogen average; however, the NMRDI data show this to be low for both the average (1.06+/ —0.15%) as well as variation in values which is much greater. Both sulfide and organic-sulfur contents are similar for the NMRDI and previous populations of data. The NMRDI data, however, indicate a greater number of samples having sulfate development. The as-received heating value for the NMRDI data is higher (10,192+/-837 Btu/lb) than that for previous data (10,021+/-672 Btu/lb). This difference becomes readily apparent when the moist, mineral-matterfree heating values are considered. The previous data indicate a rank of high volatile C bituminous (11,511+/-218 Btu/lb). The NMRDI samples also have a high volatile C bituminous rank, but a much higher average MMFBTU value (12,077+/-628 Btu/lb).

Crownpoint field coals (Table 3) are represented by 27 samples obtained from the NMRDI drilling and 12 samples from previous sampling efforts. As-received moisture averages 15.59+/-1.54% in the samples from this project, as compared to a 15.08+/-1.61% average from the previous samples. Although the NMRDI samples indicate a slightly higher average moisture content, the variability in moisture values is somewhat reduced. Data from this project have shown that the ash content is notably different from what was previously known. Ash from the NMRDI drilling is 1.08% lower (10.72+/-5.13%) than that given in previously collected data (11.80+/-6.00%).

Although the ash content decreased, the total sulfur content increased in the NMRDI samples. Earlier work has indicated a total sulfur content of 0.91+/-0.62% for this field; the NMRDI samples averaged 1.47+/-0.86%a total sulfur, demonstrating that the average total sulfur is higher than previously indicated. The mean sulfide-sulfur content likewise increased from 0.35+ /-0.46% to 0.55+ /-0.64%. There is nearly twice as much organic sulfur (0.97+/-0.57%) in the NMRDI data as is in the earlier sample population (0.47+ / —0.34%). With the exception of carbon, there are no significant differences between the remaining parameters of the ultimate analyses. Carbon in the NMRDI samples is higher (61.14+/-4.29%) than the average value of previously acquired data (55.09+/-6.11%). Both the as-received Btu and MMFBTU values are essentially equal in the two populations.

Gallup field coals (Table 4) are represented by 40 samples from this year's drilling and 131 samples from previous sampling projects. The moisture content of these coals, as represented by the NMRDI collected samples, is 13.27+ / — 2.21%, which is slightly higher than the previous average for this field, of 11.80+/-2.53%. The ash content of the NMRDI samples is 10.48+/-6.73%, higher than the average of previously collected samples by 3.10%. Looking at the maximum and minimum values, the sampling done by previous investigators seems suspect. The maximum ash content for the NMRDI samples is 29.24%, compared to the high of 40.70% for the previously collected sample population, which is well above the coal/noncoal boundary.

The fixed-carbon value for the previously collected data is significantly higher than that for the NMRDI samples (43.31+1-4.32% vs 38.48+/-3.99%, respectively). Average sulfur content of the NMRDI population is lower than that for earlier data populations (0.57+/-0.45% vs 0.62+/-0.22%). The maximum sulfur content for the NMRDI samples is much higher (3.06%) than that previously known for this area. Only 16 sulfide analyses were available prior to this year's drilling, indicating an average sulfide content of 0.15+ / —0.15%. The 40 NMRDI samples show a lower average sulfide content of 0.11+/-0.14%.

No significant differences are apparent in the ultimate analyses of these two populations of coal samples from the Gallup field. Both the as-received and moist, mineral-mat-

TABLE 3—Crownpoint field, comparison of NMRDI data with previous data (as-received basis, all but heating values in percent).

	NMRDI data			Previous data		
	No.	Mean	S.D.	No.	Mean	S.D.
Eq. Moist.	27	14.92	1.77	N/A		
Moisture	27	15.59	1.54	12	15.08	1.61
Ash	27	10.72	5.13	12	11.80	6.00
V.M.	26	35.98	2.14	12	35.96	2.54
F.C.	26	37.59	3.33	12	37.20	4.13
BTU	27	10142	900	12	9993	993
MMBTU	27	11594	547	12	11524	415
Carbon	27	61.14	4.29	9	55.09	6.11
Hydrogen	27	4.40	0.86	9	5.98	0.45
Nitrogen	27	1.07	0.31	9	1.13	0.21
Oxygen	27	5.61	1.05	9	23.90	1.86
Sulfur	27	1.47	0.86	12	0.91	0.62
Sulfide	27	0.55	0.64	7	0.35	0.46
Sulfate	10	0.07	0.08	7	0.02	0.01
Org. Sulfur	27	0.97	0.57	7	0.47	0.34

TABLE 4—Gallup field, comparison of NMRDI data with previous data (as-received basis, all but heating values in percent).

	NMRDI Data			Previous Data		
	No.	Mean	S.D.	No.	Mean	S.D.
Eq. Moist.	40	13.04	3.47	N/A		
Moisture	40	13.27	2.21	131	11.80	2.53
Ash	40	10.48	6.73	131	8.70	5.20
V.M.	40	37.76	3.25	123	38.19	4.01
F.C.	40	38.48	3.99	123	43.31	4.32
BTU	40	10682	794	123	11094	870
MMFBTU	40	12140	544	123	12274	576
Carbon	40	63.35	4.90	51	61.49	6.09
Hydrogen	40	4.60	0.42	51	5.48	0.81
Nitrogen	40	1.11	0.10	51	1.09	0.12
Oxygen	40	6.61	0.92	51	18.44	5.72
Sulfur	40	0.57	0.45	130	0.62	0.22
Sulfide	40	0.11	0.14	16	0.15	0.15
Sulfate	40	0.00	0.00	4	0.01	0.01
Org. Sulfur	40	0.40	0.09	16	0.45	0.11

ter-free heating values are higher in the data collected prior to the NMRDI drilling, possibly reflecting differences in moisture and ash contents. However, there is no change in average rank value for this field; both sets of data indicate a high volatile C bituminous coal. The minimum moist, mineral-matter-free heating value is notably higher for the NMRDI samples: 11,399 Btu/lb, compared to a minimum of 8,683 Btu/lb in the previous data. The elimination of samples with ash contents greater than 33.3% would account for this difference. This indicates a much narrower range in coal rank than previously thought for this field.

The irregular collection of samples in the past has led to a much wider range in moisture values in some areas than what is actually present. The average moisture content for both the Gallup and Crownpoint fields was somewhat lower in the previous data than that obtained from the NMRDI samples. The NMRDI data are more reliable in that the collection techniques were uniform and no samples were allowed to dry excessively between the collection and analytical phases. The previously described sampling intervals and the uniform treatment of partings resulted in some newer, more accurate ash values. None of the coal cored was selectively sampled for coal intervals only, and high-grading the sample was thus circumvented. The forms of sulfur data available for both the Gallup and Crownpoint fields were sparse; the NMRDI drilling project increased the knowledge of these parameters for these areas. In general, the ultimate analyses are often not run. In this project, since ultimate analyses were performed on all samples with less than 50% ash, the general knowledge of this set of parameters has been greatly improved.

Comparison of San Mateo and Standing Rock fields

Coals of both the San Mateo and Standing Rock fields are in the Cleary Member of the Menefee Formation. These coals directly overlie the Point Lookout Sandstone. Table 5 gives a breakdown of the combustion analyses of the coals of these two fields. The proximate analyses of coals of these two fields are very similar, with the main difference being in the moisture content. Standing Rock field coals have a higher average as-received and equilibrium-moisture content than those in the San Mateo field. The equilibrium moisture for the San Mateo field is somewhat higher (14.57+/ —1.32%) than the as-received moisture content (12.47+/ —2.03%), indicating that these coals are not at their full moisture-retaining capacity. Standing Rock field coals show just the opposite condition in that the as-received moisture (16.93+/-2.59%) is higher than the equilibrium moisture (15.39+/-1.25%), which indicates that these coals have a greater amount of moisture than their porosity will allow. The coal may act as a minor aquifer, with the excess moisture located along cleat and fracture surfaces.

Notable differences occur in the heating value of these two groups of coals. The as-received heating value of the San Mateo coals (10,192+ /-837 Btu/lb) is significantly higher than that of the Standing Rock field coals (9,300+/-886 Btu/ lb). This difference is also found in the moist, mineral-matter-free heating value. San Mateo field coals have an average MMFBTU of 12,077 ± 628 Btu/lb, indicating a rank of high volatile C; bituminous, while the Standing Rock field coals have a MMFBTU of 10,918 ± 570 Btu/lb, indicating a rank of sub-bituminous A.

Ultimate analysis values are very similar. Total sulfur content for these two populations of coals shows that the Standing Rock coals are slightly higher in total sulfur (1.07+ / —0.49%) than the San Mateo field coals (0.90+/-0.45%). Pyritic sulfur differs slightly between these two fields, with the Standing Rock field having a somewhat higher average (0.45+1-0.36% vs 0.31+/-0.26%). The amount of oxidized coals, as indicated by the presence of sulfates, is similar. Likewise, the organic-sulfur content for coals from these two fields is similar.

TABLE 5—Combustion (top) and chemical (bottom) analyses of San Mateo and Standing Rock field coals. Combustion analyses: on as-received basis, all but heating values in percent. Chemical analyses: major oxides on whole-coal basis, values in percent; trace elements on ashed-coal basis, values in ppm.

	San Mateo			Standing Rock		
	No.	Mean	S.D.	No.	Mean	S.D.
Eq. Moist.	51	14.57	1.32	14	15.39	1.25
Moist.	51	12.47	2.03	14	16.93	2.59
Ash	51	13.44	4.94	14	13.00	5.18
V.M.	51	36.94	2.44	14	34.31	2.56
F.C.	51	37.04	3.81	14	35.77	4.38
BTU	51	10192	837	14	9300	886
MMFBTU	51	12077	628	14	10918	570
Carbon	51	58.78	4.40	14	54.61	4.70
Hydrogen	51	4.43	0.28	14	4.32	0.30
Nitrogen	51	1.06	0.15	14	0.97	0.19
Oxygen	51	9.82	1.74	14	10.96	1.04
Sulfur	51	0.90	0.45	14	1.07	0.49
Sulfide	51	0.31	0.26	14	0.43	0.36
Sulfate	15	0.05	0.04	3	0.07	0.02
Org. Sulfur	51	0.62	0.33	14	0.71	0.22
Major Oxides						
SiO_2	31	7.60	3.58	13	6.53	3.08
$Fe2O_3$	31	0.77	0.50	13	0.91	0.41
Al_2O_3	31	2.88	1.31	13	2.66	1.10
TiO_2	31	0.14	0.06	13	0.11	0.05
CaO	31	0.50	0.32	13	0.55	0.24
MgO	31	0.14	0.13	13	0.10	0.05
Na_2O	31	0.15	0.05	13	0.21	0.09
K_2O	31	0.09	0.10	13	0.07	0.09
P_2O_5	31	.006	.006	13	0.02	0.03
B/A	31	0.16	0.06	13	0.21	0.07
Eq. Si.	31	83.42	5.55	13	79.46	6.17
Trace Elements						
Be	46	27	33	14	22	1
Co	46	28	12	14	36	14
Cr	46	146	70	14	170	112
Cu	46	55	20	14	47	19
Li	46	36	13	14	30	8
Mn	46	269	343	14	472	336
Ni	46	61	39	14	51	38
Pb	46	68	58	14	80	23
Sr	46	696	298	14	924	495
V	46	156	53	14	144	63
Zn	46	116	118	14	36	14

No significant differences occur between the major-oxide concentrations in the coals from these two fields, except in the P_20_5 values. Standing Rock field coals have a notably higher P_20_5 content than the San Mateo field coals. Coal ash from the San Mateo field has a base/acid ratio of 0.16+/ —0.06, giving an estimated ash fusion temperture at 250 poises of approximately 2,800°F (Sage and Mcllroy, 1960). The coal from the Standing Rock field has a base/acid ratio of 0.21+/-0.07, resulting in an estimated ash fusion temperature at 250 poises of 2,700°F. The variability in these estimates of fusion temperatures between these two populations of coal is not great.

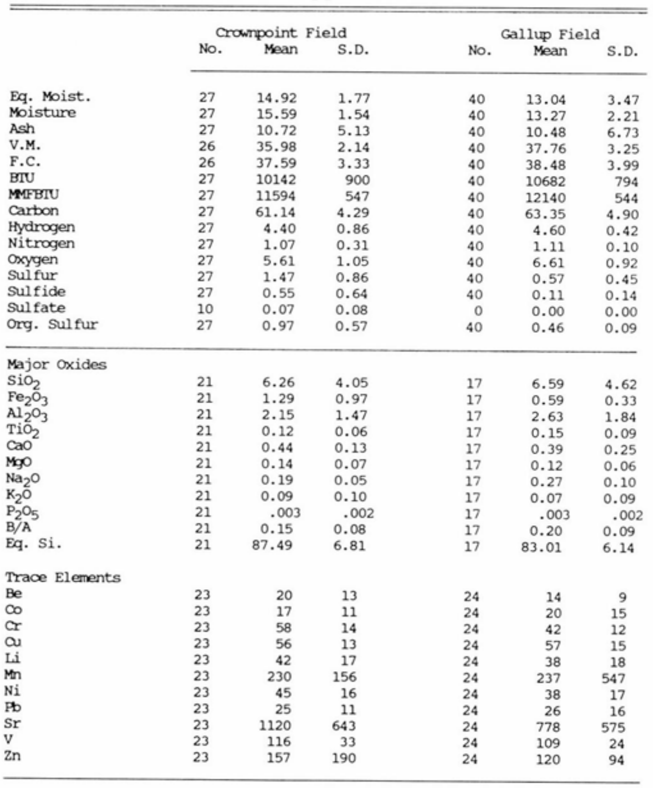
There are several notable differences in the trace-element content in the coals of the San Mateo and Standing Rock fields. The beryllium content of coals from both fields has about the same average (27+/-33 ppm vs 22+/-1 ppm); however, the variation is vastly different fror these two groups of coals. Manganese shows a significant difference in the mean value between the San Mateo (269+/-343 ppm) and Standing Rock fields (472+/-336 ppm). Lead has a much higher average in the Standing Rock field (68+/-58 ppm) than in the San Mateo field (80+/-23 ppm). The variation of lead, though, is much greater in the San Mateo field. Strontium also occurs in higher concentrations in the Standing Rock field (924+1-495 ppm) than in the San Mateo field (696+ /-298 ppm). Zinc shows the greatest difference in means, with the concentration in the San Mateo field being three times higher than in the Standing Rock field (116+/-118 ppm vs 36+/-14 ppm). Preliminary work has indicated an increase in the presence of sphalerite in San Mateo field coals.

Comparison of Crownpoint and Gallup fields

Analyses for the Crownpoint and Gallup fields are summarized in Table 6. The equilibrium-moisture values for coals of the two fields are essentially equal. As-received moisture content, though, does differ between the two populations. Crownpoint field coals have a considerably higher as-received moisture content than do the Gallup field coals. In both cases, the as-received moisture values are less than the total moisture-retention capacity as indicated by the equilibrium-moisture values. This difference is not significant for the Crownpoint field coals, but is notable in the Gallup field coals. Ash, volatile-matter, and fixed-carbon contents of the coals from these two fields are very similar. Gallup field coals have an average as-received heating value of 10,682+/-794 Btu/lb, which is a higher average than the 10,142+/-900 Btu/lb for the Crownpoint field coals. The difference in heating values is reflected in the moist, mineral-matter-free heating value, with the Gallup field coals averaging 12,140+/-544 Btu/lb, as compared with the 11,594+ / —547 Btu/lb average for the Crownpoint field coals. According to ASTM D388, coals of both fields, average high volatile C bituminous in rank.

Carbon and hydrogen values for the Gallup field coals are somewhat higher than for the Crownpoint field coals, which is to be expected considering the difference in heating values. Nitrogen content is similar in the two populations of coals. Oxygen values for the Crownpoint field coals are significantly lower than those for the Gallup field coals. The total-sulfur content for the Crownpoint field coals is much greater (1.47+/-0.86%a) than the 0.57+/-0.45%a average for the Gallup field.

TABLE 6—Combustion (top) and chemical (bottom) analyses of Crownpoint and Gallup field coals. Combustion analyses: on as-received basis, all but heating values in percent. Chemical analyses: major oxides on whole-coal basis, values in percent; trace elements on ashed-coal basis, values in ppm.



	Crownpoint Field			Gallup Field		
	No.	Mean	S.D.	No.	Mean	S.D.
Eq. Moist.	27	14.92	1.77	40	13.04	3.47
Moisture	27	15.59	1.54	40	13.27	2.21
Ash	27	10.72	5.13	40	10.48	6.73
V.M.	26	35.98	2.14	40	37.76	3.25
F.C.	26	37.59	3.33	40	38.48	3.99
BTU	27	10142	900	40	10682	794
MMFBTU	27	11594	547	40	12140	544
Carbon	27	61.14	4.29	40	63.35	4.90
Hydrogen	27	4.40	0.86	40	4.60	0.42
Nitrogen	27	1.07	0.31	40	1.11	0.10
Oxygen	27	5.61	1.05	40	6.61	0.92
Sulfur	27	1.47	0.86	40	0.57	0.45
Sulfide	27	0.55	0.64	40	0.11	0.14
Sulfate	10	0.07	0.08	0	0.00	0.00
Org. Sulfur	27	0.97	0.57	40	0.46	0.09
Major Oxides						
SiO_2	21	6.26	4.05	17	6.59	4.62
Fe_2O_3	21	1.29	0.97	17	0.59	0.33
Al_2O_3	21	2.15	1.47	17	2.63	1.84
TiO_2	21	0.12	0.06	17	0.15	0.09
CaO	21	0.44	0.13	17	0.39	0.25
MgO	21	0.14	0.07	17	0.12	0.06
Na_2O	21	0.19	0.05	17	0.27	0.10
K_2O	21	0.09	0.10	17	0.07	0.09
P_2O_5	21	.003	.002	17	.003	.002
B/A	21	0.15	0.08	17	0.20	0.09
Eq. Si.	21	87.49	6.81	17	83.01	6.14
Trace Elements						
Be	23	20	13	24	14	9
Co	23	17	11	24	20	15
Cr	23	58	14	24	42	12
Cu	23	56	13	24	57	15
Li	23	42	17	24	38	18
Mn	23	230	156	24	237	547
Ni	23	45	16	24	38	17
Pb	23	25	11	24	26	16
Sr	23	1120	643	24	778	575
V	23	116	33	24	109	24
Zn	23	157	190	24	120	94

A considerable amount of sulfur from the Crownpoint field is present in the form of pyritic sulfur. The pyritic-sulfur content of the Crownpoint coals is also greater than that in the Gallup field coals. The relative percentage of pyritic sulfur increases from 19% in the Gallup field coals to 37% in the Crownpoint field coals. Likewise, the organic sulfur is greater in the Crownpoint field coals. However, the relative percentage of organic sulfur (81%) is greater in the Gallup field coals.

When the major oxides are considered, the $Si0_2$, A1203, TiO_2, CaO, MgO, and K_20 values are similar for coals of the two fields. Only the Fe_2O_3 and Na_20 values are notably different. Iron in the Crownpoint field coals has a higher average (1.29+/-0.97%) than in the Gallup field coals (0.59 ± 0.33%). This difference is reduced when the iron tied up as pyritic iron is removed from the sample. Gallup coals then have an average iron content of 1.00+/-0.75%, as compared to the non-pyritic iron of the Crownpoint field coals (0.48+/-0.25%). Sodium content of the Gallup field coals is much greater than what is found in the Crownpoint field. The variability of this element is much more pronounced in the Gallup field coals.

The majority of the trace elements run for these two fields are very similar in concentrations. Beryllium is significantly higher in the Crownpoint field coals, averaging 20+ /-13 ppm, as compared to the 14+ /-9 ppm average for the Gallup field. Chrome occurs in the Crownpoint field coals in significantly higher concentrations (58+/-14 ppm) than in the Gallup field (42+/-12 ppm). Strontium is the remaining element in which there is a significant difference between the two fields, with the Crownpoint field having a higher (1,120+/-643 ppm) average than the Gallup field (778+/ —575 ppm).

Comparison of stratigraphic units

These four coal fields represent three different stratigraphic units. Coals of the Standing Rock and San Mateo fields are assigned to the Cleary Member of the Menefee Formation. The Crownpoint field samples are from the Gibson Member of the Crevasse Canyon Formation. Most samples from the Gallup field cannot be easily assigned to a stratigraphic unit because there is no overlying Point Lookout Sandstone. As a result, these coals are assigned to the Gibson/Cleary Member of the Crevasse Canyon/Menefee Formations.

The absence of an overlying marine unit may explain the unusually low total sulfur as well as the low pyritic-sulfur content of these coals when compared to other nearby coal-bearing areas. The low sulfur content is also found in the Salt Lake coal field, where an overlying marine unit is also absent.

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Water supply in southern San Juan Basin, New Mexico

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Abstract—Large supplies of ground water are available in the southern San Juan structural basin. Development has been minimal in much of the basin, but supplies may be close to full appropriation along the southern edge. Large amounts of ground water have been applied for, mostly in anticipation of energy-development projects, in the central area of the basin; little of the development has occurred. Aquifers are, in general, sandstone beds of relatively low transmissivity, containing water under confined conditions except near the outcrops; water is commonly of good quality near the outcrops, and progressively of poorer quality closer to the center of the basin.

Introduction

The guidebook prepared for the 1976 Geological Society of America Coal Division field trip (Beaumont et al., 1976) included a short paper on the availability of ground water for coal development in the San Juan Basin (Shomaker and Stone, 1976). That paper dealt largely with the technical aspects of ground-water availability, and was written at a time when large water demands by the coal industry and large withdrawals of water for the purpose of uranium-mine drainage were expected to dominate the pattern of ground-water development in the basin. The energy-related projects did not emerge as expected, and questions as to availability of water are now to be considered in a context quite different from that of 1976. From a position as the dominant claimant of water rights, energy development has moved to a much less significant role; the resurgence of energy development in the basin, if it occurs, will find a water market much different from that of a decade ago. It is our belief that an update of the 1976 paper, dealing with issues beyond the physical availability of water is appropriate for this guidebook. The area considered (Fig. 1) encompasses the southern part of the drainage basin of the San Juan River and much of the larger San Juan structural basin.

Understanding of ground water in the basin has been advanced significantly since 1976, especially through work by the U.S. Geological Survey and the New Mexico Bureau of Mines & Mineral Resources, and as a result of studies prepared for water-rights applications by uranium companies and by Plains Electric Generation and Transmission Cooperative. Further, intense study is taking place in parts of the area in preparation for water-rights adjudication.

Sources of information concerning the ground-water resources in the southern San Juan Basin are varied and numerous. The general geology has been addressed by numerous workers interested primarily in the wealth of energy-related resources. A comprehensive accounting of these is beyond the scope of this paper. A recent work describing the geology and hydrogeology of the entire San Juan Basin is that of Stone et al. (1983). Classical studies include those of Gregory (1916), Waring and Andrews (1935), Berry (1959), and Jobin (1962). Reports limited to the southern portions of the basin include Gordon (1961), Cooper and John (1962), Mercer and Cooper (1970), and Shomaker (1971).

Quantitative studies of the movement of ground water in, and the effects of its abstraction from, the southern part of the San Juan Basin have also been published and are ongoing. These include studies by Lyford (1979), Lyford et al. (1980), and Welder (in press) and other investigators with the U.S. Geological Survey. McLaughlin (1984) presented a comparative analysis of several unpublished ground-water models dealing with proposed ground-water appropriation for the Plains Electric Generating Station. There are also several unpublished reports, as well as ongoing studies, concerning water supplies for the Plains Electric Generating Station, the Ciniza Refinery, the City of Gallup, and others.

Regional geology

The San Juan Basin is a Laramide structural depression on the eastern side of the Colorado Plateau in northwestern New Mexico. Important structural elements in the southern portion of the basin are illustrated in Fig. 1, and include the Defiance uplift and monocline, the Gallup Basin, the Zuni uplift, the Nutria monocline, the Chaco Slope, and the Central Basin.

The basin contains predominantly marine and terrestrial sedimentary rocks ranging in age from Pennsylvanian to Tertiary. Tertiary igneous rocks occur in the Grants-Mount Taylor region, and Precambrian crystalline rocks are exposed in the core of the Zuni uplift.

Hydrogeology

The aquifers in the Paleozoic and Mesozoic rocks in the southern San Juan Basin can, in general, be grouped into three types, as suggested by Kelly (1981): areally extensive sandstone units with minor limestone and siltstone, Fruitland-Menefee aquifers of interbedded sandstone and finer-grained sediments, and Tertiary sandstone aquifers.

