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THIRD-DAY ROAD LOG FROM DURANGO, COLORADO, TO AZTEC, FARMINGTON AND SHIPROCK, NEW MEXICO

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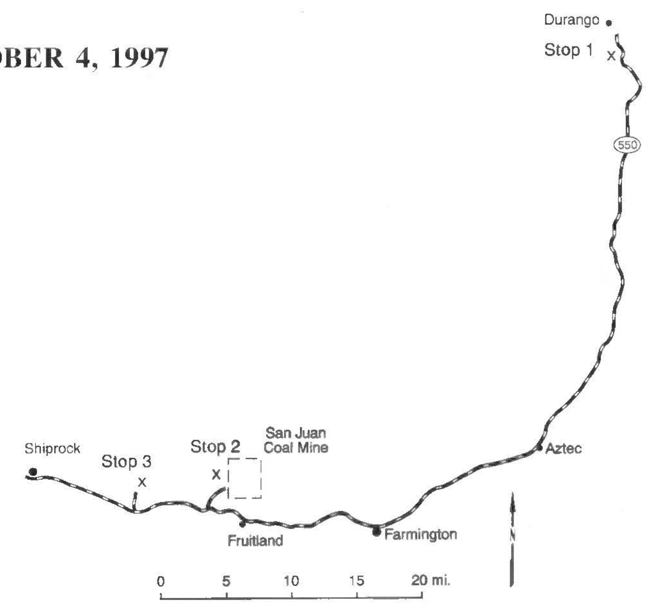
WILLIAM L. CHENOWETH and BRUCE A. BLACK

SATURDAY, OCTOBER 4, 1997

Assembly point: Tamarron Resort, N of Durango
Departure time: 7:30 a.m.
Distance: 109.9 mi
Stops: 5



Day 3

Summary

The third-day road log takes us from Durango southward through the eastern San Juan Basin into New Mexico, and then due westward along the San Juan River to just west of Farmington. At Stop 1 we examine volcaniclastic strata assigned to the McDermott Member of the Animas Formation. These strata are of latest Cretaceous (Maastrichtian) age and provide direct evidence of volcanism in the northern part of the Late Cretaceous San Juan Basin. At Stop 2 we examine the San Juan generating station. Stop 3 is in the Hogback monocline that forms the western margin of the San Juan Basin. Here, Cretaceous strata of the Mesaverde Group (locally the Point Lookout, Menefee and Cliff House Formations) can be examined. Stop 4 at Ship Rock is optional. The post-field conference Stop 5 (not described in road log) is a highly unusual stop—a cave home excavated in the Ojo Alamo Formation by New Mexico geologist Bruce Black, just north of Farmington.

Mileage

0.0 Parking lot exit of Tamarron resort. **Turn left** on US-550 and proceed S to retrace latter part of route of Second-day Road Log back to Durango. **13.2**

13.2 Durango city limit. **3.7**

16.9 Cross Animas River. **0.2**

17.1 Curve right on US-550 at light. **0.7**

17.8 Junction of US-550 and US-160; continue straight on 550. The SW corner of the intersection was the Durango smelter site at the NE edge of Smelter Mountain. **0.3**

18.1 Uranium mill tailings site (now reclaimed) on right across Animas River. **0.5**

THE DURANGO URANIUM-VANADIUM MILL

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The Durango millsite was a 147-acre tract located on the southwest side of the city of Durango, Colorado, just outside the city limits. It is bordered on the east by the Animas River. The Durango site was originally acquired by the American Smelting and Refining Company for the construction and operation of a lead smelter. At the beginning of World War II, it was acquired by the Reconstruction Finance Corporation, a Government agency, which contracted with United States Vanadium Corporation (USV) to convert and operate the plant for vanadium production. The vanadium was supplied to Metals Reserve Company, which had been established by the Government to purchase strategic materials for wartime needs. Vanadium was needed as an alloy metal to harden steel. USV operated the plant for the Government until March 1944, when the Government vanadium purchasing program was terminated because of adequate vanadium stocks. During the Metals Reserve program, the Durango mill produced 1,179,516 pounds of V_2O_5 in concentrate. USV then purchased the facilities from the Reconstruction Finance Corporation and operated them for the production of vanadium for commercial sales until August 31, 1945, when the plant closed.

During the 1943–1945 period USV also constructed and operated a uranium-vanadium sludge plant at the Durango site, under a cost-plus-fixed-fee agreement with the Manhattan Engineer District (MED). Feed for the plant consisted of vanadium tailings from past and current operations. The sludge was shipped to a refinery at Grand Junction, Colorado, also operated for the MED by U.S. Vanadium. There, the vanadium was removed to make a low grade uranium concentrate suitable for further refining to black oxide. Approximately 44,000 lbs of U_3O_8 were recovered from the Durango tailings for the Manhattan Project.