The areally extensive aquifers include, in ascending order, the Abo and Yeso Formations, the San Andres Limestone and Glorieta Sandstone, the Shinarump Conglomerate and Sonsela Sandstone Bed of the Chinle Formation, the Entrada Sandstone, the Cow Springs-Bluff Sandstone, the Westwater Canyon Sandstone Member of the Morrison Formation, the Dakota Sandstone, the Gallup Sandstone, the Dalton Sandstone Member, the Point Lookout Sandstone, the Cliff House Sandstone, and the Pictured Cliffs Sandstone. A generalized section illustrating the stratigraphy in the southern San Juan Basin is shown in Fig. 2.

The Glorieta Sandstone (Permian) is a fine-grained quartz sandstone with a maximum thickness of 300 ft. The Glorieta thins to the north and pinches out near the McKinley-San Juan County line (Baars and Stevenson, 1977, fig. 4). The San Andres Limestone (Permian) consists of two thick limestone beds separated by a sandstone layer. The intervening sandstone varies in thickness and is absent locally. The San Andres Limestone and Glorieta Sandstone have interconnecting permeability in the southern part of the San Juan Basin and have been treated as a single aquifer (Geohydrology Associates, Inc., 1982). The aquifer is confined, except near outcrop areas, by siltstone and claystone beds in the overlying Chinle Formation, and by the underlying Yeso Formation. Some leakage into and out of the aquifer is thought to occur, but is difficult to quantify. The direction and magnitude of flow are not well known, as detailed hydraulic-head distribution data are lacking. The transmissivity of the San Andres-Glorieta aquifer has been reported to range

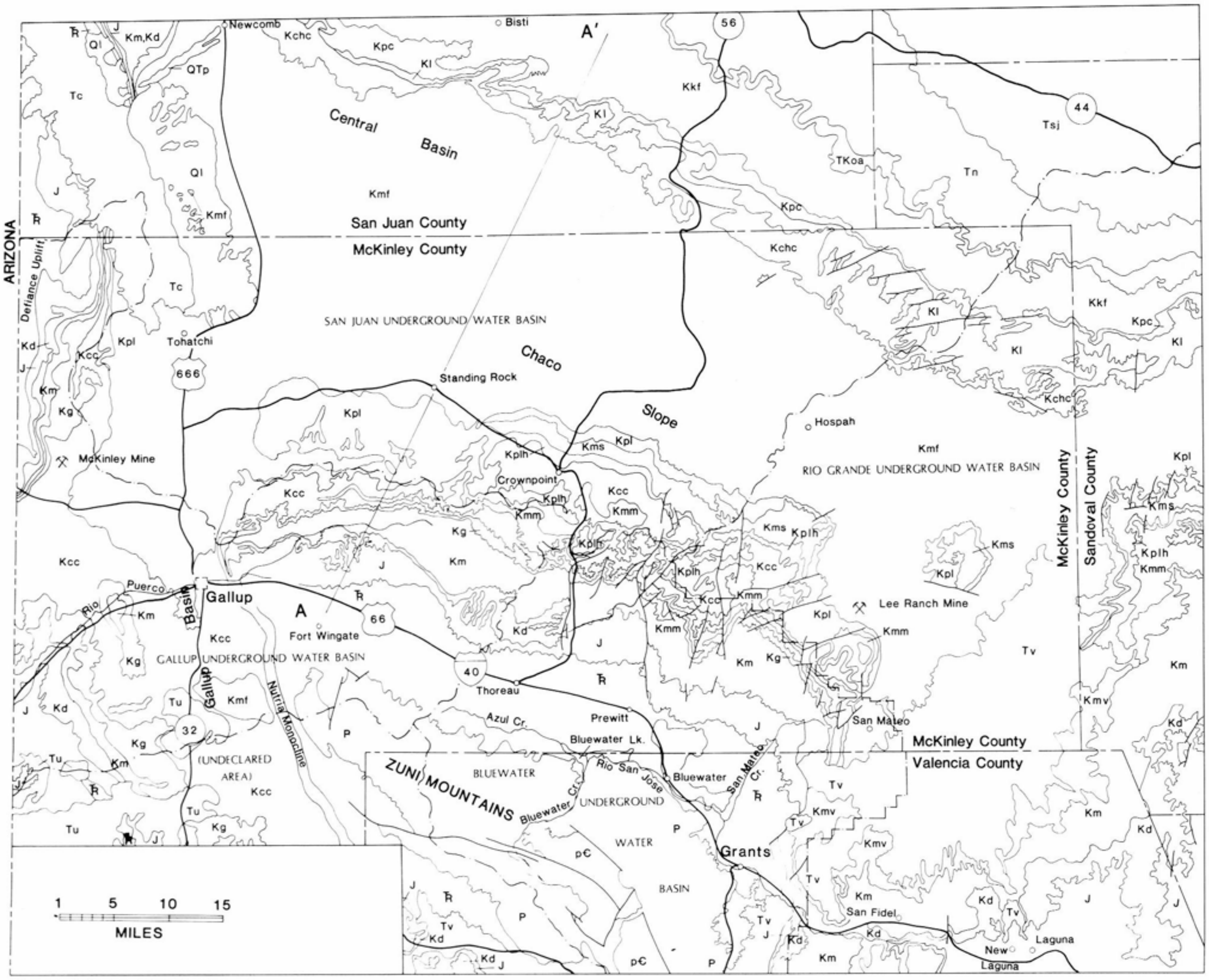

FIGURE 1—Geologic map of southern San Juan Basin, showing outcrop areas of major stratigraphic units, areas of administrative underground water basins, and features mentioned in text. Geologic symbols: pЄ = Precambrian rocks; P = Permian rocks, including the Abo Sandstone, Yeso Formation and San Andres–Glorieta aquifer; TR = Triassic rocks, including the Sonsela bed aquifer of the Chinle Formation; J = Jurassic rocks, including the Westwater Canyon Sandstone Member of the Morrison Formation; Kd = Dakota Sandstone; Km, Kmm, Kms, Kmu = Mancos Shale; Kg, Kcg = Gallup Sandstone; Kcc = Crevasse Canyon Formation, including Dalton Sandstone (Kcda) and Dilco Coal Member (Kcdi); Kpl, Kplh = Point Lookout Sandstone; Kmf = Menefee Formation; Kchc = Chacra Tongue of Cliff House Sandstone; Kl = Lewis Shale; Kpc = Pictured Cliffs Sandstone; Kkf = Kirtland Shale and Fruitland Formation (Kf); TKoa = Ojo Alamo Sandstone; Tn = Nacimiento Formation; Tsj = San Jose Formation; Tc, Tv, Tu, Ql, Qtp = Tertiary and Quaternary rocks. Some symbols appear in Fig. 2 only.

from 450,000 ft^2/day near outcrop to 70 ft^2/day away from outcrop (Gordon, 1961, table 8; Geohydrology Associates, Inc., 1982). The high transmissivities in and near outcrop areas are attributable to dissolution along fractures in the San Andres Limestone. In general, reported values for the storage coefficient range from 1.0 x $10^{\wedge-10}$ in confined areas to 1.0 x 10' in unconfined parts of the aquifer (Geohydrology Associates, Inc., 1982). Concentrations of total dissolved solids are generally less than 700 mg/1 in the southern part of the basin and increase to 1,500 mg/1 to the northwest. The San Andres—Glorieta aquifer is the principal source of water along 1-40 between Grants and Gallup, and can furnish large irrigation and industrial supplies. The aquifer in the Grants—Bluewater area is closely connected with surface flows in the upper reaches of the Rio San Jose and surface-water irrigation works, which provide recharge to it; natural discharge is to the lower Rio San Jose through springs.

The Sonsela Sandstone Bed and the Shinarump Conglomerate of the Chinle Formation (Triassic), and the sandstone beds in the Abo and Yeso Formations (Permian) are

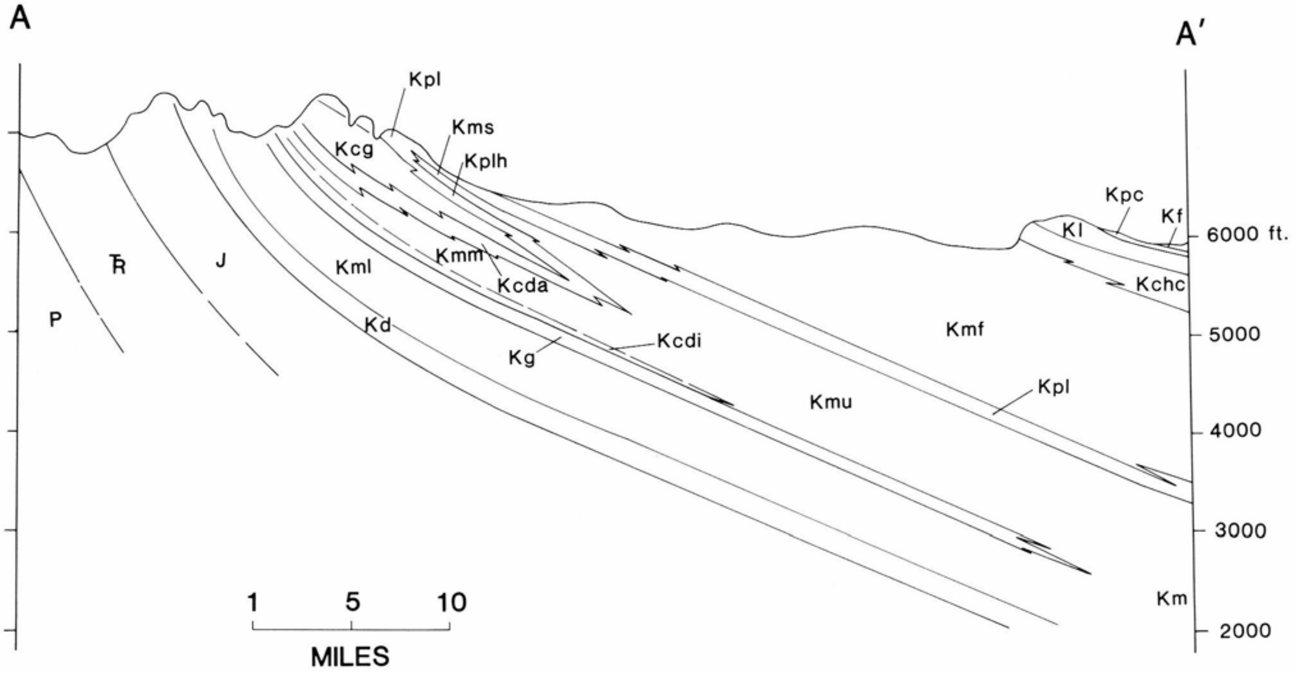

FIGURE 2—Diagrammatic cross section A–A′. See Fig. 1 for line of section and explanation of symbols.

the basin to 100 ft^2/day near the center (Stone et al., 1983). Water quality in the Entrada is generally poor, except near outcrop areas.

The Cow Springs and Bluff Sandstones (Upper Jurassic) display an intertonguing relationship and are thought to behave hydraulically as a single unit (Stone et al., 1983). The Bluff Sandstone is a medium-grained, mature arkose with a thickness ranging from a few feet to approximately 300 ft (Harshbarger et al., 1957). There is little hydrologic information available for the unit, but transmissivities appear to be low. Few wells are completed in this aquifer, and information as to water quality is limited.

The Westwater Canyon Sandstone Member of the Morrison Formation (Upper Jurassic) consists principally of fine-to coarse-grained sandstone in one to four massive beds (Shomaker and Stone, 1976). The unit has an average thickness of 250 ft (Kelly, 1977), but is not present south of Gallup. The aquifer produces relatively large quantities of water in the vicinities of Church Rock and Crownpoint and between Crownpoint and San Mateo. In that part of the basin, the Westwater Canyon is a major uranium-ore-bearing unit, and the aquifer was pumped extensively to dewater mine workings.

Transmissivity of the Westwater Canyon does not exceed 500 ft^2/day (Stone et al., 1983, fig. 74) and is substantially less near Gallup and in the area of the Fruitland Formation coal trend. The water quality in the southwestern part of the basin is relatively good, with total dissolved-solids concentrations ranging from 500 to 1,000 mg/1 (Shomaker and Stone, 1976). Water quality decreases away from outcrop areas, and there are reported total dissolved-solids concentrations ranging from 1,000 to 5,000 mg/1 in the central portion of the basin (Shomaker and Stone, 1976). The Westwater Canyon aquifer is a source of public water supply for the community of Crownpoint and the City of Gallup.

The Dakota Sandstone (Upper Cretaceous) is generally a fine- to medium-grained, submature to mature arkose lying disconformably on the Morrison Formation over much of the area. The Dakota is conformably overlain by the Mancos Shale. The thickness is generally 200-300 ft (Stone et al., 1983, fig. 66). There is little information as to the hydrogeology of the Dakota Sandstone aquifer, but the information available indicates low transmissivities, generally less than 50 ft^2/day, and relatively poor water quality.

The Gallup Sandstone (Upper Cretaceous) in general consists of several sandstone bodies which intertongue with the Mancos Shale, pinching out to the northeast. The Gallup is generally a fine- to medium-grained, submature to mature, lithic arkose (Stone et al., 1983) The highest transmissivities in the Gallup Sandstone aquifer occur near the City of Gallup in the southwestern part of the basin, with values on the order of 300 ft^2/day (Stone et al., 1983, fig. 61). Transmissivity decreases to the north and east. Water-quality information indicates total dissolved-solids concentrations range from 993 to 2,190 mg/1 (Shomaker and Stone, 1976). The Gallup Sandstone aquifer is used by the City of Gallup for its primary municipal water supply, and also furnishes supplies for coal operations near Gallup and at the Lee Ranch mine near San Mateo.

The Dalton Sandstone Member of the Crevasse Canyon Formation (Upper Cretaceous) is a fine- to medium-grained, immature, lithic arkose (Stone et al., 1983). It constitutes the lower part of the Mesaverde Group between the underlying Gallup Sandstone and overlying Point Lookout Sandstone. Transmissivity of the Dalton is probably less than 50 ft^2/day (Stone et al., 1983). The water quality is not well defined, but most of the waters are high in sulfate, sodium, and bicarbonate, decreasing in quality away from outcrop areas (Shomaker and Stone, 1976). Scattered wells and springs produce water for domestic and stock use.

The Point Lookout Sandstone (Upper Cretaceous), which overlies the Dalton Sandstone Member and the Mancos Shale, is a fine- to medium-grained, immature to submature, lithic arkose to arkose (Stone et al., 1983). Hydrologic data are sparse, but reported horizontal hydraulic-conductivity values range from 0.002 to 0.02 ft/day (Craigg, 1980), which for a 200 ft section would result in transmissivities from 0.4 to 4 ft^2/day. Water quality is fair. Only a few stock and domestic wells draw water from this unit in the southern and western parts of the basin.

The Cliff House Sandstone (Upper Cretaceous), the uppermost unit in the Mesaverde Group, consists of irregularly bedded, fine-grained, argillaceous sandstone of variable thickness. It thins from approximately 360 ft to a few tens of feet from west to east across the San Juan Basin. Hydrologic data for the Cliff House aquifer are very limited; Stone et al. (1983) give an approximate value of 2 ft^2/day or less, thought to be representative of the unit. Like most of the other aquifers in the San Juan Basin, the water quality in the Cliff House Sandstone is better near outcrop and decreases in the direction of ground-water flow (Stone et al., 1983). A few domestic and stock wells produce from the Cliff House aquifer.

The Pictured Cliffs Sandstone (Upper Cretaceous), ranging in thickness from 25 to 281 ft, is a generally fine-grained, immature to supermature subarkose (Stone et al., 1983). The Pictured Cliffs underlies the Fruitland coal beds and overlies the Lewis Shale. Aquifer tests give transmissivities ranging from 0.001 to 3.0 ft^2/day (Stone et al., 1983). Water produced from this aquifer is generally of poor quality and only a few stock wells are completed in the unit.

The Fruitland and Menefee Formations (Upper Cretaceous) have variable lithologies including interbedded sandstone, shale, siltstone, and coal. The sandstones generally occur as lenticular bodies. The Menefee is from 400 to 1,000 ft thick and overlies the Point Lookout Sandstone. It is a source of water locally for domestic and stock users, and the water quality is generally good, with total dissolved-solids concentrations less than 1,000 mg/l. The Fruitland Formation is 200-300 ft thick and includes major surface-minable coal beds. The Fruitland conformably overlies, and intertongues with, the Pictured Cliffs Sandstone. The water quality in the Fruitland is generally poor and the aquifer, if it is an aquifer at all, yields only meager amounts of water.

Tertiary sedimentary rocks exceed 3,000 ft in the San Juan Basin. These clastic rocks crop out in the central portion of the basin and unconformably overlie the Cretaceous section. The Tertiary sequence includes the Ojo Alamo Sandstone, the Nacimiento Formation, and the San Jose Formation. Sandstone aquifers are present in all three units, but in most areas have not been tested or utilized.

The Ojo Alamo Sandstone (Paleocene) is the lowermost Tertiary rock unit in the San Juan Basin. It consists of sandstone, conglomerate, and shale. The sandstone is medium-to very coarse-grained, often pebbly, immature, lithic arkose (Stone et al., 1983). The thickness of the Ojo Alamo ranges from 72 to 313 ft and the unit disconformably overlies the Kirtland Shale. Transmissivities of 50-250 ft^2/day have been determined from aquifer-test data (Brimhall, 1973; Anderholm, 1979; Stone et al., 1983, fig. 29). The water quality in the aquifer ranges from fair to poor; the zone is a source of domestic and stock water, and furnishes the supply for the Town of Cuba.

The Nacimiento Formation (Paleocene) overlies the Ojo Alamo Formation. Minor thin, medium- to coarse-grained sandstones occur interbedded within a thick (418-2,232 ft) sequence of mudstones (Stone, 1983). Very little hydrologic information is available for these thin, discontinuous sand bodies, but some of the more continuous beds may have transmissivities as high as 100 ft^2/day. The water quality in the more productive sandstones is fair to poor (Stone et al., 1983, fig. 22). Water from the Nacimiento Formation is used for domestic and stock purposes.

The San Jose Formation (Eocene) is a sequence of interbedded sandstone and mudstone ranging in thickness from 200 to 2,700 ft. The sandstones are generally coarse-grained, often pebbly, submature arkose, and range in aggregate thickness from 50 to 1,300 ft (Stone et al., 1983). The hydrologic properties of the aquifers are little known, but yields of wells penetrating the sandstone units may reach 1,440 gpm (Baltz and West, 1967). Water quality is variable; Stone et al. (1983) reported a range of specific conductance from 320 to 5,000 µmhos, with an average value of approximately 2,000 µmhos. The San Jose Formation produces water for numerous stock and domestic supplies.

Ground-water flow

Recharge to the aquifers in the southern San Juan Basin occurs primarily on or near outcrop areas. Water enters the aquifers directly through outcrop, or through adjacent permeable rocks, alluvium or soil cover. Fracturing near faults and association with folding may increase local permeability and recharge. Solution of soluble minerals along fractures and in porous sediments in outcrop areas may significantly increase permeability and recharge. The volume of water recharged in this manner is small compared with the volume of ground water pumped from the aquifers in the basin.

In general, ground-water flow in the aquifers in the southern San Juan Basin is to the north and northeast. Natural discharge from the basin is thought to occur mainly through upward leakage and discharge to the San Juan River near the northwestern corner of the basin, and to some extent to the Rio Grande drainage in the southeastern part, as indicated by potentiometric-surface and water-level maps for some of the aquifers (Stone et al., 1983, figs. 28, 43, 59, 72).

Water-quality concerns

Aside from the general chemical quality of water in the aquifers, as described above, there are several specific water-quality problems. In the vicinity of Thoreau, the water in the San Andres—Glorieta aquifer contains concentrations of radium in excess of drinking-water standards. The source seems to be natural rather than man-made. The extent of the high-radium ground water is not known.

The water-quality impacts of the uranium industry on the surface water and shallow ground waters in the southern San Juan Basin have been discussed by Gallaher and Goad (1981), Goad et al. (1980), Kaufmann et al. (1976), and EPA (1975). Waters down-gradient of uranium mining, milling, and exploration areas have in general shown some degree of water-quality degradation. The degradation primarily takes the form of heavy-metal and radionuclide concentrations above New Mexico State standards. With the decline in the uranium industry in recent years, present sources of contamination include runoff and subsequent infiltration of waters from inactive mining, milling, and radionuclides sorbed on and trapped in shallow sediments and soils, which are released to solution by later changes in their physical and chemical environment. Cleanup efforts are in progress at sites including the United Nuclear Corporation Church Rock mill and the Homestake mill tailings pile near Grants.

Contamination and the threat of contamination to shallow aquifers by hydrocarbons exist locally in the southern San Juan Basin. Contamination of the shallow ground water by hydrocarbons has occurred near the community of Prewitt, at the site of an abandoned refinery. In populated areas, leaking underground storage tanks have introduced contaminants which, in some cases, may migrate into shallow aquifers and threaten public water supplies. Migration of contaminants along fractures could facilitate their introduction into aquifers.

Availability of water rights

The availability of water will be discussed in terms of the availability of water rights in each of the administrative basins established by the New Mexico State Engineer Office within the area considered. In this section, the capitalized word Basin will refer to the administrative areas, and lower case will refer to the structural and drainage basins.

Pending water-rights adjudication suits which include parts of the area described in this paper:

Case	Filed	Number of defendants
New Mexico v. United States (San Juan stream system)	1975	3,000
Pueblo of Zuni v. City of Gallup (Zuni river; aquifers)	1982	1,000
U.S. v. Bluewater—Toltec Irr. Dist. (now: New Mexico v. Kerr—McGee) (Rio San Jose; aquifers)	1982	1,500

San Juan Underground Water Basin

The San Juan Basin is a large, relatively undeveloped artesian basin, but the history of water-rights administration suggests that new appropriations will be difficult to obtain. A 1983 letter from the State Engineer to the University of New Mexico Water-Law Study Committee indicates that the total non-saline ground water in storage in the San Juan structural basin, which includes part of the Gallup Underground Water Basin, may be about 1,180 million acre-feet (af). Of that total, some 420 million af are thought to have dissolved-solids concentration less than 1,000 mg/I, and the balance to contain less than 3,000 mg/ 1. The San Juan River itself is considered fully appropriated, so that new supplies would be obtained either by purchase of existing surface-water rights or from ground water.

The criteria under which new appropriations might be permitted without replacement of some senior rights were set in an order of October 1979 (the "Phillips order") by the State Engineer; the volume of ground-water depletion allowed under those criteria has been estimated at 1.6-21.5 million af. Only a very small annual withdrawal, relative to these amounts, is occurring now, but between the declaration of the San Juan Underground Water Basin in 1976 and the culmination of development planning in about 1981, many large applications had been filed. In the San Juan and adjoining parts of other Basins, a total on the order of 255,000 acre-feet per year (afy) had been applied for, of which some 145,000 afy were related to the uranium industry, mostly for the purpose of mine drainage. The balance were largely related to coal-mining and coal-fired electricity generation. At first glance it might appear that the applications, if all resulted in appropriations, would soon exhaust the Basin, but there are several ameliorating circumstances.

Nearly all of the water represented by uranium-industry applications was for dewatering mine workings, mostly involving pumping from the Westwater Canyon aquifer, and little further beneficial use was contemplated. Much of the water, at least in theory, would have been available for other uses. Only one uranium mine is currently active in the basin, and the developments represented by most of the pending applications are not being pursued; it is probable that pressure from other applicants will cause the State Engineer Office to act on the applications, and, with no demonstration of a near-term beneficial use, they may be denied. If uranium mining resumes on a large scale, then new applications can be made. Under the New Mexico Mine Dewatering Act, appropriations may be made even though impairment of existing rights occurs, if a satisfactory Plan of Replacement, to compensate senior rights-holders for their losses, is put into effect.

Pumping of ground water in the San Juan basin results in decrease of natural discharge to the San Juan River and to the Rio Grande, and these effects must be offset by the retirement of surface-water rights in the rivers. At large distance from the rivers, the maximum effects of relatively short-term pumping are small and do not occur for many years. For example, the Phillips order, which permitted a total appropriation near Crownpoint of 653,431 af over a period limited to 32.5 years, required that existing depletions of 82 afy be terminated in the San Juan and the Rio Puerco, a tributary of the Rio Grande. The maximum effects of 82 afy in each river were calculated to occur 210 and 180 years after the start of the 32.5 year pumping period.

It would appear that in terms of physical availability, there will be sufficient water for energy development in the San Juan Basin, but that the cost of implementing Plans of Replacement may be high and the time required for approval of water-rights applications may be great.

Gallup Underground Water Basin

The Gallup Basin and the San Juan Basin are hydrologically connected, and the comments as to San Juan Basin ground water apply also to Gallup Basin aquifers of Jurassic and Cretaceous age, i.e. to the Westwater Canyon and Gallup aquifers. Near Gallup itself, the Gallup Sandstone is heavily pumped by the city and other users, and may be considered fully appropriated. Aquifers of Permian and Triassic age, in particular the San Andres—Glorieta aquifer, may also be fully appropriated if existing rights and pending applications are exercised. Ground water in these older aquifers in the area to the south of Gallup is the subject of an adjudication suit, *Pueblo of Zuni v. City of Gallup.* The Westwater Canyon has not been much developed in the Gallup Basin, apart from the former pumping of uranium mines near Church Rock, and this aquifer may furnish new supplies as required by the city.

The Gallup Basin is related to the drainage of the Little Colorado River. The State Engineer's letter of 1983 indicates that some 24,100 afy of surface waters remain unappropriated in the Basin. Much of this is available only on Indian lands, and mostly in the form of ephemeral flows; large storage and high evaporation losses would make this water costly to develop.

Bluewater Underground Water Basin

Bluewater Basin ground water began to be developed for irrigation and industrial supplies about 1944 (Gordon, 1961, **p.** 50), and the effects on water levels were soon significant. The Basin is now considered fully appropriated, and may well be over-appropriated if all existing claims are taken into account. Bluewater Basin water rights are the subject of an adjudication suit in the State District Court, styled *State of New Mexico ex rel Reynolds v. Kerr-McGee Corp.* The suit (originally filed in U.S. District Court as *U.S.* v. *Bluewater—Toltec Irrigation District et al.)* will result in an adjudication of surface-water rights in the Rio San Jose, and rights to ground water in the drainage basin of the San Jose. The existing rights held by non-Indian claimants total some 26,000 afy, which may be on the same order as the longterm supply; the claims made by the United States on behalf of the Navajo Tribe and the Laguna and Acoma Pueblos amount to a diversion of 121,323 afy, or an estimated depletion of about 69,000 afy. The Navajo Tribe and Acoma Pueblo have made claims, which presumably include the U.S. claims, of some 140,000 afy, and Laguna Pueblo is likely to file its own claim as well.

There seems little possibility that new water rights will be available in the Bluewater Basin. The exercise of existing rights, and transfers of existing rights to other purposes or places of use, will be subject to uncertainty until the adjudication is complete.

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McKinley mine

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Introduction

This article was originally written by John Wilson in 1977 and has been updated for this volume by Stephen L. Johnson, John C. Klingler, Nancy A. Wildman (geology), and Wayne R. Erickson (reclamation).

The McKinley mine is located in west-central New Mexico, in McKinley County, about 20 mi northwest of Gallup and 2 mi east of the Arizona state line. McKinley's mining leases are held by Chevron Corporation and operated by The Pittsburg & Midway Coal Mining Company, a wholly owned subsidiary of Chevron.

Current coal lease holdings total 27,857 acres, divided as follows: The Navajo Nation, 11,157 acres; U.S. Public Lands, 8,098 acres; State of New Mexico, 989 acres; and Santa Fe Railroad, 7,613 acres. Chevon leases the surface from the Navajo Nation, 11,157 acres; State of New Mexico, 606 acres; Indian Allotment leases, 7,898 acres; and private leases, 112 acres. Chevron owns 10,678 acres of surface in fee.

McKinley mine supplies low-sulfur coal to the southwestern U.S. The mine has an annual production capacity of six million tons and is currently delivering approximately five million tons annually to electric utilities and industrial customers in Arizona and California. Arizona Public Service Company is the largest consumer of McKinley coal, requiring up to 3,300,000 tons per year for its Cholla plant at Joseph City, Arizona. The Salt River Project is the second largest consumer, purchasing 1,500,000 tons annually for its Coronado plant near St. Johns, Arizona. Tucson Electric Power Company began taking shipments in 1987, supplying the Irvington Generating Station in Tucson, Arizona. Industrial customers include Southwest Forest Industries at Snowflake, Arizona, and Kaiser Cement Corporation in Cushenbury, California.

History

During 1958 and 1959, The Pittsburg & Midway Coal Mining Company (P&M), at that time wholly owned by Spencer Chemical Company, obtained leases from the Santa Fe and Pacific Railroad Company on the odd-numbered sections and applied for federal coal prospecting permits on the even-numbered setions on lands in T16N R2OW, T17N R2OW, and T16N R21W, N.M.P.M. The permits were issued to Spencer Chemical Company in October 1960.

Exploration began in May 1959, using one drill rig owned and operated by the company. Two rigs were later operated and the initial drilling was completed about November 1960. Sufficient coal reserves were found in the area and Arizona Public Service Company decided to build the Cholla power plant at Joseph City, Arizona. Construction began on this plant during the early part of 1961. A railroad spur from the Santa Fe mainline and powerlines were constructed and strip mining began in July 1961 on sec. 13 of T16N R21W.

On 9 November 1961, the Advisory Committee of the Navajo Tribal Council passed a resolution granting Spencer Chemical a two-year drilling permit on the Navajo Indian Reservation with an option to lease. The prospecting permit became effective 25 May 1962, for 49,920 acres of land, with an option to lease land containing an estimated 150 million tons of coal reserves. By March 1964, approximately 65,000 ft of drilling had been completed. Further negotiations with the Navajo Tribe resulted in issuing a lease, having an effective date of 18 September 1964, for 11,157 acres on the reservation. Mining began on these acres in June 1972.

From 1961 through 1975, the McKinley mine produced approximately 400,000 tons of coal annually which were sold almost entirely to the Cholla plant. In 1974 and 1984, expansions occurred which raised the annual production capacity to its current 6 million ton level. Through 1986, approximately 50 million tons of coal have been sold from the McKinley mine.

Geology of the deposits

C. E. Dobbin, U.S. Geological Survey, mapped the area in 1932 and described the coal and the rocks deposited during Late Cretaceous time in about five townships south of the Navajo Reservation and east of the Arizona state line; the work is unpublished. To describe some of the general geology in the area, the writers have used Dobbin's information.

Rocks exposed in the vicinity are, in ascending order, the Dakota Sandstone, the Mancos Shale, the Gallup Sandstone, the Crevasse Canyon Formation, and the Menefee Formation. These formations comprise the limb of the Defiance monocline that extends northeast, just west of the leased area (O'Sullivan and Beaumont, 1957). The Gallup Sandstone, forming the base of the Mesaverde Group, is about 240 ft thick in this area. The Crevasse Canyon Formation is composed of the Dilco Coal, Bartlett Barren, and Gibson Coal Members. The Dilco Coal Member is about 300 ft thick, crops out in T15N R2OW, and lies beneath the coal beds in the leased area. The Bartlett Barren Member, about 375 ft thick, has sandstone beds at the base and top, with some scattered thin beds of coal. The Gibson Coal Member and the Cleary Coal Member of the Menefee Formation (undivided) are about 150 ft in combined thickness; this contains the coal beds presently being mined. The Menefee Formation above the Cleary Member is over 250 ft thick and was named the Allison Barren Member.

The regional dip of the beds is south to southeast, generally less than 2°. Local dips may exceed 2° and the direction will vary with local minor structure.

Faults, having displacements of less than 100 ft, occur along the Tse Bonita Wash and the unnamed wash east of, and parallel with, Coal Mine Wash. It is suspected that Coal Mine Wash is coincident with a fault. These faults trend northeast and apparently dip steeply. The upthrown fault blocks are usually to the southeast. The coal beds are brought to the surface several times by the faults; thus, a greater area of coal is exposed for strip mining. A complementary system of faults of small displacement has been observed during mining. These faults trend northwest and appear to dip steeply. Nearly all of them are normal faults. Step faults, hinge faults, small down-dropped fault blocks, and curved normal faults have been observed during mining. Some faults are restricted to the lower seams, with no displacement apparent in the upper seams.

Differential compaction of sediments has resulted in a distortion of the original sedimentary layers that existed upon deposition. Coal seams occasionally appear to dive or climb when near a relatively less compactible sandstone bed. The coal beds are designated by colors, in ascending order as the "green"; then "blue," "fuchsia," and "yellow." A brief description of each bed follows.

The "green" bed is stratigraphically the lowest coal bed in the Gibson Coal Member. It is thickest along the outcrop on the western edge of the Navajo leased area. The bed reaches thicknesses of 10 ft in this area. Thus, considerable reserves are available for strip mining. The old Window Rock coal mine produced coal from this bed. The bed splits and thins to the east and southeast.

The "blue" bed is less than 5 ft thick in the northern portion of the Navajo lease. This bed thickens to over 9 ft in secs. 27 and 28 on the Navajo lease and is mineable in sec. 5 of T16N R2OW. The bed thickens to about 5 ft in secs. 15, 16, 21, and 22 and reaches 10 ft in sec. 14 of T16N R2OW.

The "fuchsia" bed is in most places a zone of several seams, but in some places it forms one thick bed. For the most part, the fuchsia beds are mined in the southern portion of the Navajo lease. Due to erosion, the fuchsia beds are not present everywhere on the lease.

The "yellow" bed lies 10-20 ft above the "fuchsia" bed. It is found in the southern part of the Navajo lease and reaches a maximum thickness of 4 ft. This bed is not very extensive with any mineable thickness. It thins out to the north and east of the Navajo lease.

The quality of the coal will vary from place to place in each bed and also from zone to zone. The coal seams comprising the lowest, green zone have a slightly higher average sulfur content and a slightly lower average Btu value than the coal seams higher in the sequence.

It is interesting to note that the highest average sulfur content is found in the coals in the northernmost part of the lease, while the coals in the southernmost part of the lease have the lowest average sulfur content. The distance between these areas is 8 mi. During the Late Cretaceous the shoreline trended northwest on a line approximately 10 mi north of Gallup (Beaumont, 1971), which would probably place the north end of the lease closest to the Cretaceous sea. Whether or not this accounts for the increase in sulfur content is not known.

The company tries to maintain a Btu content of 10,000 to all its customers. However, at times the quality varies due to moisture content or the presence of parting and weathered coal. The in-place quality averages 10,600 Btu, 10% ash, 14% moisture, and 0.5% sulfur.

In order to determine coal reserves for the McKinley mine lease area, a geologic computer model has been developed from the 3,300+ drill holes available. Even with closely spaced drilling, correlation of coal seams from drill logs and electric logs is a challenge at times because of faulting, the effects of differential compaction on the sediments, and the lack of continuity of sedimentary units throughout the lease area. At current production rates, coal reserves are expected to last until the year 2020. The computer model is also being used for short-term forecasting and long-range mine planning, thus allowing an opportunity to examine such variables as stripping ratios, coal quality, and overburden depths for any given area within the lease.

Mine facilities

In order to mine, produce, store, process, and transport coal from McKinley mine, a railroad spur, haul roads, powerlines, loading facilities, service shops, and offices were constructed. The North loading facilities, shops, and office complex are located on the Navajo Indian Reservation, while the South loading facilities are located on land controlled by P&M. The South loading facilities were constructed in 1961. The North site preparation began in 1974, and construction of the plant site and these new facilities were completed in mid-1976. The North facilities currently serve as the mine's major loading point, while the South facilities are used for industrial customers. The 30 acre North plant site now consists of coal storage piles, hoppers, a crushing plant, and a loading chute. Adjacent to this area are the service facilities, which consist of a machine shop, electrical shop, personnel office, test laboratory, warehouse, safety building, parking yard, and other service buildings. These facilities occupy an additional area of approximately 25 acres.

The railroad spur extension of 8.2 mi was constructed from the existing terminal in sec. 17 of T16N R2OW. The first 6.4 mi were constructed by the Santa Fe and Pacific Railroad Company. This terminal is 0.65 mi north of the reservation line. The 1.8 mi from this point to the plant site were constructed by P&M and are maintained by Santa Fe. The maximum grades are 0.6% ascending and 2.0% descending for the loaded trains. Cuts as much as 50 ft deep, fills up to 40 ft high, and several trestles across the larger gullies were constructed to maintain these grades. The disturbed land is from 50 to 150 ft wide along the route.

Over 5,000 cubic yards of concrete were used in the construction of the preparation plant. The upper half consists of a hopper, primary crusher, secondary crusher, vibrating screens, sample systems, and traveling stacker. The coal is stockpiled at the rate of 2,000 tons per hour and sized at 3 x 0 mesh. After being stacked along an 800 ft long stockpile, the coal is selectively fed through 26 reclaim hoppers onto a belt running to the train load-out station. One-hundred-car unit trains having 100 ton capacity are flood-loaded in just over three hours at a rate of 3,000 tons per hour.

Equipment

The following information gives some idea of the equipment required to mine five million tons per year and the overall complexity of the operation.

NUMBER OF EMPLOYEES

At current production:	475

ANNUAL PRODUCTION

Current:	5,000,000 tons
Capacity:	6,000,000 tons

STRIPPING EQUIPMENT

Four Bucyrus Erie 1370-W Draglines, 55 cubic yard buckets

Working weight:	7,000,000 lbs
Height:	Taller than a 20 story building, 200 ft from ground to point sheave at top of boom
Boom:	320 ft long
Boom angle:	35°
Maximum dumping height:	128 ft
Effective spoil radius:	242 ft
Power:	Provides 6,000 horsepower under normal operating conditions and 12,000 horsepower under peak loads. All four draglines will use power equivalent to that used by a community of 50,000 people.
Tub diameter:	58 ft
Approximate digging-cycle time:	60 seconds
Normal walking speed:	One $8^{1}/2$ ft step every 45 seconds, 0.14 mph
Bucket:	Capacity of 55 cubic yards or approximately 82 tons of material
Erection information:	Construction time 15-18 months

DRILLING EQUIPMENT

Six vertical overburden/prestrip/parting drills Two vertical parting/coal drills

LOADING EQUIPMENT
One hydraulic shovel, 16 cubic yards
Two coal-loading shovels, 11.5 cubic yards
Three rubber-tired front-end loaders, 16 cubic yards
One rubber-tired front-end loader, 20 cubic yards
One overburden shovel, 20 cubic yards
One overburden shovel, 29.5 cubic yards

HAULAGE UNITS
Five 100 ton end-dump trucks
Nine 170 ton end-dump trucks
Ten 120 ton end-dump trucks Six
120 ton bottom-dump trucks

OTHER MAJOR
PIECES Four graders
Five scrapers
Twenty-three dozers
Five wheel tractors
Four water trucks

Reclamation

Overview

Reclamation at the McKinley mine has been conducted under four major regulatory frameworks including: 1) Pre-law (prior to 1973), 2) New Mexico and USGS permits (1973 through 1977 and 1975 through 1977, respectively); 3) Office of Surface Mining and New Mexico Mining & Minerals Division Surface Mining Control and Reclamation Act (SMCRA) interim program permits (1978 through 1986 and 1979 through 1986, respectively); and 4) New Mexico Mining & Minerals Division and Office of Surface Mining SMCRA permanent program permits (1986 through the present). General practices and characteristics of the reclamation created during these periods are described by time period in the following paragraphs.

Pre-law

Pre-law reclamation at the mine consisted of knocking off the peaks of spoils and conducting aerial or rangeland drill seeding operations. Crested wheatgrass and brome grass were the principal species contained in the early seed mixes. Topsoil was not salvaged or replaced prior to 1973. Numerous small ponds were created by the mining operations, with nominal attention being given to recreation of drainages during grading operations.

New Mexico Surface Mining Act and USGS permits

Reclamation conducted under these two permits changed significantly in terms of grading, topdressing, and revegetation operations. Spoils were graded out and rudimentary drainages created, with small ponds being created opportunistically along the drainages. Soil could either be salvaged from in front of mining or topdressing taken from borrow areas located in alluvial areas and replaced on the graded areas. Most topdressing replaced during this time period came from borrow areas and was replaced at an average depth of 6 in. Seed mixes included additional plant species with an emphasis on native plants and the removal of crested wheatgrass.

SMCRA Interim Program permits

These permits contained additional environmental and reclamation requirements. The most significant was the requirement to pass and treat all surface runoff from areas disturbed by mining in sediment ponds or other alternate sediment-control structures. Because of the semiarid climate in the McKinley mine region, the permits placed an emphasis on the use of alternate sediment-control features in lieu of sediment ponds. Alternate sediment controls used on reclaimed lands included contour furrowing, straw mulching at a minimum rate of two tons per acre, establishment of temporary quick-growing cover crops on topdressed areas, timely establishment of permanent vegetation, and the continued use of small depressions along drainages. Detention berms were used for the retention of runoff from areas disturbed by mining that could not be routed to the pit for treatment.

Grading requirements remain essentially unchanged, except that completion time limitations were placed on back-filling and grading operations. Topdressing requirements changed in that the option to use borrow areas was limited to the areas that had been previously disturbed. Lands disturbed under the interim permits were required to have topsoil materials removed prior to overburden removal. Revegetation operations remained essentially unchanged under these permits.

SMCRA Permanent Program permits

These permits were issued to McKinley mine in 1986 by the State of New Mexico and the Office of Surface Mining after a protracted permitting process. Review of the permits was prolonged due to the number of Federal, State, and Navajo regulatory agencies involved in review of these permits, and the need to revise operational information contained in the permit applications to include a truck/shovel pre-stripping operation.

The permanent program permits have included a number of additional environmental and reclamation requirements in grading, topdressing, revegetation, hydrology, post-mining land-use planning and wildlife monitoring, and habitat development. Backfilling and grading operations are now required to create terraces on reclaimed lands. These terraces direct water into reconstructed drainages which consider pre-mining drainage densities and watersheds.

McKinley mine is currently investigating potentially acid and toxic materials and their effect on overburden and graded spoils. Mitigation of graded spoils containing such materials usually requires importation of a minimum lift of 3.5 ft of neutral material prior to topdressing placement. A minimum depth of 6 in. of topdressing is replaced once potentially acid and toxic materials mitigation is completed.

Certified as-built berms are now required as the primary alternate sediment control for areas actively disturbed by mining that do not drain into the pit. On OSM jurisdictional areas certified berms are also required for reclaimed lands which have not been released from bond.

Revegetation seed mixes currently contain 21 plant species, most of which are native to the mine region. Increased amounts of tree, shrub, and forb species have been included in an attempt to increase diversity and the value of the reclamation for wildlife use. The mine has also committed to custom plantings in drainage bottoms, the periphery of small depressions, and northwest- to northeast-facing slopes in an effort to develop improved reclaimed-land wildlife habitat. Wildlife monitoring programs are currently being conducted to assess the custom planting programs' success in creation of improved habitat for mule deer, scale quail, raptors, small mammals, reptiles, and threatened and endangered species.

Conclusion

Coal is one of the important basic natural resources, and the production, distribution and utilization of coal as a source of energy directly and indirectly influences almost every phase of community, state, and national well-being. Large reserves, easily accessible transportation, and uniquely flexible facilities for the production of coal to meet current and long-term requirements of electric utilities and industrial plants make it possible for P&M and McKinley mine to help meet the demand for energy, and, in doing so, make a significant contribution to the local and national economy.

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Stratigraphy and coal occurrences of the Tres Hermanos Formation and Gallup Sandstone (Upper Cretaceous), Zuni Basin, west-central New Mexico*

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Abstract—Studies in the Zuni Basin of west-central New Mexico have resulted in interpretations of the depositional environments for coal accumulation in the Tres Hermanos Formation (and in the landward, partly equivalent, Moreno Hill Formation) and Gallup Sandstone. The Tres Hermanos Formation (middle and late Turonian) is a regressive-transgressive wedge composed of three members, 1) the Atarque Sandstone Member at the base, a regressive coastal barrier deposit 25-75 ft thick, 2) the overlying nonmarine Carthage Member which consist of 90-200 ft of paludal shales, channel and overbank sandstones, and thin lenticular coals, and 3) the Fite Ranch Sandstone Member, a transgressive barrier complex 2-48 ft thick. The Tres Hermanos Formation is separated from the slightly younger Gallup Sandstone by a thin wedge of marine shale—the Pescado Tongue of the Mancos Shale.

The Pescado Tongue thins from 90 feet in the northeast to 28 ft in the southwestern part of the basin, and thus during this transgressive cycle the sea inundated a large portion of the present basin. One of the principal effects of a reversal of the direction of the shoreline migration (a turnaround) is an increase in extent and thickness in the laterally equivalent nonmarine rocks and a corresponding increase in coal accumulation. In accordance with this pattern the thickest coals in the Salt Lake coal field at the southern end of the basin occur in the Moreno Hill Formation just landward of the Fite Ranch-Gallup turnaround. The F sandstone (late Turonian) forms the basal member of the Gallup Sandstone and is a 10-45 ft regressive coastal-barrier sequence. The overlying, regressive, nonmarine rocks, in a interval as thick as 140 ft, are informally called the Ramah unit of the Gallup Sandstone. Coal near the base of the member accumulated in a back-barrier environment; coal near the top on the member accumulated in an alluvial-plain environment. The upper coal zone was mined for local use around the turn of the century and again between 1928 and 1951, and has a maximum thickness of 7 ft, variable ash content, low sulfur, and an apparent rank of high volatile C bituminous. The Ramah unit is overlain throughout much of the Zuni Basin by the distinctive, medium- to very coarse-grained, reddish-brown, feldspathic Torrivio Member of the Gallup Sandstone. In the northern and northeastern portions of the basin the Dilco Coal Member of the Crevasse Canyon Formation is present above the Torrivio, and at the far northern end the upper members of the Crevasse Canyon are also present.

Introduction

During Late Cretaceous time the western margin of the epicontinental seaway advanced and retreated across New Mexico, leaving a complex record of the intertongued marine and nonmarine sediments. The coal beds associated with the intertongued marine/nonmarine sequence in this area were noted by Shaler (1907) and were described by Sears (1925). Molenaar (1983) has described five such transgressive/regressive cycles in the San Juan Basin of northwest New Mexico. The earliest three of these five cycles can be identified in the rocks that crop out in the northern portion of the Zuni Basin; however, only the earliest two can be documented from the rock record that remains in the middle and southern portions of the basin, the area of interest in this paper (Fig. 1).

Detailed geologic mapping (1:24,000), using the modern stratigraphic framework based on a revised Tres Hermanos Formation (Hook et al., 1983), has been completed for most of the study area. The heretofore lower interval of the Gallup Sandstone is now recognized as the Tres Hermanos Formation, a regressive/transgressive wedge of marine, marginal marine, and nonmarine deposits that separates the Mancos Shale into two parts: the Rio Salado Tongue below and the Pescado Tongue above. The Pescado thus records the second and last marine transgression across the Zuni Basin, and set the stage for deposition of the Gallup Sandstone regressive sequence and the lower part of the Crevasse Canyon Formation.

This paper summarizes the stratigraphy of the Zuni Basin and discusses the coal occurrences and major coal beds in relation to the lithogenetic units that make up the members of the Tres Hermanos Formation and the partly equivalent Moreno Hill Formation, Gallup Sandstone, and Crevasse Canyon Formation.

Stratigraphy

The initial transgression of the Cretaceous interior seaway has been ascribed to the Greenhorn cycle (Hook et al., 1983) and resulted in the deposition of the Dakota Sandstone and the lower part of the Rio Salado Tongue of the Mancos Shale. At the transgressive maximum the Greenhorn Limestone was deposited, a unit that is recognized both in outcrop and in the subsurface across a large portion of the Rocky Mountain states. The first regression following this initial marine phase began during late Cenomanian time and was for the most part restricted to Arizona and New Mexico. This regression is recorded in the upper part of the Rio Salado Tongue of the Mancos, in the basal Atarque Sandstone Member of the Tres Hermanos Formation, and in most of the overlying nonmarine Carthage Member (Fig. 2). The Atarque Sandstone Member is a regressive coastal-barrier sandstone or shoreface complex that was deposited in a wave-dominated system. It is a diachronous unit that becomes younger to the northeast, but in the Zuni Basin if is of middle Turonian age (Hook et al., 1983). The regression resulted in deposition of the Atarque Sandstone Member across the entire Zuni Basin; however, in the area just southwest of Gallup, New Mexico, the Atarque, and the entire

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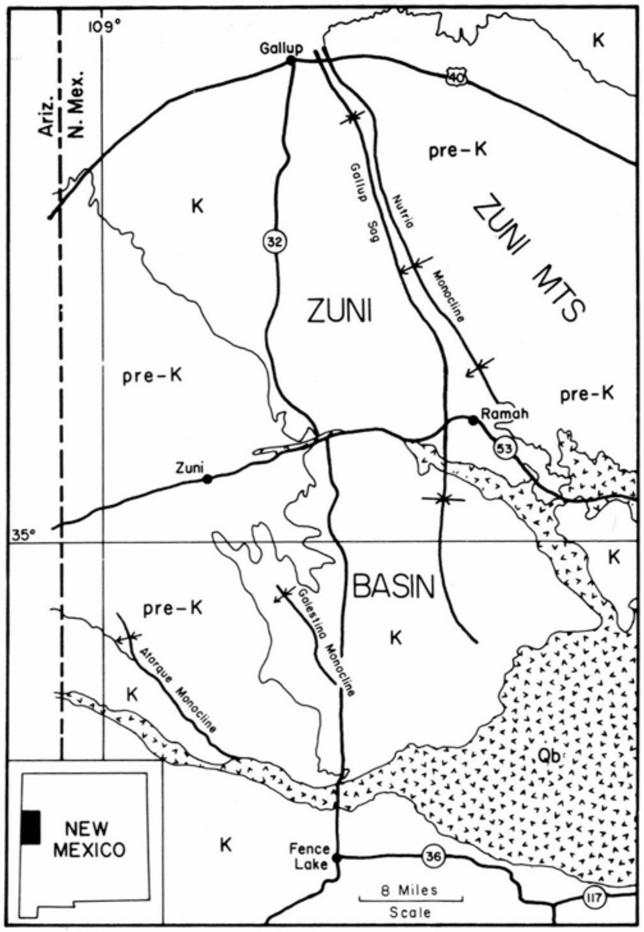

FIGURE 1—Index map of Zuni Basin showing Zuni Mountains, distribution of Cretaceous (K) and pre-Cretaceous (pre-K) rocks, and major structures; North Plains lava flow (Qb) in pattern.