In 1948 the U.S. Atomic Energy Commission (AEC) purchased the Durango plant from USV. On October 8, 1948, the AEC entered into a contract with the Vanadium Corporation of America (VCA) to purchase uranium concentrates produced by VCA. The AEC then leased the plant to VCA giving the firm the option to purchase the plant by June 30, 1953. The option was exercised and VCA therefore operated the plant as a privately owned facility.

When the Durango mill was reactivated in 1949 for the production of concentrates for sale to the AEC it had a nominal capacity of about 175 tons per day, which was expanded to 430 tpd by 1956 and 750 tpd by 1958. During the period of this operation (1949–1963), the mill processed ore at an average rate of about 350 tpd and treated a total of 1,605,234 tons of ore averaging 0.29% U_3O_8 and 1.55% V_2O_5.

Ore for the Durango operation came from numerous small underground mines in western Colorado, southeastern Utah, northern New Mexico and the Monument Valley area of Arizona. Fifty-three percent of the millfeed was mined from properties controlled by the VCA and the remaining 47% was purchased by the VCA concentrates from VCA's upgrader at Naturita, Colorado, which operated from late 1961 to early 1963, and upgraded material from the Monument No. 2 Mine in Monument Valley, Arizona.

The mill process used provided for separate salt roasting of ores and of concentrates from VCA's upgrader plants and for carbonate leaching of the calcines. Ore calcines were quenched and percolation leached while the concentrate calcines were quenched and then treated by counter-current washing on a series of three drum filters. Pregnant solutions from these two circuits were then combined and a sodium uranyl vanadate, or artificial carnotite, product was precipitated by addition of sodium chlorate, acidification and boiling, then neutralizing to pH 7. The bulk of the vanadium remained in the filtrate and was precipitated as red cake. The reducing fusion and water leaching process was then used to remove the vanadium from the uranium concentrates. The uranium was recovered as black oxide (UO_2), and soluble vanadium subsequently was recycled and precipitated as vanadium red cake. The red cake was dried and fused to produce the flake fused oxide.

Tailings from the carbonate leaching operations were reclaimed and retreated for additional uranium and vanadium recovery by acid-percolation leaching, using a combination of hydrochloric acid solution recovered from the salt-roaster gas scrubbers and additional sulfuric acid. Beginning in the late 1950s the pregnant acid leach liquor was treated by solvent extraction to recover both uranium and vanadium into a final concentrated and purified carbonate liquor suitable for return to the plant precipitation circuit.

The Durango solvent extraction was unique in that it extracted uranium and vanadium simultaneously rather than employing separate extraction circuits, which was the practice at other mills.

On March 1, 1963, VCA purchased the mill at Shiprock, New Mexico, operated by the Navajo Uranium Division, Kerr-McGee Oil Industries, Inc. The Durango mill closed and VCA's milling operations were transferred to Shiprock. During its operation under the AEC program, the Durango mill produced 7,851,425 lbs of U_3O_8, in yellowcake, which the AEC purchased at the average price of $9.77/lb. Also produced were 37,065,953 lbs of V_2O_5. Of this total, only 5,791,735 lbs were purchased by the AEC at the price of $0.9875/lb. The remainder was sold by VCA to the commercial market.

After the milling operation ceased in 1963 the mill was dismantled. Ranchers Exploration and Development Corporation had planned to move the tailings to another site near Durango for processing similar to that used by Ranchers on the Naturita tailings to recover uranium and vanadium. Production at Durango was projected by Ranchers to commence in mid-1979 and to continue for about 32 months. However, Ranchers was unsuccessful in obtaining the required State permits and abandoned the project. The mill site was reclaimed in 1994 under the Uranium Mill Tailings Radiation Control Act of 1978 (modified from Albethren and McGinley, 1982 and material in the AEC files).

18.6 Cross Animas River; coal-bearing Menefee Formation crops out on right. The Spanish word *animas* refers to the soul of one who has died. According to Pearce (1965), the river was so named because of its treacherous crossings, where many Indians and early Spanish explorers lost their lives. Formerly called the Rio de las Animas, it empties into the San Juan River at Farmington, New Mexico. **0.8**

19.4 Note aggregate pit high on slope to left. **0.5**

19.9 Intersection and traffic light; note outcrops of Lewis Shale and Pictured Cliffs Sandstone to left in cuts. **0.3**

20.2 Continue on frontage road to Animas Air Park (La Plata County Road 213). **1.2**

21.4 **STOP 1**. Here we will examine the Cretaceous-Tertiary boundary section in a well-exposed and accessible section of the McDermott Member of the Animas Formation. Reeside (1924, p. 24) introduced the name McDermott Formation "for a series of lenticular sandstones, shales, and conglomerates containing much andesitic debris and usually in part of purple color." The type section of the formation is in McDermott Arroyo (secs. 18 and 19, T32N, R11W, La Plata County, Colorado) about 15–17 mi SSW of Stop 1. Previous to Reeside (1924), the strata he termed the McDermott Formation were called "andesitic beds on Animas River" (Cross, 1892), "Animas River beds" (Emmons et al., 1896) or "Animas Formation" (Shaler, 1907; Gardner, 1909).