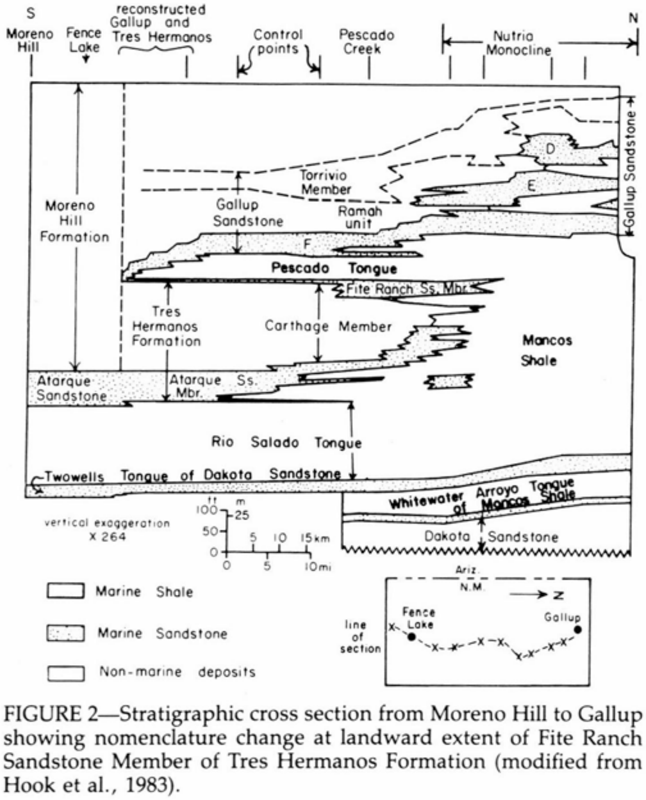

FIGURE 2—Stratigraphic cross section from Moreno Hill to Gallup showing nomenclature change at landward extent of Fite Ranch Sandstone Member of Tres Hermanos Formation (modified from Hook et al., 1983).

Tres Hermanos Formation, loses its lithologic identity. Thus the Gallup area represents a minor embayment at the regressive maximum (Fig. 3). The time of maximum regression, marking the end of the Greenhorn cycle, is latest middle Turonian to earliest late Turonian (Molenaar, 1983).

The next transgression of the seaway initiated the Carlile cycle, and is represented by the Fite Ranch Sandstone Member of the Tres Hermanos Formation and the lower part of the Pescado Tongue of the Mancos Shale, This is the T2 transgression of Molenaar (1983). The Pescado is for the most part late Turonian; the time-equivalent rocks in a more seaward position are represented by the calcareous Juana Lopez Member of the Mancos, while in a landward direction beyond the limits of this transgression the time-equivalent rocks are represented by the coal-bearing Moreno Hill Formation (McLellan et al., 1983). In the current stratigraphic framework, proposed in Hook (1983), there is a nomenclature change at the landward pinchout of the Fite Ranch Sandstone Member. Landward from this pinchout the name Tres Hermanos is not applied; the Atarque is raised in rank to formation and the overlying nonmarine section has been designated as the Moreno Hill Formation. The exact point of nomenclature change is somewhat arbitrary as Tertiary erosion has stripped off the part of the section in which the Fite Ranch pinchout occurs, or else this part of the section is covered by the North Plains lava field.

The nomenclature change corresponds with a change in coal-field terminology. The coals of the Moreno Hill Formation delineate the Salt Lake coal field which lies at the southern end of the Zuni Basin, south of the Gallup—Zuni coal field. The major coal zones in the Salt Lake field occur just landward of the Fite Ranch transgressive maximum (Fig. 3). Coals in the Gallup—Zuni coal field, on the north side of the turnaround, are in the Carthage Member of the Tres Hermanos Formation, Gallup Sandstone, and Crevasse Canyon Formation. Coal occurrences just landward of a turnaround or a thick buildup of marine sand are somewhat predictable. One explanation that has been advanced for this association is that the rates of strandline migration at these points were very slow, allowing for an increase in extent and thickness of sediments in the adjacent paludal environment (Shomaker et al., 1971).

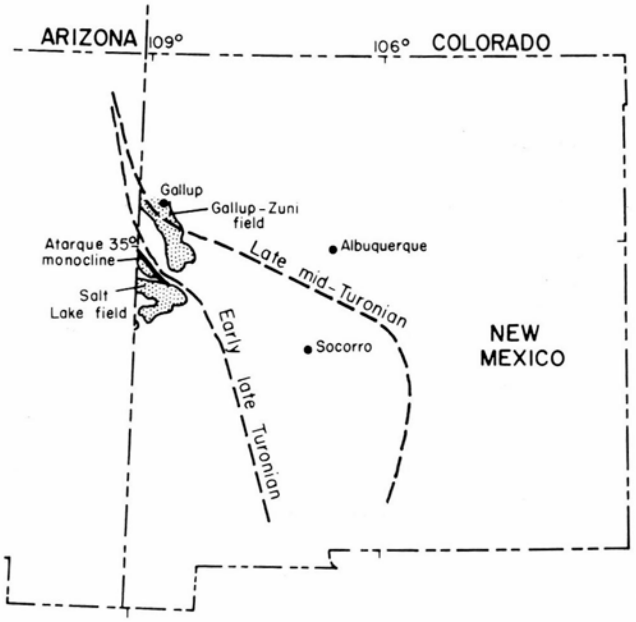

FIGURE 3—Map showing positions of shorelines during deposition of Tres Hermanos Formation and their position with respect to Zuni Basin coal fields and Atarque monocline.

The Fite Ranch Sandstone Member, the uppermost member of the Tres Hermanos Formation, is a coastal-barrier complex of highly variable thickness in the Zuni Basin. These thickness variations are likely to represent periods of relatively rapid transgression followed by periods of progradation during which the thicker portions of the unit were deposited. This "punctuated" transgressive style, suggested by Hook et al. (1983), is also consistent with the slight coarsening upward characteristically noted at the thicker outcrops. At the Tres Hermanos reference section in sec. 5 of T1ON R17W, McKinley County, New Mexico, the Fite Ranch is 48 ft thick; elsewhere it thins to less than a foot. At the southwesternmost occurrence in sec. 24 of T7N R17W, Cibola County, New Mexico, it is 6 ft thick and at the base contains the bivalve *Inoceramus dimidus,* a late Turonian guide fossil. The landward pinchout was not more than 4 or 5 mi to the southwest of this occurrence inasmuch as the section south of the North Plains lava field is all nonmarine above the Atarque Sandstone. In all probability the turnaround at the apex of this transgressive cycle was influenced by subtle pre-Laramide structures trending parallel to the Atarque and Defiance monoclines. Late Turonian strandlines trended NW parallel to the monoclines and some relationship between the two is suggested (Fig. 3).

The regressive phase of the Carlile cycle, which began during the late Turonian, resulted in deposition of the basal member of the Gallup Sandstone, the F member, a coastal-barrier/shoreface complex that can be traced with a considerable amount of stratigraphic rise up into the southern and western San Juan Basin. This regression was unique to New Mexico and northeastern Arizona (Molenaar, 1983), and, as mentioned above, was likely related to pre-Laramide crustal movements along a northwest trend parallel to the present Defiance and Atarque monoclines.

The upper two members of the Gallup are nonmarine: the Ramah unit, an informally named paludal and alluvial sequence, and the overlying Torrivio Member. The Ramah unit, which exceeds 130 ft in thickness locally, contains at least two coal zones. The lowermost coals at the base of the member (0-10 ft above the F sandstone member) are very lenticular and represent accumulation in a back-barrier environment. They rarely exceed 1.2 ft in thickness. The upper coal zone in the Ramah unit was referred to as the School mine coal group by Sears (1925) and is separated from the lower zone by as much as 70 ft. The School mine coals are lenticular and accumulated in an alluvial-plain environment. These coals were mined at the turn of the century for local use, and again during 1928-1951, from the Zuni and Zuni No. 2 mines (Shomaker et al., 1971). Total production during this latter period was reported as 46,000 tons.

The Torrivio Member overlies the Ramah unit throughout much of the Zuni Basin. It is a distinctive reddish-brown, medium- to very coarse-grained, feldspathic, fluvial-channel sandstone that varies from 40 to 80 ft in thickness. Although genetically it would be more reasonable to include the Torrivio with the nonmarine Crevasse Canyon Formation, it does provide a mappable top to the Gallup in much of the outcrop area. In those few areas where the Torrivio is not present as a distinct unit, the top of the Gallup becomes the top of the marine F member of the Gallup Sandstone.

Mostly nonmarine deposits continued to accumulate above the Gallup Sandstone and constitute the Crevasse Canyon Formation of Allen and Balk (1954). Only part of the Crevasse Canyon Formation, including the Dilco Coal Member and the overlying Bartlett Barren Member, are present in the Zuni Basin and only in the northern part. In the extreme northern part of the basin, at the arbitrary boundary between the Zuni and San Juan Basins, the remaining members of the Crevasse Canyon Formation are present, the Dalton Sandstone Member (marine) and the Gibson Coal Member; but that area is beyond the scope of this paper. These upper units are mentioned here only as additional examples of principal coals occurring landward of a marine turnaround or sand buildup. The principal coal beds of the Dilco occur in the upper part of a sequence that was deposited landward of the Dalton—Mulatto transgressive maximum, and the Gibson coals are concentrated in a sequence opposite the landward pinchout of the Point Lookout Sandstone.

Coal occurrences

Coal occurrences within the Zuni Basin are segregated into two coal fields, the Salt Lake coal field on the extreme south and the Gallup—Zuni field in the central and northern parts (Fig. 3). The two fields are separated by a narrow neck of the North Plains lava field and a structural high produced by the northwest-trending Atarque monocline which brings Jurassic and Triassic rocks to the surface in a 6-20 mi wide non-coal area between the two coal fields.

Salt Lake coal field

Much of the recent work on this coal field has been summarized by Roybal and Campbell (1981). Coal zones are for the most part limited to the approximately 400 ft thick lower member (Fig. 4) of the Moreno Hill Formation. This member consists of fluvial-channel sandstones, crevasse splays, and floodplain deposits, and includes three coal zones, only the upper two of which contain coal of any economic significance. The upper two coal zones are the thickest in the eastern part of the field, east and south of Fence Lake, in T4&5N R16&17W, and locally R18W. The principal coals of the field are within 7-8 mi of the projected landward pinch-out of the marine Fite Ranch Sandstone Member.

The two principal coal zones lie about 200 ft and 290 ft above the Atarque Sandstone Member, with the lower zone being the more extensive and having a somewhat greater average individual-seam thickness, 4.2 ± 2.5 ft (Roybal and Campbell, 1981). At the southernmost outcrop of the Tres Hermanos Formation on the line between T6&7N R16W, the Fite Ranch Member is 200 ft stratigraphically above the Atarque Sandstone Member. Thus the stratigraphic intervals suggest that the lower, more extensive coal accumulated in a coastal swamp just landward of the Fite Ranch transgressive maximum. An isopach map of the thickest coal in the lower zone reveals a northwest trend, parallel to the projected shoreline.

The upper of the two zones is less extensive and has an average individual seam thickness of only 2.7 1.1 ft. An isopach map of aggregate thickness shows a northeast trend. This zone occurs higher up in the depositional system in an alluvial-plain environment, and this trend probably reflects accumulation in a back swamp parallel to a northeast-flowing drainage. The thickest bed has one kaolinitic parting (tonstein). Analyses of samples from both the upper and lower zones show the coal to be high ash (17-20%), low sulfur (0.8-1.1%), and of high volatile C bituminous rank.

Gallup—Zuni coal **field**

The work of Sears (1925), which included much of Winchester's work, provides a valuable data base for modern investigators in the Gallup—Zuni coal field. More recently Shomaker et al. (1971) summarized geologic and resource data from previous workers and from their own observations in the Zuni—Ramah areas. Most recently Sticker and Mapel have completed detailed geologic mapping (unpublished) and coal resource evaluation for a large part of the Gallup—Zuni field. Anderson and Mapel (1983) mapped and

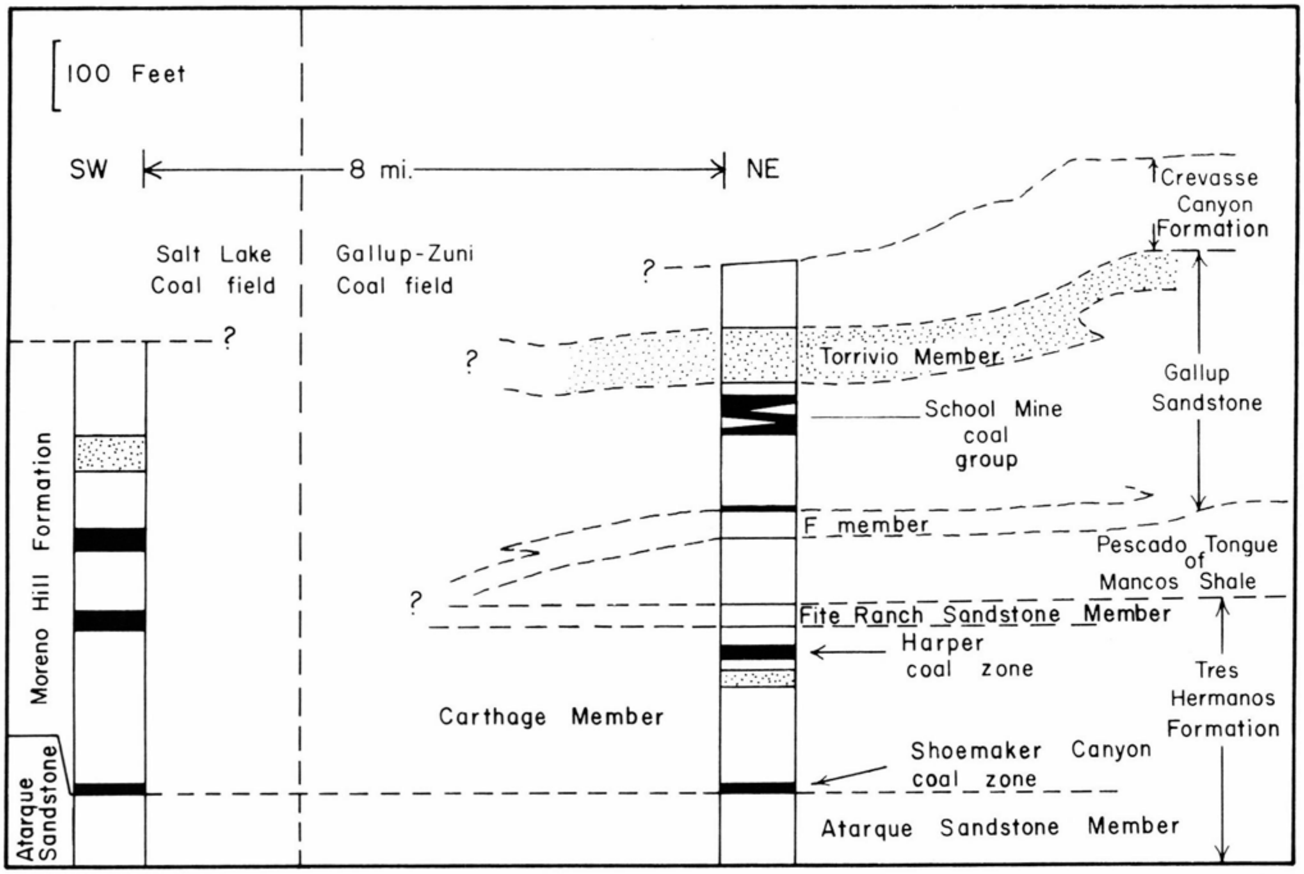

FIGURE 4—Major coal zones, Salt Lake and Gallup–Zuni coal fields.

evaluated the coal resource potential in the southern portion of the field.

Coal zones of the Carthage Member

The coals in this member of the Tres Hermanos Formation were originally referred to as the "Pescado coal group" by Sears (1925). Subsequently, the name Pescado has been applied to the tongue of the Mancos Shale that separates the Tres Hermanos Formation and the Gallup Sandstone, and use of the name to define a coal zone in the Carthage is confusing. We have therefore assigned the names Shoemaker Canyon coal zone for coals near the base of the "Pescado coal group" and Harper coal zone for coals at the top of the "Pescado coal group" (Fig. 4). The Shoemaker Canyon coal zone is named after the exposures of this zone near Shoemaker Canyon, Cibola County, New Mexico, and the Harper coal zone is named for the Harper mine which worked this coal at the turn of the century in sec. 7 of T11N R17W (Shaler, 1907).

The Shoemaker Canyon zone is best exposed in the southern portion of the field. It rests directly on the Atarque Sandstone and locally, in T7N R17W, it may contain up to three beds. The lowest bed is the thickest, and is as thick as 1.7 ft with a 0.2 ft kaolinitic parting (tonstein). The upper two coal beds are less than 1.2 ft thick and thus are of no economic significance. These coals accumulated in back-barrier basins or in the seaward part of a coastal swamp. The coals are interbedded with flat-bedded, lower-finegrained, burrowed and root-penetrated, laterally persistent sandstone, in beds 1-2 ft thick. These were deposited during minor oscillations of sea level as foreshore sandstones that transgressed across the back-barrier basin.

The Harper zone consists of a 3-4 ft thick coaly-carbonaceous shale interval in the southern part of the field. The zone lies just above a fluvial-channel-sandstone complex that varies from 5 to 30 ft in thickness and is about 25 ft below the base of the Fite Ranch Member. In the central part of the field, between the towns of Ramah and Zuni, New Mexico, this zone thickens somewhat and lies close to the base of the Fite Ranch Member. Coals in this zone accumulated in an alluvial-plain environment. At the Harper mine, the zone was 4.8 ft thick with many partings of shale and bone coal.

Coals in the Ramah unit

The coals in the Ramah unit of the Gallup Sandstone are found in two main zones. The lower zone, at the base of the member, is rarely exposed and is not of any economic significance. Coals in this zone are as thick as 2.8 ft, but contain shale partings including tonsteins. The lower coal zone is commonly separated from the overlying coal zone, the School mine coal group, by a thick sandstone channel complex 5-30 ft thick. Coal in this upper zone is as thick as 7 ft, commonly with two tonsteins. Analyses made by the U.S. Bureau of Mines and the U.S. Geological Survey yield the following ranges for coals in this zone: moisture 4.4-10.6%; volatile matter 31.8-37.6%; fixed carbon 38.7-42.4%; ash 8.8-36%; sulfur 0.6-1.5%; and heat of combustion 10,470-11,250 Btu/lb. The School mine coal group commonly is overlain by a sandstone channel complex which in turn is overlain by the 40-80 ft thick Torrivio Member. Of all the coals investigated in the Moreno Hill and Tres Hermanos Formations and the Ramah unit, the School mine coal zone contains the thickest and most widespread coal. The economics of surface mining considered, these coals would be marginal because of the many partings, their lenticularity, and the overburden of the massive sandstone of the Torrivio Member.

Summary

1. In the Salt Lake coal field (Moreno Hill Formation), coals having the greatest economic potential accumulated 4-8 mi from the Fite Ranch—Gallup turnaround.

2. The Shoemaker Canyon coal zone (basal part of the Carthage Member) accumulated in a back-barrier environment. In the southern and central portions of the Zuni Basin the coals are thin and contain numerous shale partings and bone coal. In the northern part of the basin the coal zone is rarely exposed and few drill holes have penetrated it.

3. The Harper coal zone (upper part of the Carthage Member) in the southern portion of the basin is shaley and rarely exceeds 1.2 ft. In the central part of the basin (north of Highway 53) coal in the zone is as thick as 4.8 ft (Harper mine), but contains numerous shale partings and bone coal. The coal in this zone accumulated in a back-swamp—alluvial-plain environment.

4. The lower coal zone in the Ramah unit rarely exceeds 1.2 ft in thickness, is seldom exposed, and contains shale partings and bone coal. Coals in this zone accumulated in a back-barrier setting. These coals have little economic potential.

5. The upper coal zone in the Ramah unit (School mine coal zone) are the thickest and most laterally persistent and accumulated in an alluvial-plain environment. These coals are low sulfur, contain variable amounts of ash, and are high volatile C bituminous. The coals of the School mine zone have by virtue of their proximity to existing transportation facilities the best development potential of all the coals in the Moreno Hill Formation, Carthage Member of the Tres Hermanos Formation, and Gallup Sandstone. Presently, however, the surface mining of these coals would appear to be subeconomic because of an unfavorable stripping ratio.

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Blasting at Carbon Coal Company, Carbon no. 2 mine, February 1986. Photo O. J. Anderson.

Reclamation at Carbon Coal Company, Carbon no. 2 mine. Photo O. J. Anderson.

Coal geology of the Salt Lake coal field

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Abstract—The Salt Lake coal field is located in west-central New Mexico. A study undertaken by the New Mexico Bureau of Mines & Mineral Resources in co-operation with the U.S. Geological Survey has attempted to map the geology of this little known coal field. Drilling and coring of the coals has provided much information concerning the coal quality and geology. The coals present are amongst the oldest in the state and are assigned to the Moreno Hill Formation. Five coal zones are present in this field, four of which are in the Moreno Hill Formation and one in the Dakota Sandstone. Of these five zones two are economic in both thickness and quality. In general, these coals are high-volatile C bituminous, with a high ash content and low sulfur values. Other than the ash content, the remaining combustion analyses are relatively uniform, not showing wide trends in their variability. The general depositional environment of these coals is that of a braided-stream-type deposit.

Introduction

Over the past seven years the New Mexico Bureau of Mines & Mineral Resources, jointly with the U.S. Geological Survey, has been studying the geology and coal deposits of the Salt Lake coal field (Fig. 1). The focus of this work has been on the stratigraphy of the area as well as the quality and quantity of the coal reserves (Anderson, 1981; Anderson and Frost, 1982; Campbell, 1981; Roybal and Campbell, 1981; Campbell and Roybal, 1984; Landis et al., 1985; McLellan et al., 1984).

Structure

The structure of this field is relatively simple. The regional dip for this field is 3-5° to the southeast although Tertiary volcanism caused many small flexures due to local deformation throughout the field. A few significant faults are present, the most prominent of which is located in the western portion of the field, along NM-32. USGS mapping indicates extensive faulting in the central portion of the field. Displacement on these faults is difficult to determine, as there are no dips recorded for this area and outcrops are sparse. Based on the derived dips by utilizing geophysical logs and available outcrops, the displacements on these faults are no more than a few feet.

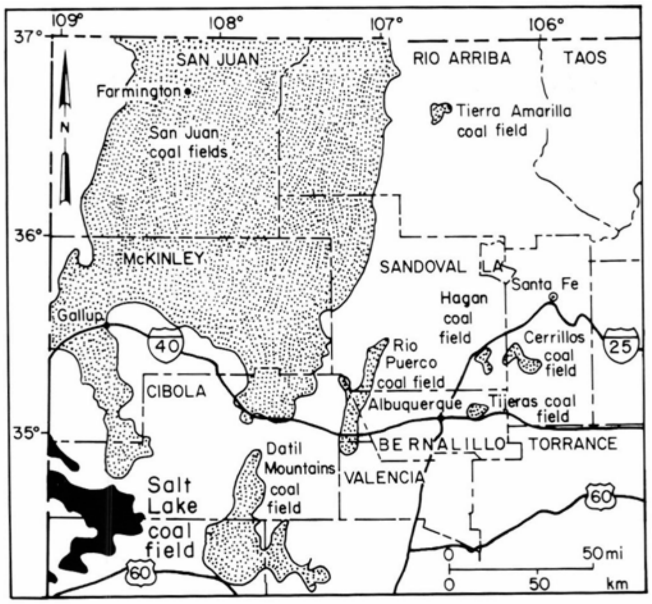

FIGURE 1—General location map.

Coal geology

Most of the coal in this field occurs in the lower member of the Moreno Hill Formation as defined by McLellan et al. (1984). This member is 490 ft thick in the eastern portion of the field and thins to less than 100 ft to the west, near the Arizona border. Studies by the New Mexico Bureau of Mines & Mineral Resources have shown that the Moreno Hill Formation thickens greatly south and west of the Zuni Salt Lake. Subsurface data as well as reconnaissance geologic mapping have indicated little to no coal in this portion of the field.

The Moreno Hill Formation is a coal-bearing continental sequence of sandstones, siltstones, mudstones, claystones, and coal. The lower member of the formation is a fluvial sequence consisting of meandering-stream deposits and related coal-bearing marsh deposits. The middle member of the Moreno Hill Formation is a sandstone, possibly deposited by a braided stream. Campbell (1981) indicated that the middle member is equivalent to the Torrivio Member of the Gallup Sandstone. No coals are found in this member. The upper member of the Moreno Hill Formation is dominantly siltstones and mudstones, with few sandstones and very little coal. Fig. 2 is a generalized stratigraphic column for the Moreno Hill Formation.

Most of the coal reserves of the Salt Lake coal field are in the eastern portion, in the region covered by the Cerro Prieto and The Dyke quadrangles. Roybal (1982) indicated a southward continuation of the coals present in the southern part of the Cerro Prieto quadrangle into the northern portion of the Tejana Mesa quadrangle. Work by Campbell (1981), Campbell and Roybal (1982), and Campbell (1987) demonstrated that the coals in the eastern portion of the Salt Lake coal field are high-volatile bituminous C in rank. Coal reserves are calculated by projecting this rank for coals to the western portion of the field and using the minimum thickness of 1.2 ft (96 cm) for reserve calculations of bituminous coals, according to Wood et al. (1983). The coal reserves for the Salt Lake coal field are 480 million tons, of which 142 million tons have a stripping ratio of 20:1 or less. These reserves are distributed between four coal-bearing zones in the Salt Lake area. Table 1 shows the measured and indicated tonnages for three depth categories and a stripping ratio of 20:1 for the four coal zones in the Moreno Hill Formation. Weathered coal extends to a depth of approximately 60 ft. Separation of these reserves on the basis of weathering results in 69 million tons of weathered coal and 411 million tons of unoxidized coal.

Dakota zone

The oldest coal zone is in the Dakota Sandstone present in secs, 1 and 2 of T3N R19W and in sec. 18 of T6N R18W.

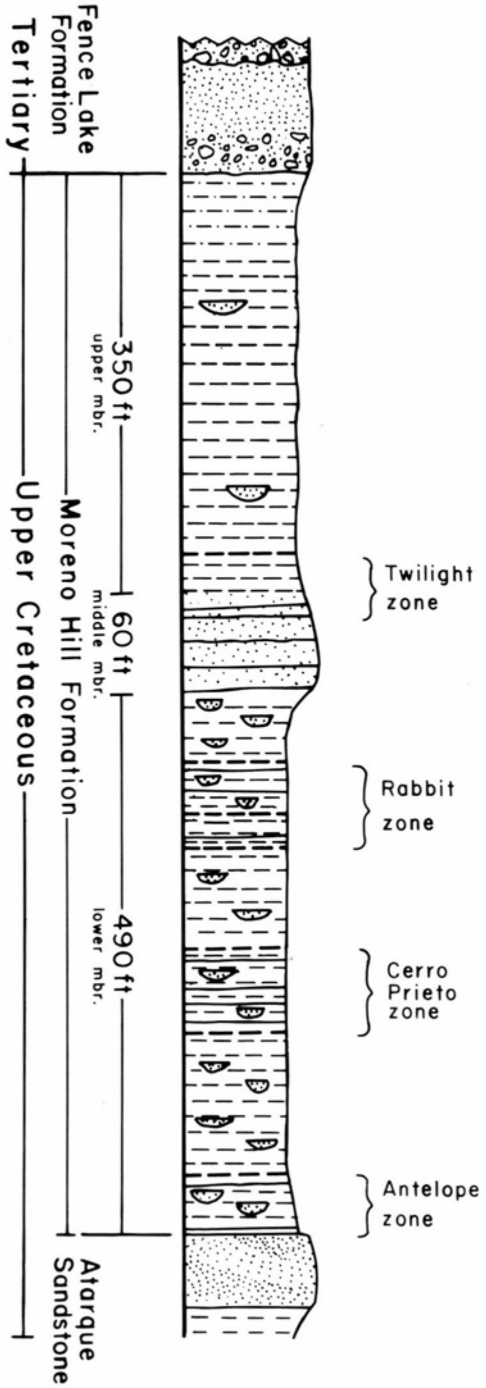

FIGURE 2—Generalized stratigraphic column of Moreno Hill Formation.

TABLE 1—Coal reserves of the Salt Lake coal field (1.2 ft [0.4 m] minimum thickness).

Coal Zone	20:1		0-150 ft		151-250 ft		250 + ft	
	Meas.	Ind.	Meas.	Ind.	Meas.	Ind.	Meas.	Ind.
Antelope	4.1	30.2	5.5	39.4	4.7	33.5	2.4	17.3
Cerro Prieto	11.7	64.7	24.5	93.1	11.8	46.8	9.3	61.5
Rabbit	6.6	24.9	18.5	82.7	3.5	10.0	1.7	13.6
Twilight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 2—Combustion analyses of the Salt Lake Field coal zones (as received).

	No.	Ave.	S.D.		No.	Ave.	S.D.
Antelope Zone				Rabbit Zone			
Moisture	4	13.01	2.92	Moisture	36	14.45	2.44
Ash	4	17.88	7.65	Ash	36	10.23	5.59
V.M.	4	30.00	4.59	V.M.	36	31.70	3.49
F.C.	4	39.20	7.36	Btu	36	9405	1018
Btu	4	9472	1680	Carbon	12	51.44	3.53
Carbon	3	50.04	5.88	Hydrogen	12	3.68	0.51
Hydrogen	3	3.91	0.50	Nitrogen	12	1.02	0.05
Nitrogen	3	0.96	0.20	Sulfur	36	0.70	0.23
Oxygen	3	11.41	1.23	Pyritic	36	0.14	0.08
Sulfur	3	0.94	0.68	Sulfate	16	0.06	0.07
Pyritic	4	0.41	0.39	Org. S.	36	0.47	0.22
Sulfate	0	0.00	0.00				
Org. S.	4	0.49	0.23	Twilight Zone			
				Moisture	4	3.07	0.39
Cerro Prieto Zone				Ash	4	24.94	3.85
Moisture	52	13.89	2.33	V.M.	4	34.12	0.88
Ash	52	18.22	7.84	F.C.	4	37.87	2.71
V.M.	52	29.37	2.41	Btu	4	8926	1136
F.C.	52	39.33	9.45	Sulfur	4	0.79	0.38
Btu	52	8914	1294				
Carbon	32	51.31	5.64				
Hydrogen	32	5.33	0.41				
Nitrogen	32	0.96	0.08				
Oxygen	32	12.06	2.52				
Sulfur	52	0.65	0.24				
Pyritic	52	0.18	0.14				
Sulfate	26	0.07	0.06				
Org. S.	52	0.43	0.15				

These coals are poorly exposed, but appear to be thin, 2-3 ft (0.6-0.9 m) in maximum thickness, and are generally discontinuous. No analyses are available for these coals and no reserves were calculated.

Antelope zone

The four coal zones present in the Moreno Hill Formation are (ascending) the Antelope, Cerro Prieto, Rabbit, and Twilight. All four are identifiable from both outcrop and geophysical log data. The Antelope coal zone is in the 50 ft (15.1 m) interval above the top of the Atarque Sandstone. The coals of this zone do not crop out in the eastern portion of the field; however, drilling located some coals in this zone. In the western portion of the field, only the Antelope zone is present in the Moreno Hill Formation. Based on available data, there is no trend in thickness other than that the thickest coals are in the western portion of the field. Fig. 3 shows the areal distribution and thicknesses of Antelope zone coals. Both drill and outcrop data indicate that these areas are separated by non-coal-bearing intervals. This zone consists of at most two beds, with their average aggregate thickness being 2.8+/-1.3 ft (0.84+1-0.39 m). They appear to be thin beds, averaging 1.9+/-0.9 ft (0.6+/-0.3 m) in thickness, rapidly grading into carbonaceous shales. Coals of this zone are not laterally continuous for distances greater than 0.5 mi. Locally, the Antelope zone coals are thick, up to 5.8 ft (1.8 m) in an outcrop in sec. 31 of T5N R18W, but these thicknesses do not continue for any distance laterally. In some outcrops these coal beds have thin kaolinitic layers present throughout the entire thickness of the beds.

The few analyses available for these coals show an ash content of 17.88+/-7.65%a, and an as-received heating value of 9,472 Btu/lb. The moist, mineral-matter-free heating value is 11,194 Btu/lb, indicating a high-volatile C bituminous rank. Sulfur content is 0.94+/-0.68%. The pyritic sulfur is high, 0.41+/-0.39%. Table 2 gives the average and standard deviation of the analyses available for the Antelope zone. The demonstrated reserves (1.2 ft) in the zone amount to 83 million tons, with 34 million tons having a stripping ratio of less than 20:1.

Cerro Prieto zone

The Cerro Prieto zone overlies the Antelope zone. In the eastern portion of the field, this is approximately 150 ft above the Atarque Sandstone. This zone is not present in the western portion of the field, but attains a thickness of 76 ft (22.9 m) in the eastern area. A maximum of four coal beds are present and range in thickness up to 9.5 ft (0.3—

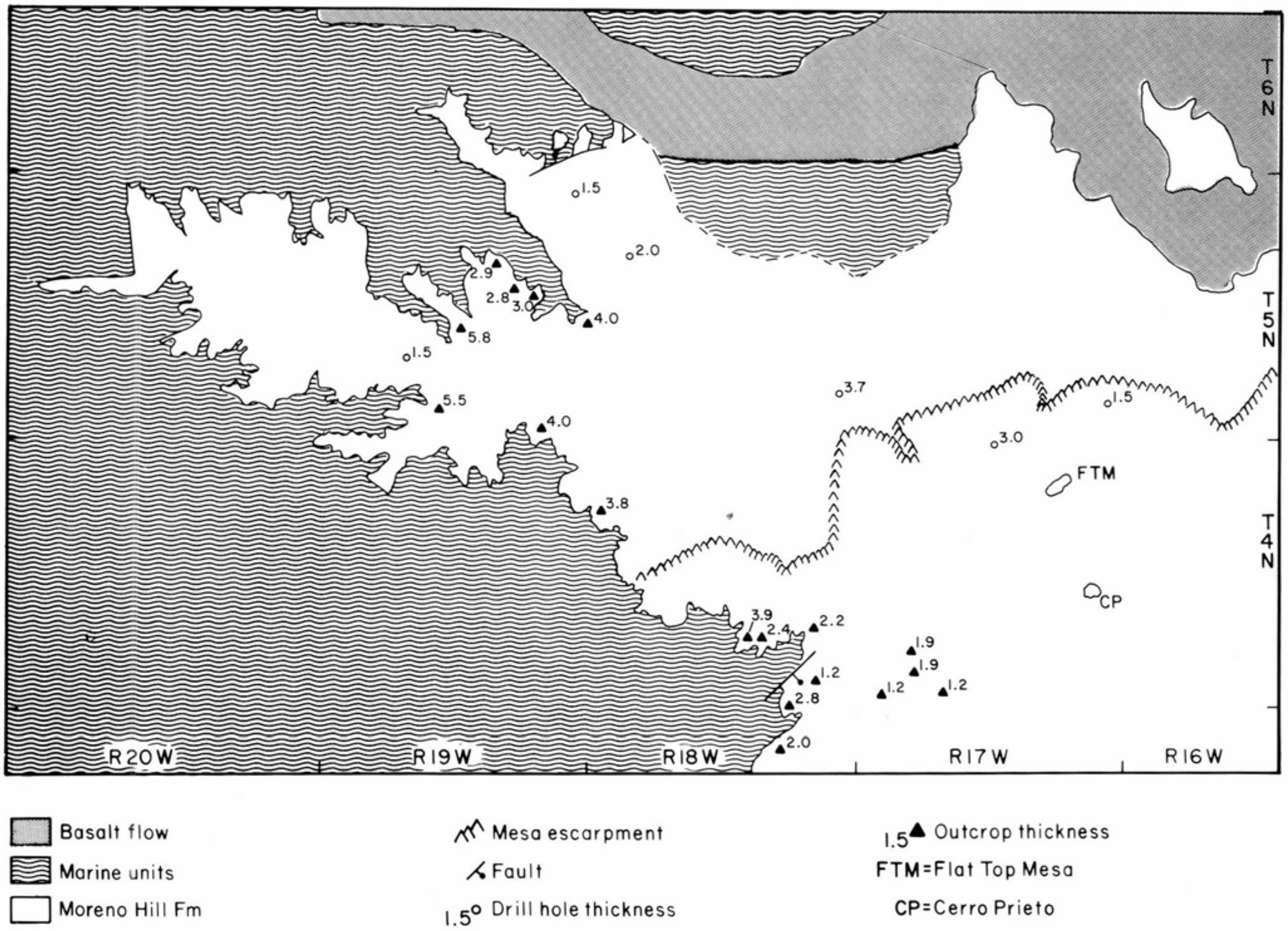

FIGURE 3—Distribution of Antelope zone coals.

2.9 m) for a single bed. Fig. 4 is an isopach map of the total coal thickness of the Cerro Prieto zone. It shows the area of thickest coal to have a northwest—southeast trend. The major bed varies from 6 to 9.5 ft (1.8-3.0 m) in thickness and is readily recognizable, having two thin, kaolinitic partings that are uniformly 22 in (55 cm) apart; the upper parting is 0.25 in (0.6 cm) thick and the lower parting is 0.5 in (1.2 cm) thick. This bed is referred to as the Double T bed; it is best exposed in 7.5 ft (2.3 m) bed in a bulldozer cut in sec. 9 of T4N R17W, and can be seen also in a 9.5 ft (2.9 m) coal cored in sec. 31 of T4N R16W. The three remaining coal beds of the Cerro Prieto zone are discontinuous and grade laterally into carbonaceous shales.

This zone contains numerous thin beds of coal in the northwest portion of the Cerro Prieto quadrangle. These coals, although laterally continuous, rarely exceed 3 ft (0.9 m) in thickness. Coals in this area are associated with channel sandstones which in many cases fill channels cut into the coals. The vertical interval between sandstone bodies is generally less than 15 ft (4.5 m). The high frequency of thinner coals with numerous channels indicates a high intensity of channeling, restricting coal-swamp development. In the area south of Flat Top Mesa (FTM) the frequency of channel sandstones is much less, with the vertical interval being 30+ ft (9.0 m). The Cerro Prieto zone coals in the area south of Flat Top Mesa are generally 5-6 ft (1.5-1.8 m) thick. Where the thickest coals occur, in sec. 31 of T4N R16W, there are only three sandstones within a 260 ft (78.4 m) vertical interval. These thicker coals associated with thicker and less stratigraphically frequent sandstones are indicative of a more stable environment with less fluctuation of stream channels that allowed for thicker coal development. A drill hole located in sec. 31 of T5N R17W penetrates the entire lower Moreno Hill Formation and the Cerro Prieto zone is present as three thin beds over a 40 ft interval. This indicates a western boundary for this zone. Only two 1.0 ft thick sandstones are present in this interval.

The average total coal thickness for the Cerro Prieto zone in the study area is 5.2+/-3.2 ft (1.8+/-1.0 m), and the average individual-bed thickness is 3.6+/-1.9 ft (1.1+/-0.6 m). Ash content of coals from this zone is 18.22+/-7.84%, with an average moisture content of 13.89+/-2.33%. The Double T bed does not vary significantly from the other Cerro Prieto coals, except in ash content that averages 13.9+/ —6.7%. Coals of this zone have an average moist, mineralmatter-free heating value of 11,496 Btu/lb, indicating a rank of sub-bituminous A/high-voltile C bituminous. Removing coals that have been oxidized, this heating value increases to 11,611 Btu/lb, making these coals high-volatile C bituminous. Table 2 gives the combustion analyses of these coals. The known demonstrated reserve base for the Cerro Prieto zone is 247 million tons, of which 76 million tons has a stripping ratio of less than 20:1.

Rabbit zone

The next higher coal zone in the Moreno Hill Formation is the Rabbit zone, located approximately 290 ft (87.4 m) above the top of the Atarque Sandstone and approximately 60 ft (18.1 m) below the base of the middle member of the Moreno Hill Formation in the eastern part of the Salt Lake field. The thickness of this zone varies from west to east, as does the Cerro Prieto zone, being 3.0 ft (0.9 m) thick at

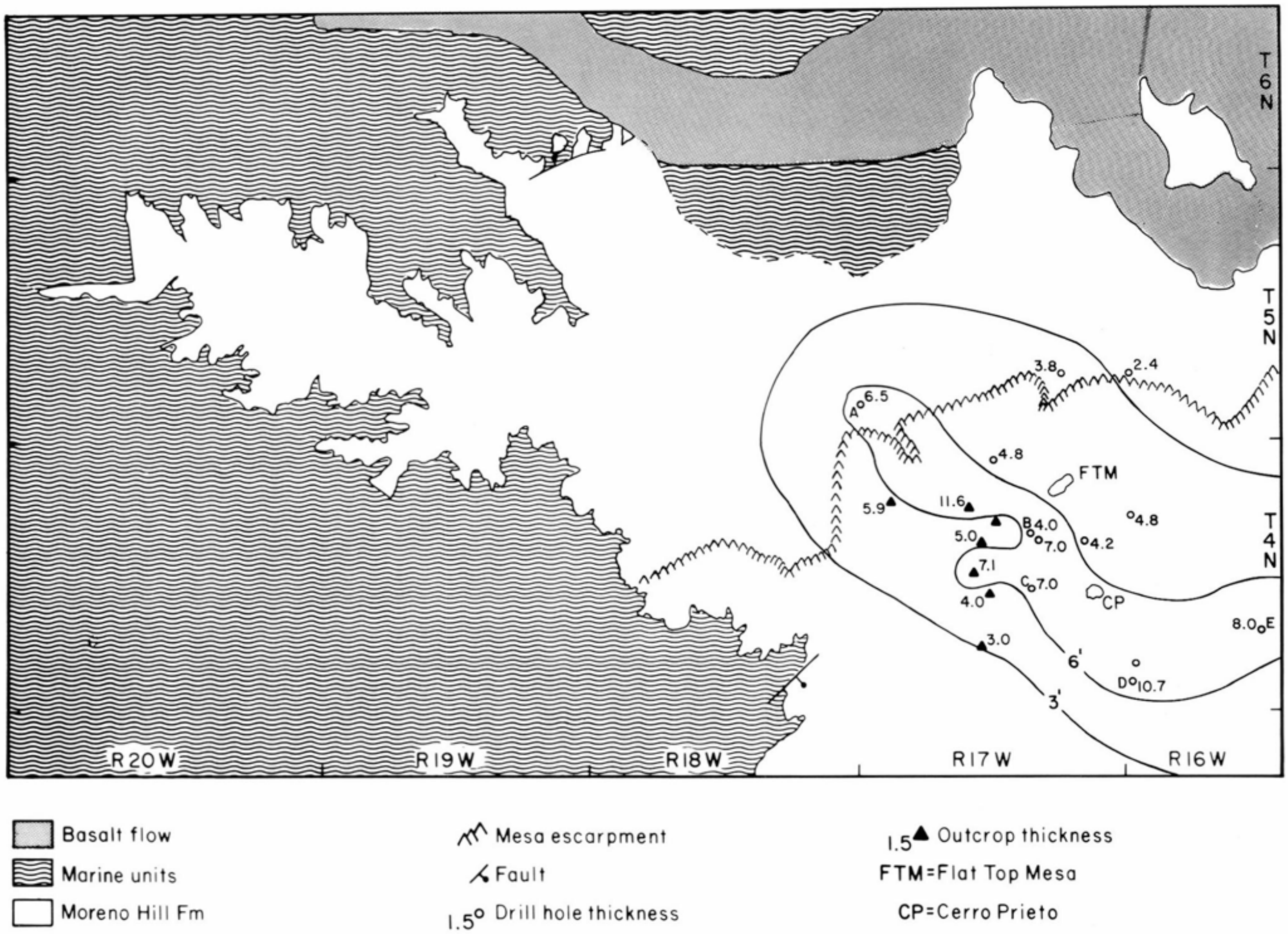

FIGURE 4—Isopach map, total coal thickness of Cerro Prieto zone.

the western end and 70 ft (21.1 m) thick in the east. The Rabbit zone has up to four coal beds. Generally, the second coal from the bottom is the thickest. One bed has a single kaolinitic parting, which distinguishes this zone from the lower Cerro Prieto zone; this bed is referred to as the Lagus bed. The kaolinitic parting has a uniform thickness of 0.5 in. (1.2 cm) and is found near the top of the Lagus bed. This bed has a maximum thickness of 12.0 ft (3.6 m) in an outcrop in sec. 27 of T5N R17W. In a drill hole in sec. 30 of T5N R16W this bed is 7.5 ft (2.3 m) thick. This bed is not present in sec. 23 of T4N R16W, indicating a rapid thinning to the east. Coal in sec. 28 of T6N, R16W also contains a single tonstien, indicating a northeast trend for the Rabbit zone. In this drill hole, 11 ft (3.3 m) of coal was present over a 60 ft (18.1 m) vertical interval as three beds. Coal present in this hole does not continue to the north, as shown by drilling.

Fig. 5 is an isopach map of total coal thickness in the Rabbit zone; it shows the trend of greatest coal thickness to be northeast—southwest. In contrast to Cerro Prieto zone coals, the thickest coals are located north of Flat Top Mesa (FTM). The Rabbit zone does not extend north of sec. 12 of T5N R17W, where it is present as a 2 ft (0.6 m) bed. To the south, Rabbit zone coals are found as a 2 ft (0.6 m) outcrop in sec. 31 of T4N R16W. Roybal (1982) noted the presence of Rabbit coals in the Tejana Mesa quadrangle. The average total thickness in the Rabbit zone is 4.4+/-3.1 ft (1.3+/-1.0 m), while the average single-bed thickness is 3.2+/-1.9 ft (1.0+/-0.6 m).

The average as-received heating value for this zone is 10,083 Btu/lb, with the average moist, mineral-matter-free value being 11,282 Btu/lb, indicating a rank of sub-bituminous A/high-volatile C bituminous. As with the Cerro Prieto zone, the average moist, mineral-matter-free heating value of this zone increases to 11,562 Btu/lb upon removal of the oxidized coals. The average as-received ash is 14.67+/-4.98%, with a moisture content of 14.45+/-2.44%a. The total sulfur content is 0.70+/-0.23%, with the pyritic sulfur averaging 0.14+/-0.08%. Average analyses are given in Table 2. The known demonstrated reserve base for the Rabbit zone is approximately 130 million tons of coal, with 32 million tons having a stripping ratio of less than 20:1.

Twilight zone

The highest coal zone in the Moreno Hill Formation is the Twilight zone, found in the lower 50 ft (15.1 m) interval of the upper member of the Moreno Hill Formation. This zone consists of 1-3 beds, which are up to 2.5 ft (0.9 m) thick and are not traceable to any extent. Fig. 6 shows that this zone is restricted to the eastern portion of the field. Contouring was not attempted due to the isolation of the coal occurrences. The average bed thickness is 1.8+/-0.5 ft (0.7+/-0.2 m). The known demonstrated reserve base for the Twilight zone was not calculated due to a lack of data. Coals from outcrops samples in this zone have an average as-received ash content of 24.9+/-3.9%, moisture of 3.1+/ —0.4%, and a heating value of 8,926+/-1,136 Btu/lb. This coal has a moist, mineral-matter-free heating value of 12,229 Btu/lb, indicating a rank of high-volatile B bituminous.