Reeside (1924, pl. 1) mapped the McDermott Formation as a narrow outcrop belt in the northern and west-central San Juan Basin that extended from a point about 10 mi due east of Durango westward and then southward to a point about 6 mi south of Ojo Alamo, well south of the San Juan River in New Mexico. In so doing, Reeside (1924) assigned to the McDermott Formation strata south of the San Juan River that had been assigned to either the uppermost part of the Kirtland Formation or the lower part of the Ojo Alamo Sandstone by Bauer (1916) and Bauer and Reeside (1921). Reeside's (1924, p. 26) observation that "near the type locality of the McDermott formation indeterminable bones of dinosaurs, fragments of turtle bone, and fossil wood have been collected at a number of localities" is still the primary biostratigraphic basis for assigning a Late Cretaceous age to the McDermott.

Subsequent to Reeside (1924), two major changes have altered his concept of the McDermott Formation. First, Barnes et al. (1954) included this unit within the Animas Formation as the lower, McDermott Member. These authors justified their decision as follows:

> Reeside's typical section of the McDermott...is subdivided in this report as follows: the lowest 95 feet of pebble-bearing sandstone and sandy shale is part of the Kirtland shale, the overlying 127 feet of purplish beds is the McDermott member of the Animas formation, and the top 106 feet is included in the upper member of the Animas formation. It is thus proposed to reduce the McDermott from the status of a formation to that of a locally present member of the Animas formation. The two units are gradational, and aside from a contrast in color they show no consistent lithologic distinction...Where the maroon and purple sequence is present in Colorado the Animas formation consists of the basal McDermott member and an upper member; elsewhere in Colorado the Animas formation is not subdivided...The McDermott is conformable on the upper shale member of the Kirtland and is conformably overlain by the upper member of the Animas.... The McDermott member is of Late Cretaceous age and probably records an early outburst of volcanism during the time of Laramide mountain-building.

Work in other areas by Barnes (1953) and Zapp (1949) supported these observations.

The second change that altered Reeside's (1924) conception of the McDermott came through the work of Hayes and Zapp (1955), O'Sullivan et al. (1972) and other U.S.

Geological Survey geologists. This work has restricted the distribution of the McDermott Member of the Animas Formation to north and east of the La Plata River and reassigned strata south and west of the La Plata that Reeside (1924) mapped as McDermott to the upper part of the Kirtland Formation (see, for example, Fassett and Hinds, 1971, pl. 1).

About 300 ft of the purple McDermott Member are exposed at Stop 1 (Fig. 3.1). The McDermott here is overlain by "a sequence of olive-brown, olive-green, and gray and green tuffs in which the andesite detritus is more weathered and which contains increasingly greater amounts of normal sedimentary material" (Zapp, 1949). According to Newman (1982, 1983), palynomorphs from the McDermott Member at this outcrop indicate an early Maastrichtian age. Nevertheless, there are not enough biostratigraphic data to enable a precise placement of the Cretaceous-Tertiary boundary in this section, although most workers tentatively place the boundary between the McDermott and upper members of the Animas Formation (e.g., Fassett and Hinds, 1971) or stratigraphically low in the upper member of the Animas Formation (e.g., Baltz, 1967).

After Stop, continue S on County Road 213. **0.4**

21.8 Animas Formation crops out at 9:00 to 11:00; aggregate quarry on right. **2.3**

24.1 Pavement ends; roadcuts here and for next several miles are in upper part of Animas Formation. **2.9**

27.0 Junction of county roads 213/214; proceed to left across Animas River bridge. **0.3**

27.3 Sharp curve to left at intersection; stay on main road to left. **0.3**

27.6 Note lone oil well 600 ft to the N (left). **0.3**

27.9 Turn left (leave County Road 215) and follow County Road 214 as it ascends the hill. **0.2**

28.1 Road bends left and ascends hill. **1.2**

29.3 Intersection with paved US-550; **turn right** to proceed S on 550. **1.4**

30.7 At 3:00, note the extensive burned out forest area, a result of the Black Ridge fire of July 1994. We are on the Southern Ute Indian Reservation. **3.7**

FIGURE 3.1. Andesitic boulder-breccia in McDermott Formation at Stop 1.

COAL RESOURCES OF UPPER CRETACEOUS FRUITLAND FORMATION IN THE SOUTHERN UTE INDIAN RESERVATION, SOUTHWESTERN COLORADO

Dorothy T. Sandberg

(reprinted from U.S. Geological Survey Bulletin 1505-D, 1990, R. S. Zech, ed.)