The mineral content of the Moreno Hill Formation coals, as determined by x-ray diffraction, consists of carbonates, sulfides, kaolinite, quartz, and sulfates. The kaolinite and

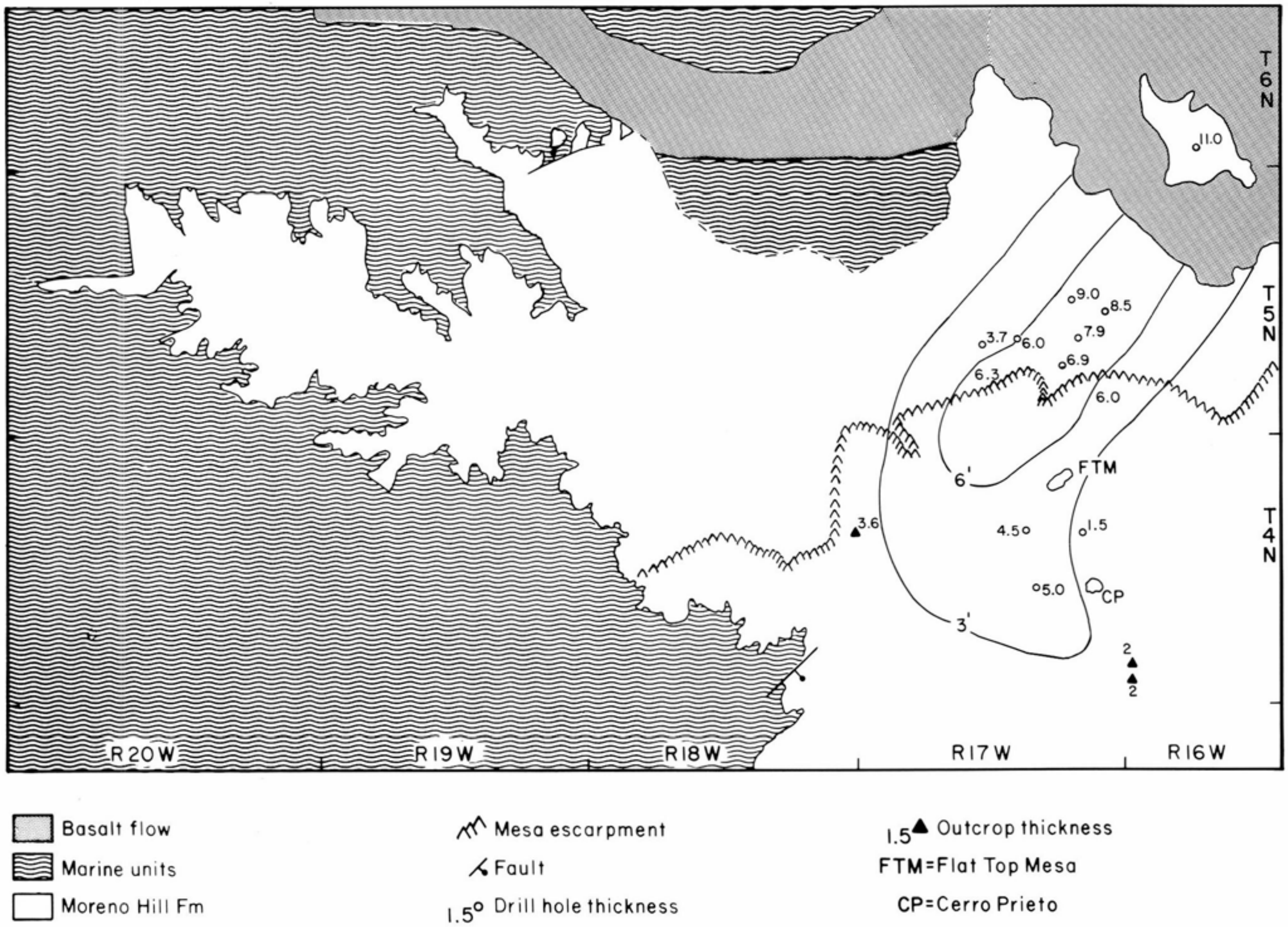

FIGURE 5—Isopach map, coal thickness of Rabbit zone.

quartz occur as finely disseminated grains within the coals. Pyrite, calcite, and gypsum are found largely as sheet-like growths along cleat surfaces. Gypsum is present on outcropping coals and in shallow cores, probably the result of weathering. At present, none of the zones can be characterized based on mineral content.

Chemical analyses

The chemical analyses run on the coals from the Salt Lake coal field include the major oxides (SiO_2, Al_2O_3, TiO_2, CaO, MgO, K_20, Na_2O, P_20_5) and the water-soluble alkalies. The major oxides for the three zones do not differ greatly. There are not enough samples from the Antelope zone to allow meaningful comparisons. The Cerro Prieto and Rabbit zones differ only in the amounts of SiO_2 and $A1_20$, present. Use of Student's distribution shows that only the $A1_20$, values appear to be from different populations, making the Cerro Prieto zone slightly richer in aluminum than the Rabbit zone. This could be explained by an increase in kaolinite in the Cerro Prieto zone coals over that present in the Rabbit zone. The estimated ash fusion temperatures are uniform, averaging approximately 2,700°F, due to the uniform nature of the mineral content of these two zones.

The water-soluble alkalies differ considerably between the Cerro Prieto and Rabbit zones. The water-soluble sodium in the Cerro Prieto zone is significantly higher (0.05+ / —0.03%) than that present in the Rabbit zone (0.03+/-0.01%). Water-soluble potassium is approximately equal, averaging 0.003+ /-0.003% for the Cerro Prieto zone and 0.004+ /-0.002% for the Rabbit zone. Table 3 gives a statistical breakdown of the major-oxide analyses. The alkali content of the water in this coal field averages 0.021+/-0.1%a (McGurk and Stone, 1986), considerably less than the water-soluble alkali content of the coals; the local water thus could be used to remove some of the alkali content of the coals to establish a better control on the ash-fusion characteristics of these coals.

A statistical summary of the trace-element content of the Cerro Prieto and Rabbit coal zones is presented in Table 4. Trace-element averages for both the Menefee and Fruitland Formations are provided for comparison. These two coal zones do not differ in the average concentration of any element except manganese and vanadium. The Cerro Prieto zone has a notably higher average (122+/-115 ppm) of manganese than does the Rabbit zone (62+/-40 ppm). Vana-

TABLE 3—Major-oxide analyses of Salt Lake coal zones (whole-coal basis). All values in percent.

	Antelope			Cerro Prieto			Rabbit		
	No.	Mean	S.D.	No.	Mean	S.D.	No.	Mean	S.D.
SiO_2	3	9.31	6.22	44	9.64	4.38	32	8.27	3.39
Al_2O_3	3	2.88	0.69	44	4.35	2.21	32	3.57	1.57
Fe_2O_3	3	1.03	0.54	44	0.74	0.56	32	0.61	0.34
TiO_2	3	0.23	0.11	44	0.25	0.14	32	0.21	0.10
CaO	3	0.54	0.09	44	0.72	0.46	32	0.74	0.42
MgO	3	0.09	0.02	44	0.10	0.07	32	0.09	0.03
Na_2O	3	0.13	0.06	44	0.14	0.40	32	0.11	0.37
K_2O	3	0.07	0.44	44	0.05	0.05	32	0.04	0.05
P_2O_5	3	0.01	0.00	44	0.02	0.01	32	0.02	0.01
HNa	3	0.079	0.008	32	0.05	0.03	12	0.03	0.01
HK	3	0.003	0.001	32	0.003	0.003	12	0.004	0.003
B/A	3	0.19	0.14	44	0.13	0.06	32	0.15	0.13
Eq. Si	3	81.10	13.10	44	85.40	5.14	32	84.00	8.00

HNa = water soluble sodium
HK = water soluble potassium
B/A = Base/acid ratio
E. Si = Equivalent silica

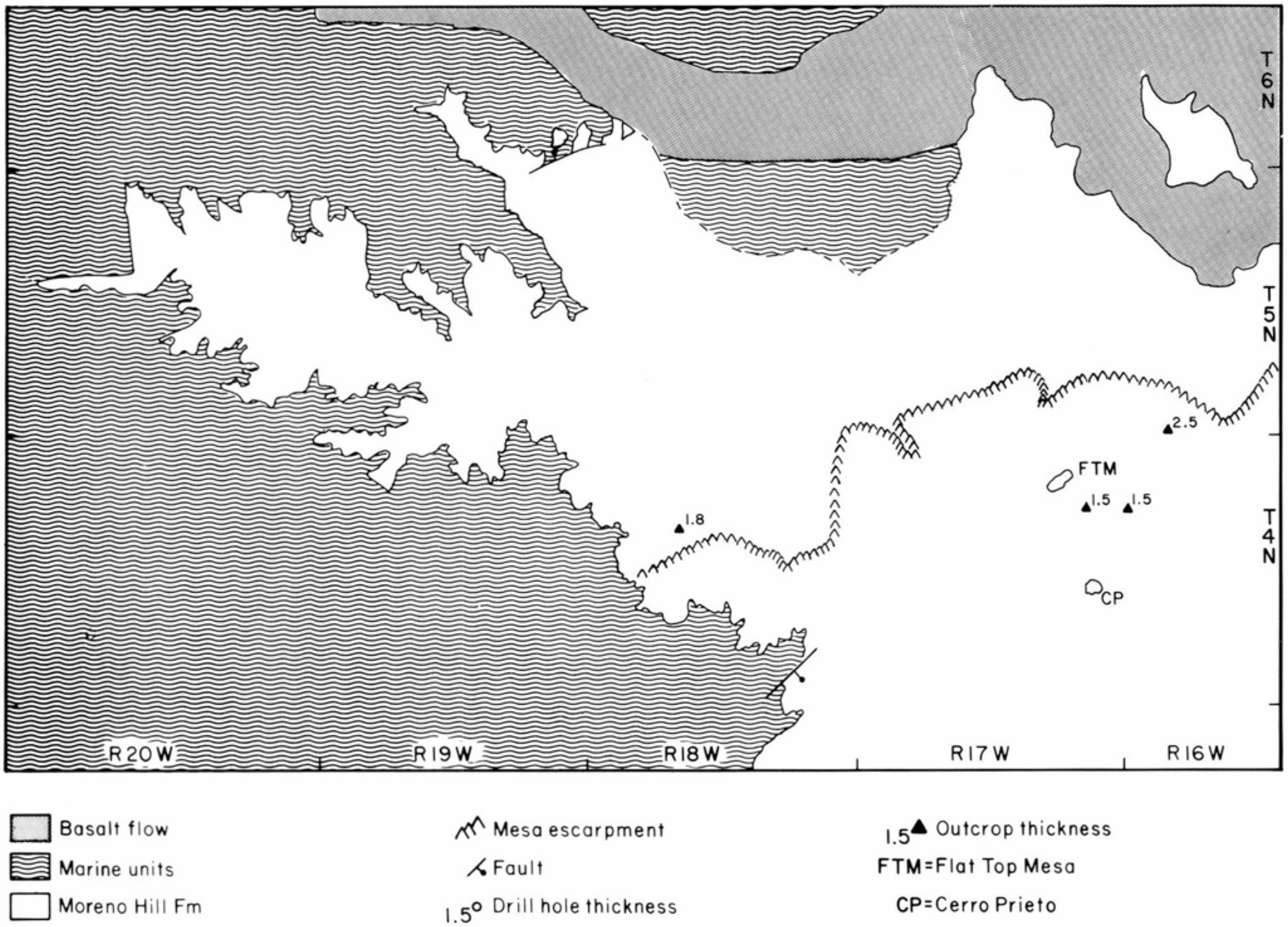

FIGURE 6—Distribution of Twilight zone coals.

dium in the Rabbit zone is significantly higher (18+/-15 ppm) than that present in the Cerro Prieto zone (10+/-7 ppm). The chlorine content of these two coals is similar, with the Cerro Prieto zone coals being slightly higher (171+/ —96 ppm) than those of the Rabbit zone (160+1-60 ppm). Fluorine values are essentially the same for both, with the Cerro Prieto zone coals averaging 134+/-28 ppm and the Rabbit zone coals averaging 135+/-52 ppm. Trace-element concentrations for the Salt Lake coals are generally lower than those found in either the Menefee or Fruitland Formation coals.

Conclusions

The major coal-bearing formation in the Salt Lake coal field is the Moreno Hill Formation. This and the other Cretaceous units show a regional dip of approximately 5° to the southeast. The major area of faulting is in the Santa Rita Mesa area. Faulting has little influence in the eastern part of the field, where the coals of the lower Moreno Hill Formation have the greatest stripping potential.

TABLE 4—Trace-element analyses of Salt Lake coal zones (whole-coal basis). All values in ppm.

	Cerro Prieto			Rabbit			Menefee			Fruitland		
	No.	Mean	S.D.	No.	Mean	S.D.	No.	Mean	S.D.	No.	Mean	S.D.
Be	14	2	2	16	2	1	33	2	1	55	4	2
Cl	14	171	96	16	160	60	0	0	0	0	0	0
Cr	14	8	6	16	9	7	33	13	9	55	17	16
Cu	14	12	6	16	10	5	33	8	5	55	11	4
F	14	134	28	16	135	52	0	0	0	0	0	0
Li	14	4	3	16	6	4	33	3	2	55	10	3
Mn	14	122	115	16	62	40	33	37	63	55	17	17
Ni	14	4	3	16	4	2	33	6	3	55	16	7
Pb	14	5	3	16	7	6	33	5	3	55	7	8
Sr	14	60	55	16	50	30	33	65	43	55	105	69
V	14	10	7	16	18	15	33	14	9	55	33	13
Zn	14	6	5	16	5	4	33	4	9	55	19	13

The northern half of the Salt Lake coal field contains an estimated 480 million tons of coal. This reserve occurs in four coal zones in the Moreno Hill Formation. These zones are (ascending) the Antelope, Cerro Prieto, Rabbit, and Twilight. The Antelope zone has only 103 million tons of coal, with high stripping ratios (66:1). No reserves were calculated for the Twilight zone due to a lack of data. The Cerro Prieto and Rabbit zones have the greatest mining potential. The Cerro Prieto zone has a demonstrated reserve of 247 million tons with an average stripping ratio of 23:1. The Rabbit zone has a demonstrated reserve of 130 million tons, with an average stripping ratio of 21:1.

The chemical characteristics of these coals are uniform. Both the total sulfur and pyritic-sulfur content are low for the two major coal-bearing zones. Only in the Antelope zone are these two parameters significantly higher. The Rabbit zone has the lowest ash content of these coals, although the MMFBTU values are similar. Analyses of the major oxides show similaritites for all parameters except SiO_2, which is higher in the Cerro Prieto zone. The estimated temperature at which the ash achieves a 250 poise viscosity is the same for both the major zones and quite uniform within each zone.

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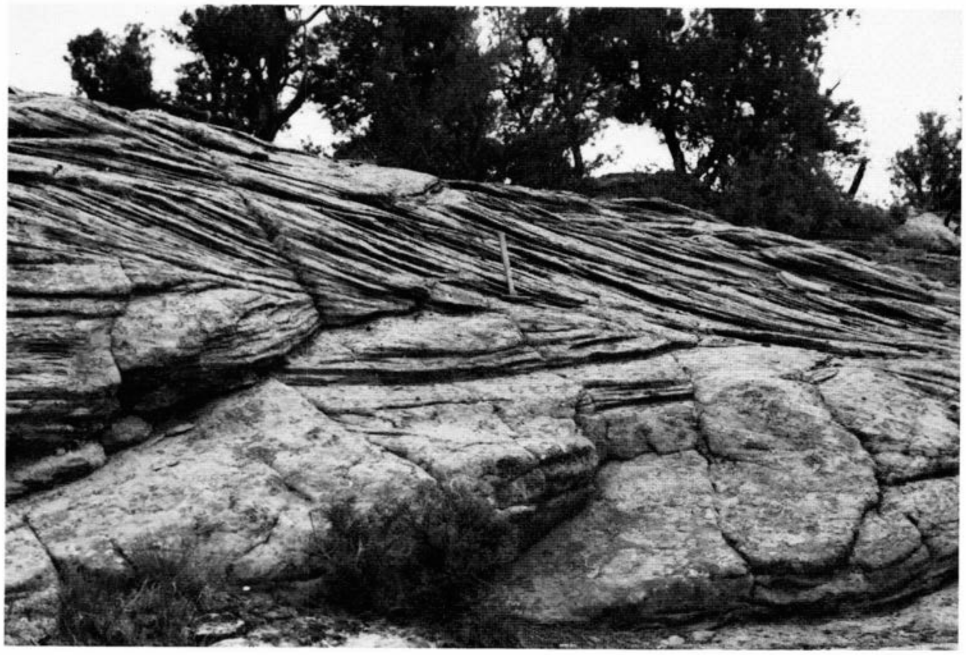

Trough crossbeds in Dalton Sandstone Member of Crevasse Canyon Formation, Hogback area, Gallup, New Mexico. Photo O. J. Anderson.

Hydrogeologic considerations in mining, Nations Draw area, Salt Lake coal field, New Mexico

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Abstract—The Nations Draw area, in west-central New Mexico, has been the focus of considerable coal leasing and exploration. The major leaseholder, Salt River Project (Phoenix), began operations in 1987 with a pilot mine. Prior to mining, the New Mexico Bureau of Mines & Mineral Resources made a detailed hydrogeologic study of the surrounding region. This paper summarizes that work, emphasizing implications for mining in the leasehold.

The water table lies at depths ranging from <20 ft in valleys to >900 ft beneath mesas. Major aquifers to be disturbed by mining include alluvium (Quaternary) and the Moreno Hill Formation (Cretaceous). The alluvium is 0-190 ft thick and consists of a fine-grained upper unit and a basal sand and gravel. Saturated thickness ranges from 0 to 79 ft. Transmissivity ranges from approximately 7 to >900 ft^2/day. Water is most suitable for stock watering, the main current use. In most places the Moreno Hill consists of three members, all of nonmarine origin: two coal-bearing sequences divided by a sandstone. Mineable coal is in the lower member. Both rock and saturated thickness range from 0 to 1,200 ft. Transmissivity of sandstones above and below the coal range from 1.25 to nearly 460 ft^2/day. The Moreno Hill supplies domestic and stock water throughout the region.

This hydrogeologic setting has several major implications for mining. Dewatering will be required, but pit inflow rate is expected to be on the order of 100 gpm after 30 days, declining continually after that. Pit-floor heaving is unlikely in most places. Water required for mining can be readily obtained from dewatering and production wells in the alluvium and Dakota Sandstone. Mining is not expected to impact the level or quality of water in existing wells. Hydrologic balance will be disturbed by mining, but specific impact cannot be determined until reclaimed ground is tested. Ultimate impact will depend on the life of the larger production mine.

Introduction

Nations Draw is a west-flowing ephemeral stream in west-central New Mexico. In recent years the area around it has been the site of considerable coal leasing and exploration activity. This includes geologic mapping and/or drilling by the New Mexico Bureau of Mines & Mineral Resources (NMBMMR), the U.S. Geological Survey (USGS), and private companies. The major leaseholder is Salt River Project (SRP), Phoenix, who plans to utilize coal from this area in its St. Johns, Arizona, power plant. As of May 1987, SRP was operating a pilot mine in the area.

Prior to mine planning, considerable geologic and hydrologic data had been collected or published separately, but no comprehensive picture of the hydrogeology of the area existed. Thus, in 1985, the NMBMMR conducted a study to formulate a conceptual hydrogeologic model of an eight-quadrangle (7.5') region to assist mine planners and regulatory personnel alike (McGurk and Stone, 1986). The purpose of this paper is to give a brief summary of that work, with special emphasis on implications for coal surface mining in the leasehold.

Acknowledgments

The regional conceptual-model study was funded under contract with SRP. They also granted access to their leasehold and provided selected geologic and hydrologic data, some of which were proprietary. USGS data were provided by Joe Baldwin and Robert Myers. BLM data were provided by Carol Marchio.

Regional setting

In this report, "Nations Draw region" refers to the area studied by McGurk and Stone (1986), whereas "Nations Draw area" refers to those portions of the Cerro Prieto and Tejana Mesa 7.5' quadrangles shown in Figs. 1 and 2. The nearest settlement is the village of Quemado, approximately 3 mi to the south. Access is by state highways 32 or 117 **and** unpaved roads.

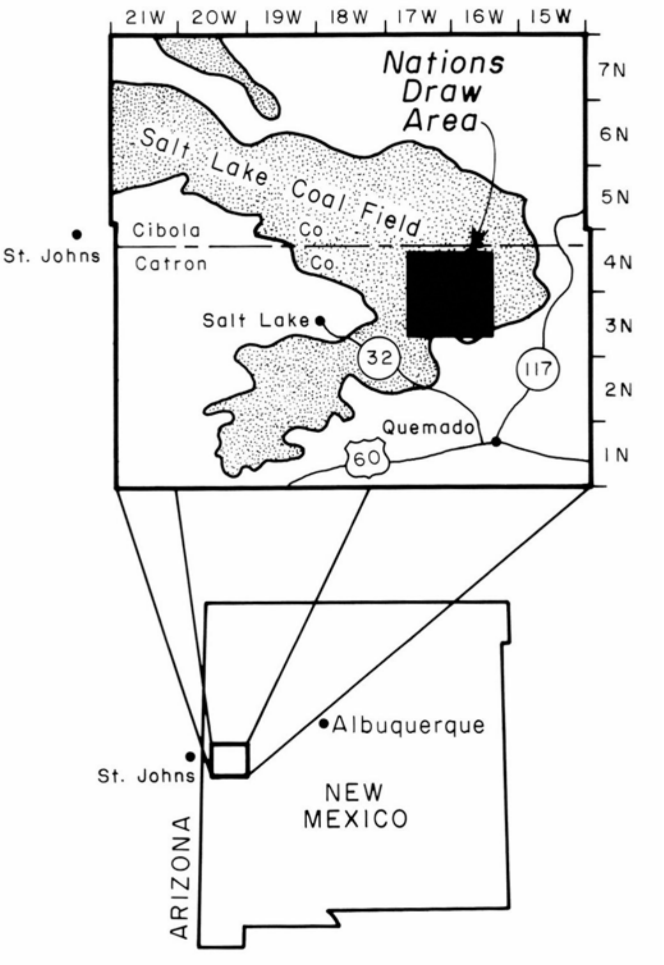

FIGURE 1—Location of Nations Draw area; scale given by township and range.

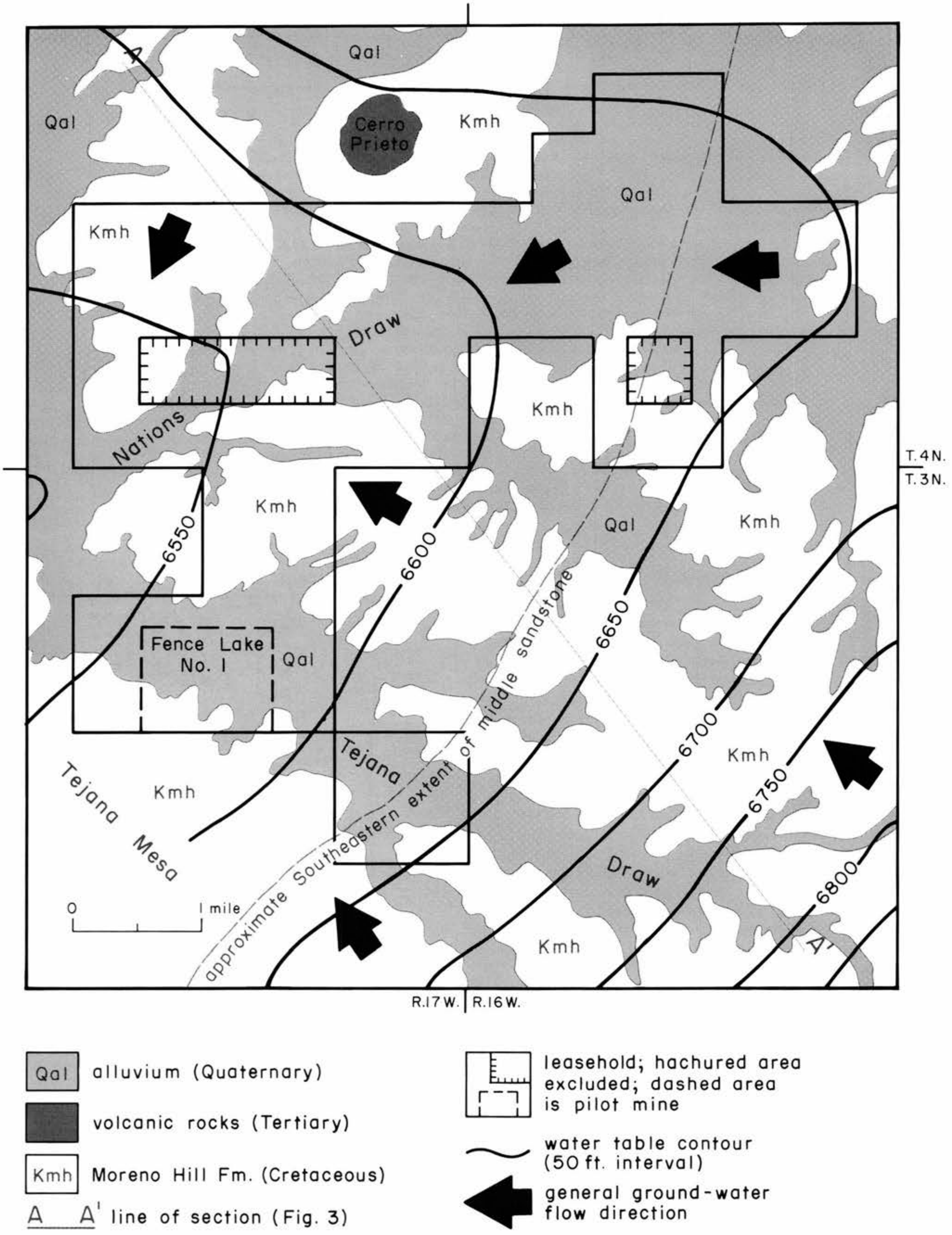

FIGURE 2—Hydrogeologic map of Nations Draw area (modified from McGurk and Stone, 1986, pls. 2, 5).

Physiography and climate

The Nations Draw area lies within the Zuni—Acoma section of the Colorado Plateau physiographic province. Topography is characterized by broad ephemeral stream valleys, volcanic necks, and broad mesas with gently sloping tops. Elevation of the land surface rises gradually toward the east. Local relief of up to 800 ft occurs near mesas. Maximum relief across the area approaches 1,000 ft.

The area is drained by west-flowing ephemeral streams. These feed into Carrizo Wash, a tributary of the Little Colorado River. The continental divide lies approximately 10 mi to the east.

The climate is arid to semiarid, with average annual precipitation ranging from 9 to 15 in. (Johnson, 1985; Morris and Haggard, 1985). Half the annual precipitation is associated with summer thunderstorms. Potential evaporation is roughly three times the precipitation at 31.04 in. (Gabin and Lesperance, 1977).

Geology

Cretaceous coal-bearing deposits (Moreno Hill Formation) lie at the surface in the area (Fig. 2). Tertiary sedimentary strata (Baca and Fence Lake Formations) and volcanic rocks (Spears Formation) cap these deposits at higher elevations near the continental divide to the east. Deep petroleum tests have penetrated Triassic and Permian sedimentary rocks beneath the Cretaceous strata. Precambrian was reached at depths of approximately 4,000-6,000 ft. Alluvium (Quaternary) covers the broad valley floors.

Structure is relatively simple. Regional dip is gentle at <5° to the southeast. Locally steeper dips (<10°) occur near Tertiary volcanic features. The Tejana Mesa fault zone, a northeast-trending zone of high-angle, normal faults crossing the southeastern corner of the area, causes 250 ft of stratigraphic throw in places (Guilinger, 1982).

Hydrology

Recharge occurs directly from precipitation on higher elevations or by transmission loss along ephemeral stream channels. Rates have been estimated at 0.05 in./yr in bedrock settings, and 0.08 in./yr in alluvial fill settings, based on a chloride mass-balance approach (Stone, 1984b). Chloride data also suggest the region was wetter 7,000-13,000 yrs ago (Stone, 1986).

Although water could be obtained from any of the Cretaceous sandstones and even the San Andres Limestone/Glorieta Sandstone (Permian), most wells in the area are screened in the shallower sandstones of the Moreno Hill Formation and/or the alluvium. Depth to regional water table ranges from less than 20 ft in the major valleys in the west to more than 900 ft beneath higher elevations such as Tejana Mesa (Fig. 2). Perched-water bodies may occur at shallower depths in some localities on mesas. This usually occurs where sandstone is underlain by mudstone.

Fig. 3 is a hydrogeologic cross section of the area around the leasehold and Fig. 4 shows the hydrogeologic units on a regional scale. The Permian and Triassic units are part of a deep flow system. Those Cretaceous units below the Moreno Hill Formation represent an intermediate flow system. The Moreno Hill and alluvium constitute a shallow flow system. Flow in the shallower system is from upland recharge areas toward and then beneath valleys (Fig. 2).

Hydrologic characteristics of units in leasehold

As mining activity will be confined to SRP's leasehold, this discussion is restricted to water-bearing units likely to

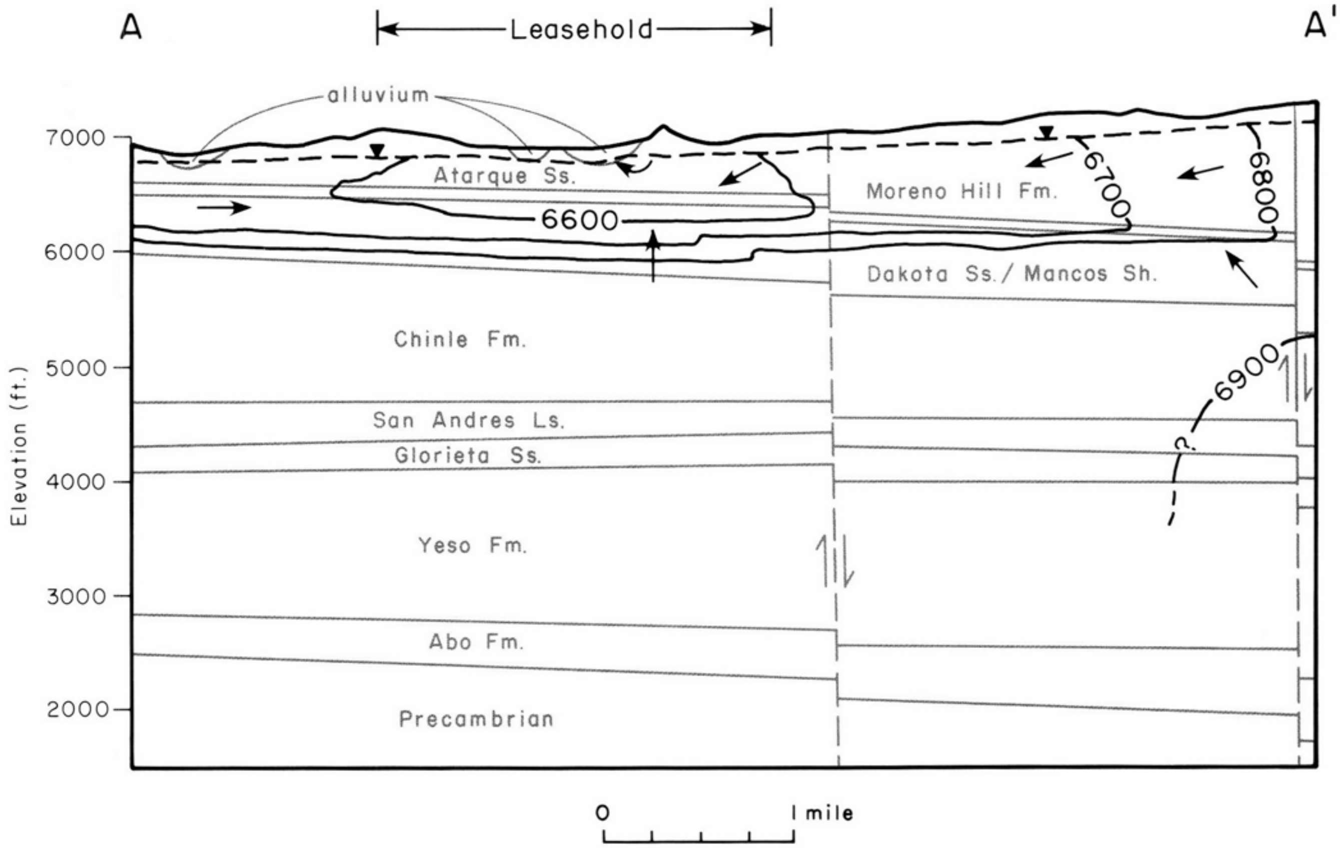

FIGURE 3—Hydrogeologic cross section of Nations Draw area showing generalized equipotential contours and flow directions (modified from McGurk and Stone, 1986, pl. 3).

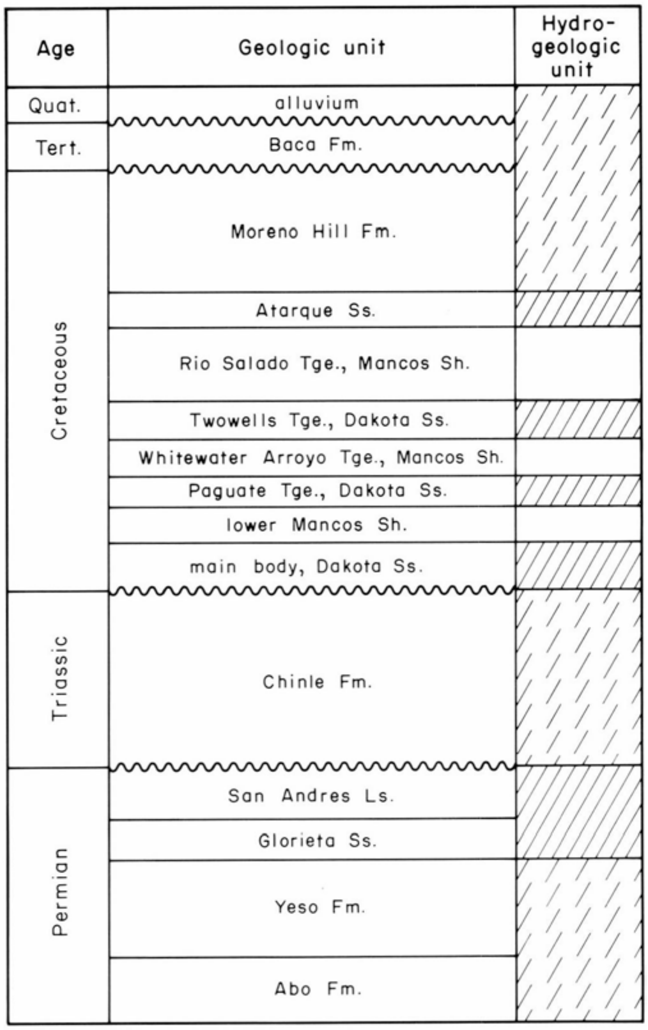

FIGURE 4—Regional hydrogeologic units in Nations Draw area (McGurk and Stone, 1986). See Fig. 5 for explanation of symbols; not to scale.

be disturbed there. These include the alluvium and Moreno Hill Formation (Fig. 5). For hydrologic characteristics of other units see McGurk and Stone (1986).

Alluvium (Quaternary)

Unconsolidated deposits of gravel, fine- to coarse-grained sand, silt, and clay occur along ephemeral-stream valleys in the area. The alluvial fill is usually characterized by two distinct units. The upper layer includes 0-130+ ft of light-brown sand, sandy clay, with gray, sticky clay at the bottom. The basal unit consists of up to 80 ft of buried valley deposits of coarse sand and gravel. The gravel is composed of large, angular, rock fragments near the bottom and volcanic cinders near the top. This unit is continuous within buried valleys, but not necessarily beyond their boundaries. Between the sand and gravel and the underlying Moreno Hill Formation there is usually a thin interval of very fine-grained alluvium or weathered bedrock. Maximum known thickness of the alluvium is 190 ft near the confluence of Frenches and Nations Draw.

The alluvium is probably saturated in the center of Nations Draw. Saturated thickness in this valley ranges from 0 to 79 ft, the maximum occurring 1 mi southeast of Cerro Prieto windmill. In Tejana Draw saturated thickness ranges from 0 to 55 ft, with the maximum located approximately 1 mi southeast of Tejana windmill (McGurk and Stone, 1986, pl. 11).

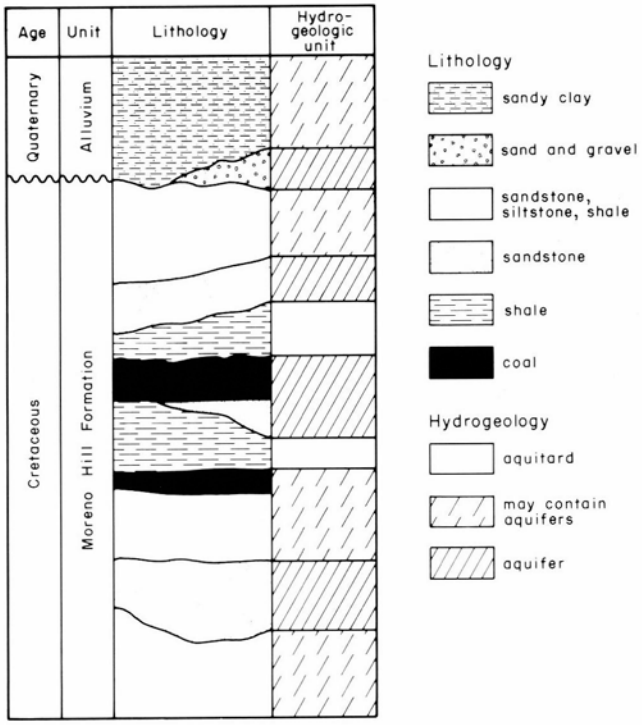

FIGURE 5—Typical hydrogeologic units in leasehold; not to scale (McGurk and Stone, 1986, figs. 8, 9).

SRP has completed one production well and seven observation/monitoring wells in the basal sand and gravel on their leasehold. A 15 day yield of 200 gpm has been projected for the production well (SRP, 1986). A specific capacity of 5.7 gpm/ft of drawdown was obtained from pumping 350 gpm for 1 hr. Transmissivity and horizontal hydraulic conductivity values are given in Table 1. Storativity at one well tested by SRP is 0.000337, indicating that the sand and gravel are confined or semiconfined by the overlying fine-grained unit.

Specific conductance values for water from the alluvium range from 211 to 1,093 µmhos/cm. Analyses plot in the sodium-bicarbonate fields on a trilinear diagram (Fig. 6). Water from the alluvium is suitable for use by livestock, but only marginally suitable for human consumption. It is unsuitable for irrigation. Main existing use of water from the alluvium is stock watering.

Moreno Hill Formation (Cretaceous)

Nonmarine sandstones, mudstones, claystones, and coal of the Moreno Hill Formation crop out over all the lease-

TABLE 1—Average transmissivity (T) and horizontal hydraulic conductivity (Kxy) for major lithologic units in the leasehold (McGurk and Stone, 1986).

Lithologic Unit (no. of tests)[1]	Ave. T (ft^2/day)[2]	Ave. Kxy (ft/day)[2]
ALLUVIUM		
sd/gvl (2)	263.5-909.2	7.5-14.66
sd ? (1)	41.2	2.06
sdy cly (1)	6.8	0.34
MORENO HILL FORMATION		
ss, ba (1)	63.0	2.10
ss, ac (1)	458.7	10.20
sh, ac (1)	3.6	0.14
coal (5)	2.0-39.2	0.20-4.36
ss, bc (10)	1.25-457.5	0.12-13.42

[1] sd/gvl = sand and gravel; sd? = probably sand; sdy cly = sandy clay; ss = sandstone; sh = shale; ba = below alluvium; ac = above coal; bc = below coal.

[2] arithmetic average of values determined by various methods.

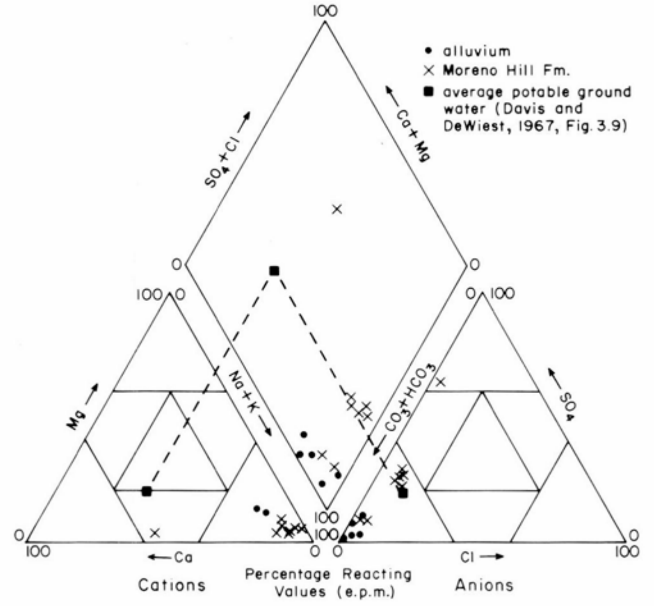

FIGURE 6—Trilinear diagram showing major ions in ground water from alluvium and Moreno Hill Formation (modified from McGurk and Stone, 1986, figs. 3, 4).

hold, except where covered by alluvium. These strata represent deposition in meandering to braided fluvial systems. In the western third of the Nations Draw region, the Moreno Hill is easily divisible into three members based on the presence of a middle sandstone unit. In the study area, the upper member (0-600 ft thick) is present only on Tejana Mesa and as scattered erosional remnants in the area covered by Cerro Prieto quadrangle. It is dominated by yellow and green siltstones and claystones with minor amounts of carbonaceous shale, coal, and ledge-forming sandstones (Campbell, 1984). The distribution of the middle member (0-80 ft thick) is similar to that of the upper member. This unit is a pinkish-yellow, medium- to coarse-grained, cross-bedded sandstone with little or no silt or clay matrix. The middle member pinches out in the subsurface along a northeast—southwest-trending line (Fig. 2). East of that line the Moreno Hill is not easily subdivided. The lower member (0-600 ft thick) occurs over a broader area than the other two, lying at the surface in much of the Cerro Prieto, Fence Lake SE, and Lake Armijo quadrangles. It is lithologically similar to the upper member except that sandstones, carbonaceous shale, and coal are more abundant.

The mineable coal seams occur in two zones within thelower member. The lower of these, the Cerro Prieto zone, lies approximately 200 ft below the top of the lower member. This zone is the main target in SRP's leasehold (Greenberg et al., 1984). More specifically, mining will involve two of the three coal seams in the Cerro Prieto zone (SRP, 1986).

The upper and middle members are above the regional water table throughout their extent. Thus, the saturated thickness of the Moreno Hill Formation in the area where the formation is subdivided is essentially that of the lower member. Saturated thickness thus ranges from zero in the northwestern part of the Nations Draw region to 1,200 ft in the southeast, where regional dip takes the entire formation (undifferentiated) below the water table.

Hydraulic properties of the various materials in the Moreno Hill Formation have been estimated from results of slug and pumping tests conducted by SRP (Table 1). Coals are usually characterized by fracture porosity, however, this was detected in only one of the slug tests. Application of a procedure described by Schwartz (1975) showed that although fractures account for only 3% of the total porosity of one of the Moreno Hill coals, they account for 20 times the conductivity of the matrix. Yields of Moreno Hill wells range from <1 gpm to 20 gpm.

Specific conductance of water from the Moreno Hill Formation ranges from 211 to 1,250 µmhos/cm. Most analyses plot in the sodium-bicarbonate or calcium-bicarbonate fields (Fig. 6). Some waters have subequal amounts of calcium, sodium, bicarbonate, and sulfate. Shallower sandstones in the Moreno Hill provide water for stock and domestic use throughout the Nations Draw area. Some wells are open to both the alluvium and Moreno Hill. Deeper sandstones, such as that below the coal, produce water unsuitable for human consumption.

Implications for mining

In April 1986, SRP applied for and subsequently obtained permission to operate a pilot mine, the Fence Lake No. 1, covering approximately one section in Tejana Draw (Fig. 2). At the time of preparing this paper, only the pilot mine was in operation and permit application materials for a larger-production mine were not available. Thus, information given here is drawn from the regional hydrogeologic study (McGurk and Stone, 1986) or the pilot-mine plan (SRP, 1986).

This hydrogeologic setting has several implications for mining. Three general areas of concern regarding water and coal surface mining in the Nations Draw area are recognized: 1) dewatering, 2) water supply, and 3) hydrologic balance. Several specific concerns are recognized under each of these broader topics.

Dewatering

Two important questions in mine planning relate to dewatering. Is the coal sufficiently saturated or below water table to produce significant pit inflow? Is dewatering likely to lead to pit-floor heaving?

The entire hydrogeologic system must be examined in evaluating dewatering. Presumably mining will proceed in a downdip (southeasterly) direction. However, in many places water table slopes in the opposite direction (toward drainage). Thus, saturated thickness increases faster than would be expected from dip alone (Fig. 3). Also, even for similar saturated thicknesses, pit inflow rate can vary with geology (Fig. 5). More water drains from sandstones than from fine-grained rocks. Maps showing saturated thickness of sandstone above and below the coal, prepared for the regional study (McGurk and Stone, 1986, pls. 22, 23), show that the proportion of sandstone in the saturated zone is quite variable.

Vertical gradients were estimated at multiple well-monitoring sites using static-water elevations. Downward gradients are indicated at four sites, upward gradients at four others, and gradients in both directions are indicated at three points. The total range of values is —0.366 to + 0.187 (McGurk and Stone, 1986).

Four potential sources of pit inflow were recognized by SRP (1986) in their permit application for the Fence Lake No. 1 mine: the alluvium, the coal and bedrock overburden, sandstone below the coal, and precipitation. SRP calculated potential pit inflows using mainly the analytical method of McWhorter (1981). Alluvium will only be intersected in the last stages of the pilot-mine operation. Pit inflows will be higher initially, then decline as mining proceeds. More specifically, total inflow from alluvium was estimated to be 101 gpm after 30 days, 41 gpm after 6 months, and 29 gpm after 1 yr, assuming a 1,000 ft long pit. For the same pit size, inflow from the coal and bedrock overburden would be 3.9 gpm after 30 days. The sandstone below the coal would reportedly yield an inflow rate of only 2.1 gpm if the entire acreage of the pit were opened instantaneously. Dewatering due to precipitation should also be minimal as several diversions and control structures are planned to divert runoff. Thus, the only precipitation which may end up in the pit is that falling directly on it. In view of the arid setting, this is not perceived as a problem.

Pit-floor heaving is potentially a problem only when artesian pressure of an underlying aquifer exceeds twice the thickness of strata between the aquifer and the bottom of the overlying pit (Terzaghi and Peck, 1967). At Fence Lake No. 1, this interval is generally 30 ft thick. Thus, 60 ft of artesian pressure or more is required to induce heaving. This corresponds to a pit-floor elevation below 6,555 ft. As the pit floor of Fence Lake No. 1 will be above this elevation in most areas, heaving is not a major problem.

Water supply

Four concerns are associated with water supply and mining. Is there a water source of sufficient quantity in the area for projected mining needs? Does this source yield water of suitable quality? Will extraction of water for mining (pumping production wells and dewatering) impact existing water levels in the area? Will mining impact the quality of area water?

Surface water is not a major water source in this arid setting. Also, the area contains no alluvial valley floors (Love and Hawley, 1984). Thus, mining will have no impact on these types of systems.

Estimated requirements for the pilot mine (Fence Lake No. 1) were 18,900 gpd, 240 days/yr (SRP, 1986). Adequate quantities and qualities of ground water are readily available locally. SRP has constructed production wells in both the alluvium and Dakota Sandstone. Primary sources of supply include a well in the alluvium and pit inflow. Secondary sources include another well in the alluvium and the deep Dakota well. Well water was reserved for drinking and sanitary purposes; water from the pit was to be utilized for dust control.

SRP has water rights to 50 gpm for their primary well in the alluvium and to 300 gpm for the Dakota well (SRP, 1986). To meet drinking and sanitary needs, the alluvium well could reportedly be pumped at 13 gpm, continually for the 5 yr life of the pilot mine. After 5 yrs of pumping at this rate there would be a maximum drawdown of 14 ft in the pumping well and a drawdown of 5 ft approximately 100 ft from the well (SRP, 1986). Little interaction is expected between the pumping of the production well and pit dewatering. Mining should not impact water levels in any existing wells (SRP, 1986).

Mining can impact pH, electrical conductivity, and sodium-adsorption ratio. SRP installed 47 monitoring wells over an 18 mil area in the coal as well as material above and below it (Siefert and Greenberg, 1985). No significant change in ground-water quality is expected as a result of mining at Fence Lake No. 1 (SRP, 1986).

Hydrologic balance

All mining activities disturb the hydrologic balance, at least during the life of the mine. Diversion structures may enhance or retard runoff and recharge. Stripping of topsoil and excavation of the pit may reduce evapotranspiration and recharge while increasing runoff. Construction of roads and buildings generally increases runoff and decreases recharge.

Reclamation may restore some of the hydrologic balance parameters to near premining conditions. Post-mining studies will have to be made to evaluate this. Fortunately, much information has already been gathered. For example, a preliminary assessment of pre-mining recharge has been made (Stone, 1984b). Recharge studies elsewhere in the San Juan Basin (Stone, 1984a, 1985, 1986, in prep.) show that there are methods for comparing pre- and post-mining recharge. As noted by SRP (1986), disturbances at Fence Lake No. 1 will be short-lived. A larger-scale mine would presumably have a longer life and possibly greater impacts.

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Large-scale combustion test of Fence Lake coal at the Coronado Generating Station

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Abstract—Salt River Project (SRP) is considering coal from the Salt Lake coal field, Catron County, New Mexico, to fuel its Coronado Generating Station at St. Johns, Arizona. Based on Black and Veatch's study that models the combustion of the coal, the results of the bench-scale test performed by Energy & Environmental Research, and the available testing technology reflected in current industry literature, SRP decided to test-burn the coal at its generating station. In order to obtain the 100,000 tons that are required for the test burn, SRP opened the Fence Lake No. 1 mine in secs. 10 and 11 of T3N R16W, Catron County, New Mexico. The A and BC splits of the Cerro Prieto seam were mined, shipped, and stockpiled at the generating station for testing. As of June 1987, SRP was still testing and evaluating the Fence Lake coal and blends of the Fence Lake coal with other New Mexico coals. The testing is designed to evaluate potential problems with the boilers, performance of the boilers, slagging and fouling, control of particulate emissions, and the handling characteristics of the coal and ash.

Introduction

Until the June 1987 test burn at the Coronado Generating Station (CGS), St. Johns, Arizona, Fence Lake coal had never been burned at any power plant. Fence Lake coal was unique when viewed as a coal supply because no data from a full-scale combustion existed. Unlike Fence Lake coal, coals from the San Juan Basin proper and Raton Basin have been burned at power plants. So, general performance and quality data were available on these sources as future supplies of fuel for CGS. In order to obtain more data on the Fence Lake coal, Salt River Project (SRP) opened the Fence Lake No. 1 mine in Catron County, New Mexico. The location of the mine and CGS are shown in Fig. 1. SRP mined 100,000 tons that were allocated for testing.

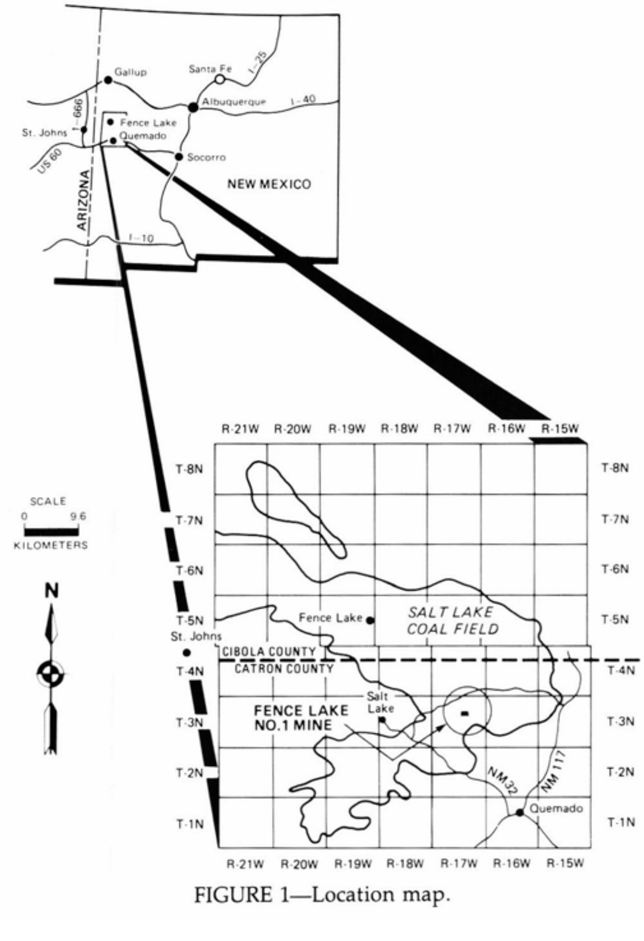


FIGURE 1—Location map.

Recommendations by SRP's consultants from previous studies of Fence Lake coal played a major role in SRP's decision to open a small mine in order to test-burn the coal. Black and Veatch Engineers (B&V) modeled a burn of Fence Lake coal from the quality data from SRP's 1982 exploration program. The 1983 report recommended a test burn of Fence Lake coal at CGS so SRP could determine if any fouling problems which may exist could be adequately controlled. B&V suggested that SRP explore problems with respect to mill and precipitator performance and the handling of fly ash.

Slagging, fouling, poor precipitator performance, and poor handling of ash all are major problems that may have serious economic consequences. Slagging causes problems when these furnace deposits cannot be removed without dropping the load. Fouling is considered a problem when the plant must use soot blowers to remove these hard deposits on the superheater tubes. Experiments have been done to gather proof that fouling and slagging are not predictable from ash-fusion data. The mixture of ash minerals in each coal particle will determine the fusion temperature of ash from that particle, and different particles that may contain different constituents. The loss-of-boiler availability from slagging-related problems is very costly to the utility industry (Batelle, 1980).

At CGS, electrostatic precipitators are used to control the emissions of total and fine particulates from the boilers. The efficiency of the precipitators is largely dependent on the electrical resistivity of the dust particles of the electrical fields. According to *Coal Preparation* (Leonard, 1968), each potential application should be carefully studied as each type of dust presents different problems.

Because coal is pulverized in a mill before it is burned, coal quality can impact the mill with respect to increased fires in the mill, increased power consumption by the mill, coal-handling problems, mill reject levels, and mill deposits (EER, 1986). Therefore, it is recommended that the performance of the mill is evaluated during a test burn.

Energy & Environmental Research (EER) burned twelve tons of Fence Lake coal to assess relative performance of the coal and blends of the Fence Lake coal from bench-scale tests during 1986. EER recommended a large-scale test burn at CGS. They stated that bench-scale or pilot tests just screen the coals for the specific coals that the utility company is willing to test in their boilers. According to EER, coal always should be tested in boilers because all coals, even from the same general area, are different from each other in regard to performance.

Literature review

The literature in the coal industry, as well as SRP's consultants, recommended large-scale sampling. According to the industry references, the tests conducted on the exploration samples provide information on the coal available as well as on the characteristics of the coal that affect its recovery, beneficiation, and use. However, before the design of the preparation plant has been made final and the use of the coal established, large-scale sampling is necessary. These samples, representing the full seam to be mined, are large enough to require that they be obtained from operating mines, pits, outcrop opening, or development shafts (Leonard, 1968).

Mineral Impurities in Coal Combustion (Raask, 1985) discussed the fact that mineral matter in coal plays a dominant role in the selection of fuels, design of the furnace, and how the furnace will be operated. The aim of this book was to dose the gap between "practice" and "research." Raask stated that the state of the art in predicting ash behavior is based largely on empiricism. The application of these empirical measurements to predict the behavior of an unfamiliar coal in a given furnace is often unreliable.

Effects of Coal Quality on Power Plant Performance and Costs, published in 1986 by Electric Power Research Institute (EPRI), reviewed the current procedures for evaluating the effects of coal quality on performance of power plants. It also identified the status of the science of coal combustion in relation to processes in power plants. It highlights the conclusion that the state of the art is a test burn. The book relates the results of test burns at several plants.

Influence of Coal Mineral Matter on Slagging of Unit Boilers, published by EPRI (1980), explored the role of coal minerals in boiler slagging and fouling. EPRI conducted large-scale test burns at five boilers and made field measurements.

Bryers' (1983) *Fouling and Slagging Resulting from Impurities in Combustion Gases* addressed the problems associated with ash. Experiments reproduce fouling and slagging in the utilities' large boilers under laboratory conditions of experimental furnace designs, firing rates, configuration, and modeling parameters, and interpret the results and the relationship to real-life systems.

Bryers (1977) addressed corrosion in *Ash Deposits and Corrosion Due to Impurities in Combustion Gases.* External corrosion of boiler tubes and gas turbine blades caused by the inorganic matter in fuels has been a problem for many years.

EPRI (Meteorology Research, Inc., 1983) took field measurements at a test burn at the San Juan Unit No. 1 near Farmington, New Mexico. The report, *Evaluation of Electrostatic Precipitator Performance at San Juan Unit No.* 1 presented the results of an extensive evaluation of a hot-sided electrostatic precipitator that is similar to the one at CGS.

EPRI (Southern Research Institute, 1985) published information about test burns at the Martin Drake Unit 6, Ray D. Nixon Unit 1, Cherokee Unit 3, Cameo Unit 2, and Arapahoe Unit 3 in *Field Tests of Fabric Filters on Full-Scale Coal-Fired Utility Boilers.*

Because test burns are considered the state of the art technology, many utility companies test-burn coal before they purchase it. New coal supplies may cause problems with existing systems. For example, in the past, Detroit Edison burned high-sulfur coal and switched to a western, low-sulfur coal. The new coal supply produced more fines and, therefore, more dust which caused many fires. As a result, the utility company spent more money on fire protection systems. There are several utilities who have test-burned or are planning to test-burn coal. Omaha Public Power District found from a test burn of Powder River Basin coal that another Powder River Basin coal located only 20 mi away had a completely different effect on their hot-sided precipitator. The Public Service Company of Oklahoma's Units 3 and 4 were designed to burn Powder River Basin coal. They recently test-burned an Oklahoma supply of coal. Public Service Company of New Mexico is planning a test burn of coal at their San Juan plant. Farmers Electric Coop test-burns fuel in their Hugo Unit No. 1. Other western utilities have test-burned coal in the St. Claire Unit 4 and Tanners Creek Unit 3 (Galluzo, 1986).

Basis of SRP's decision to test-burn Fence Lake coal

SRP determined that a test burn of Fence Lake coal and blends of Fence Lake coal with other New Mexico coals was necessary to determine the impacts to CGS from the coal quality. SRP concluded that this test burn was necessary based on three sources: B&V's model, EER's tests, and the literature search of utilities' methods of determining impacts from coal quality as outlined in the previous section.

B&V modeled the potential impacts to CGS from the blends of potential coal supplies shown in Table 1.

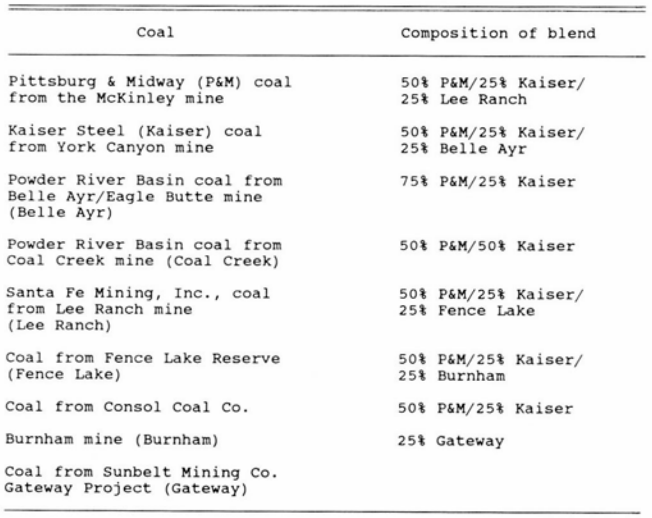
For Fence Lake coal, B&V used the results from the coal-quality analyses of the cores from SRP's 1982 exploration program. These tests were: Proximate, Ultimate, Hardgrove Grindability Index, Ash-Fusion Temperatures, Pyrites, and Ash Analysis. Other mining companies transmitted data from the mines specified in Table 1 for the B&V model. Based on their model, B&V predicted the ability of CGS to handle each specific coal type and blend. B&V evaluated the non-fuel costs associated with burning the coal. From the results of the computer model, they addressed the costs associated with, and the ability of CGS to handle, the coals listed in Table 1. They developed relative slagging, fouling, and other indices from qualitative observations and calculations, and related these results to expected impacts to the performance of the CGS equipment.

SRP wanted as large a data base as possible before committing CGS to burning Fence Lake coal as a test. So, in order to minimize the risk to the equipment of CGS and to determine any special procedures to be followed at CGS, SRP retained EER to burn 12 tons of Fence Lake coal. This coal was obtained from a small test pit located less than 0.5 mi north of the Fence Lake No. 1 mine. The coals burned during the 1986 pilot-scale combustion tests are show in Table 2.

EER tested each of the coals for the following:

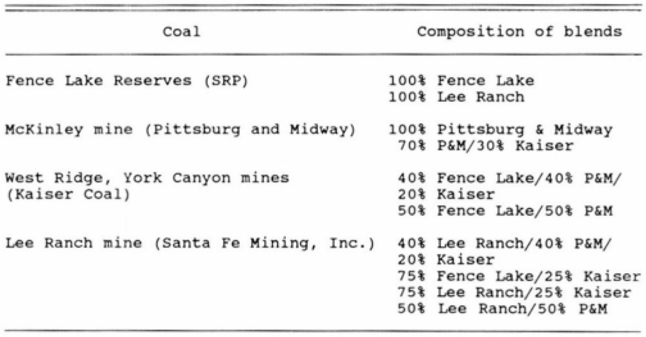
Coal characterization
Calculated indices
Mill performance
Flame stability
CGS simulation

TABLE 1—Black & Veatch model.



Coal	Composition of blend
Pittsburg & Midway (P&M) coal from the McKinley mine	50% P&M/25% Kaiser/ 25% Lee Ranch
Kaiser Steel (Kaiser) coal from York Canyon mine	50% P&M/25% Kaiser/ 25% Belle Ayr
Powder River Basin coal from Belle Ayr/Eagle Butte mine (Belle Ayr)	75% P&M/25% Kaiser
Powder River Basin coal from Coal Creek mine (Coal Creek)	50% P&M/50% Kaiser
Santa Fe Mining, Inc., coal from Lee Ranch mine (Lee Ranch)	50% P&M/25% Kaiser/ 25% Fence Lake
Coal from Fence Lake Reserve (Fence Lake)	50% P&M/25% Kaiser/ 25% Burnham
Coal from Consol Coal Co.	50% P&M/25% Kaiser
Burnham mine (Burnham)	25% Gateway
Coal from Sunbelt Mining Co. Gateway Project (Gateway)	

TABLE 2—EER pilot-scale combustion tests.



Coal	Composition of blends
Fence Lake Reserves (SRP)	100% Fence Lake 100% Lee Ranch
McKinley mine (Pittsburg and Midway)	100% Pittsburg & Midway 70% P&M/30% Kaiser
West Ridge, York Canyon mines (Kaiser Coal)	40% Fence Lake/40% P&M/ 20% Kaiser 50% Fence Lake/50% P&M
Lee Ranch mine (Santa Fe Mining, Inc.)	40% Lee Ranch/40% P&M/ 20% Kaiser 75% Fence Lake/25% Kaiser 75% Lee Ranch/25% Kaiser 50% Lee Ranch/50% P&M

Combustion performance
Slagging
Fouling
Ash-fusion temperatures
Soot-blowing cycles
Radiant flux
NO emissions and control
SO_2 emissions
ESP performance (Electrostatic Precipitator)
Erosion

From these tests EER assessed the relative performance of the different coals and blends of coal. They predicted qualitatively the expected results of a full-scale combustion test at CGS.

From the B&V reports, the results of the tests most critical to operations at CGS are related to potential problems with respect to mill and precipitator performance and the handling of fly ash. B&V determined slagging and fouling indices, but still recommended test burns to determine if slagging and fouling problems can be controlled.

EER's pilot-scale testing produced the following general results:

Inexpensively identified coals with poor combustion performance.
Provided technical assessment for coal selection.
Provided a confidence level for the boiler trail at CGS.
Specified conditions to ensure a successful boiler trial at CGS.

The results of the EER study most critical to assessing the impacts of coal quality to CGS are related to NO emissions and flame stability. Because of Fence Lake coal's high nitrogen level and low heating value, B&V's model predicted that NO_x emissions may exceed the statutory maximum allowable limits. Currently, with respect to NO_R, CGS's boiler performance is marginal. According to EER, a test burn at CGS had to be performed because it is difficult to relate the results from tests to absolute values (EER, 1986). Pilot-scale tests serve only as a first approximation (EPRI, 1986).

EER predicted problems with flame stability. According to EER, the bench-scale test of flame stability is subjective and strongly influenced by the burner characteristics and the furnace environment. For that reason the determination of flame stability in the small-scale facility, as influenced by the type of coal, can only be expected to provide qualitative comparisons between different coals. Also, it is not cost-effective to simulate the exact burner or furnace conditions for the pilot-scale tests; therefore, EER recommended a test burn to obtain quantitative comparisons (EER, 1986).

From the results, EER concluded that Fence Lake coal would perform satisfactorily in the CGS boilers during a test burn. However, differences in performance can be expected from the Fence Lake coal, Pittsburg and Midway, Kaiser, and blends of Pittsburg and Midway and Kaiser. EER emphasized that the results of the bench-sale test supplement, but do not replace, a boiler trial at CGS.

Industry maintains that a test burn in the utility's unit is the best method for determining the impacts to the equipment from coal quality. According to EPRI (1986), several approaches may be taken to evaluate the impact of changes in coal supplies on slagging at an existing unit. Among these approaches were analyzing a similar coal at a similar unit. It is preferable if coals are from the same mine and the same seam. EPRI states that it was difficult to find a similar unit. Also, the Cerro Prieto seam at Fence Lake was not being mined anywhere; so, there was no Fence Lake coal available for testing. EPRI suggests another method of evaluating impacts, by comparing slagging and fouling indices; however, these just give a qualitative range. EPRI recommends that instead of relying on slagging indices alone, test burns can be conducted to provide a direct measurements of slagging. These burns should be conducted in the unit under consideration or a unit of similar design (EPRI, 1986).

EBASCO identifies the steam generator as the major area of uncertainty with respect to impacts from coal quality. The most important problem is the prediction of fouling and slagging. Based on EBASCO's experience, slagging and fouling cannot be predicted adequately by using indices and overall boiler parameters. EBASCO's approach to evaluating slagging and fouling problems is to conduct field measurements or a test burn. EBASCO recently test-burned coal at the Lidell unit owned by Electric Trust of New South Wales (Australia) (EPRI, 1986).

To confirm the combustion characteristics of coal, Sargent and Lundy (S&L) analyzed the results of a two-month test burn at an unnamed utility's 600 MW unit. As a result of the test, S&L recommended special coals and modifications to the utility (EPRI, 1986). These tests also examined emission limits of SO_2.

EPRI refers to the S&L test as "a detailed example illustrating the use of an existing state-of-the-art coal quality impact analysis methodology. Since every power plant and coal are different, no single example can include all aspects of coal quality impact evaluation." The test burn at the 600 MW unit coordinated several analytic tools including correlations, indices, test-burn data, and engineering judgment. EER suggested this type of test for Fence Lake coal as a result of their tests. According to EPRI (1980), empirical correlations of slagging and fouling characteristics of coal with ash content, ash elemental analysis, and/or ash-fusion temperatures have been used for boiler designs with relatively good success. However, boiler designs based on such correlations may have unexpected slagging or fouling problems.

B&V (1983) concluded that a test burn of Fence Lake coal was necessary because if 100% Fence Lake coal were burned, its low sodium content combined with its high ash may cause problems of emissions of particulates. B&V also recommended a test burn was necessary because of CGS's practice of blending fuels. Tests are required when blending fuels to determine if the temperature of ash fusion has been lowered below that of the composite fuels, because ash fusion is an eutectic function. Fence Lake coal was predicted to have low slagging and fouling indices, and, therefore, no real slagging or fouling problems. However, these predictions are not always accurate. In the 1983 report B&V predicted slagging problems for one of the New Mexico coals; however, when it was actually burned at CGS, there was not a slagging problem.

The Cerro Prieto coal seam has a 0.3 ft clay parting. Coal must be pulverized at the CGS mill to determine if the clay will affect the mill's performance.

EER (1986) concluded that Fence Lake coal will burn satisfactorily in CGS boilers during a test bum. However, based

on the bench-scale test, Fence Lake coal may have the following:
Reduced flame stability
Reduced burnout
Larger, but easier to remove, fouling deposits
More difficult to control NOx
Higher SO, emissions depending on CGS's sulfur control system

Methods of evaluation of Fence Lake coal during June 1987 test burn

SRP began testing the coal during the week of 1 June 1987. At the time this paper was written, the test was still in progress. SRP is evaluating the quality of the coal, the coal handling system, and burning of the coal which includes detailed emissions-control testing. The evaluation of the coal handling system addresses the following items: compaction, transfer points, dust, crushers and crusher feeders, sampling system, and belts. This evaluation takes place just prior to and during the test burn.

For the determination of compaction, the coal is evaluated for its ability to be compacted with heavy equipment without causing a bridging problem over the coal-mixing plow feeders. The coal is observed and evaluated at all transfer points for possible problems, passing through chute and belt to belt transfers.

For dust control, SRP determines the extent of control that will be required for the Fence Lake coal. After dust control is applied, SRP examines the characteristics of the coal handling system. SRP determines the rate of maximum feed for the crushers and conveyor crusher feeders. SRP monitors all the belts. Any problems with the conveyors are recorded. The coal is evaluated for its ability to be sampled with the existing sampling systems within ASTM standards.

The results of the test burn are used to determine the operation, performance, and efficiency of the boilers. Evaluations of the removal of particulates, control of SO, and NO_x emissions, and ash handling are an important part of the test burn.

During the burn, SRP evaluates the boiler for its ability to achieve designated operating temperature, to change load, and to operate in a stable condition at various load points. Boiler efficiency will be measured by two methods: Boiler Losses Method, using ASME Performance Test Code 4.1, and the Input/Output Method which measures the coal flow rate and the coal heating value.

Slagging and fouling potential will be measured by three methods: boiler inspections, heat absorption, and fly-ash samples. The boiler was inspected before the test and will be inspected after the test. Computer logs were installed to record temperature trends of the boiler headers. Based on these trends, SRP will estimate the heat absorption. Test periods are 8-10 hours long and followed by a soot-blowing cycle. After the test, SRP will compare the rate of accumulation and the removability of the deposit to those characteristics of the current coal supply. Ash-fusion temperatures is determined by analyzing fly-ash samples. Ash fusion is an indication of slagging potential. The ability of the existing fly-ash and bottom-ash handling equipment will be evaluated by observation during the period of operation and maintenance.

SRP plans an in-depth test of the control of emissions while burning the coal. Units 1 and 2 at CGS use precipitators. Unit 3, currently under construction, will use a fabric-filter system or baghouse. So two tests are planned: One to determine operating conditions for the Fence Lake coal with the current system, and the other to predict its behavior with the system planned for Unit 3.

During the burn, the performance of the precipitator is continuously monitored by chart records of opacity. All operating conditions of interest are documented. In addition to the continuous monitoring, precipitator data are recorded once each shift throughout the test burn. These data include all electrical readings and flue-gas-balancing data. Tests for total particulates are performed at the stack. These tests are similar to Environmental Protection Agency (EPA) compliance tests and are conducted annually.

NQ control is primarily evaluated during the boiler-control response testing. Existing station instrumentation is used to monitor NO_x emissions throughout the test burn. Specific combustion configurations are tested during the boiler-control testing. Units 1 and 2 are equipped with wet scrubbers for SO, removal. Each unit has two scrubber modules. The SO, removal requirements for our current coal supply is such that only one scrubber module is needed to meet compliance standards at maximum unit load. Two scrubber modules will be available for the test burn. During the last week of the test burn, the maximum unit load possible will be determined while operating with one module in service and without exceeding the compliance limit.

Fabric-filter testing has been contracted to Southern Research Institute (SoRI). The testing is scheduled to start during the first week of the test burn and continue throughout the test burn. Temporary testing equipment will utilize four different fabrics, including the Unit 3 specified fabric. Use of laboratory fly-ash analysis is also planned. The report of the results will indicate relative performance of the fabrics and coals at various operating conditions (Severson, 1987).

Conclusion

As of 17 June 1987, the coal has been tested for two weeks and is scheduled to burn for approximately one month longer. Final results of the test are pending; however, several preliminary observations have been made. Because of the small scale of the Fence Lake No. 1 mine, blending the A and BC splits of the Cerro Prieto seam has not been possible. Therefore, the generating stations has not received a homogeneous sample of coal. The variability of the coal has affected the repeatability of the tests.

CGS has experienced minor dusting problems with the Fence Lake coal. CGS has observed some opacity problems which could be a result of the variability of the coal that was shipped and/or could indicate the need for adjustment to the precipitator. However, the current opacity problem is not as bad as that experienced when the current fuel supply is burned. Emissions of NOx and SO, have not been a problem. The flame generated by the Fence Lake coal is cooler than the flame for the current supply. The flame appears to control NO_x

The design load of the unit has not yet been reached. This situation may be remedied by mixing the Fence Lake coal with a higher Btu coal or by adjusting feeder controls to the plant's original design. It should be noted that results to date are observations outside the boiler and that an inspection has not yet been performed (Patton, 1987).

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Selected conversion factors*

TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, µm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-1}	m^2
mi^2	2.590	km^2
acres	4.047×10^{3}	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^{1}	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^{3}	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}
Pressure, stress		
lb in^{-2} (= lb/in^2), psi	7.03×10^{-2}	kg cm^{-2} (= kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^2, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{2}	mm of Hg (at 0° C)
inches of Hg (at 0° C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^{1}	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	m^2 sec^{-1}
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British thermal units, BTU	2.52×10^{-1}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F − 32	5/9	°C (Celsius)

**Divide by* the factor number to reverse conversions.
Exponents: for example 4.047×10^{3} (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929.

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