Coal resources of the Upper Cretaceous Fruitland Formation in the Southern Ute Indian Reservation are estimated to total 16 billion short tons of bituminous coal in beds 2 feet thick or more. The coal-bearing Fruitland Formation underlies about 700 square miles of the Southern Ute Indian Reservation and crops out in a roughly semicircular band around the northern edge of the structural San Juan Basin. The coal beds locally dip more than 10° to southeast along the northwestern rim of the basin.

The estimate of coal resources is based on a study of about 500 geophysical logs, mostly of oil and gas wells. Total coal resources include 15 billion short tons of identified resources, based on data points 3 miles or less apart, and about 1 billion short tons of undiscovered or hypothetical resources, based on data points more than 3 miles apart.

In this report, the coal-bearing interval is divided into three overlapping zones: lower, middle, and upper. Coal resources were estimated by aggregate thickness for each zone. The lower zone, which is southwest of a large stratigraphic rise of the Pictured Cliffs Sandstone, contains the thickest coal beds, generally in two thick beds that locally have an aggregate thickness as much as 50 feet. The lower zone contains about 28% of the estimated resources; in the lower zone, 6% of the resources are less than 500 feet beneath the surface, 10% of the resources are 500–2,000 feet beneath the surface, and 84% are more than 2,000 feet beneath the surface. The middle zone contains 22% of the estimated resources; in the middle zone, only 2% of the resources are less than 500 feet beneath the surface, 4% of the resources are 500–2,000 feet beneath the surface, and 94% are more than 2,000 feet beneath the surface. The upper zone contains about half the estimated resources, in part because it occupies about three-fourths of the area underlain by the Fruitland Formation; in the upper zone, about 2% of the resources are less than 500 feet beneath the surface, 11% are 500–2,000 feet beneath the surface, and 87% are more than 2,000 feet beneath the surface. In general the coal beds are thinner in the middle and upper zones than in the lower zone. Although the coal on the Reservation is of comparatively high rank, coal in the Fruitland is generally characterized by high ash content. Mining on the Reservation has been restricted generally to small underground and strip mines within 200 feet of the surface along the edges of the San Juan Basin.

34.4 Trough-crossbedded sandstones and green mudstones of Animas Formation on left look very similar to Nacimiento Formation of northwestern New Mexico. Nacimiento is down-depositional-dip equivalent of part of the Animas Formation. **0.6**

35.0 Road begins descent to Animas River floodplain. Note roadcuts to left in Animas/Nacimiento strata for next 0.5 mi. **0.9**

35.9 Road to Ignacio, Colorado 310/318, to left; continue south. At 11:00, Ignacio highway climbs the east wall of valley, with Eocene San Jose sandstones intertonguing with underlying dark-gray shales of Nacimiento Formation. **0.7**

36.6 Cross Animas River, downstream (left, east) note abandoned bridge of Denver and Rio Grande Western Railroad, route from Farmington to Durango. Canyon narrows ahead where river cuts through the more resistant San Jose Formation. Here it is fine- to coarse-grained arkose, with conglomeratic lenses and interbedded shales, including andesitic debris. **0.4**

37.0 Bondad Village; good outcrops of San Jose sandstones in bluff to left. Broad axis of San Juan Basin, plunging slightly to southeast, is crossed in the next few miles. **1.5**

FIGURE 3.2. Slope-forming Nacimiento Formation overlain by sandstone ledges of lower part of San Jose Formation.

	WOOD et al. (1941)	1997 consensus	
PALEOCENE	CLARKFORKIAN	WASATCHIAN	PALEOCENE
		CLARKFORKIAN	
	TIFFANIAN	TIFFANIAN	
	TORREJONIAN	TORREJONIAN	
	DRAGONIAN		
	PUERCAN	PUERCAN	

FIGURE 3.3. Paleocene land-mammal "ages" of western North America.

38.5 Twin Crossings Trading Post on right. On left, historic marker for State of Colorado. Sandstone ledges of San Jose Formation to left. **1.9**

40.4 Enter New Mexico. **1.7**

42.1 To left, 0.3 mi past truck weight station on right, near base of northwest flank of Mt. Nebo, the contact of San Jose Formation above Nacimiento Formation is exposed (Fig. 3.2). Nebo is capped by Pliocene Bridge timber gravel (Manley et al., 1987). **2.4**

44.5 Highway descends through sandstones in the upper Nacimiento Formation to Animas River floodplain. **0.8**

45.3 Cross Animas River. Nacimiento Formation crops out in river bank to right; another abandoned railroad bridge to left. **0.3**

PALEOCENE LAND-MAMMAL "AGES" OF THE SAN JUAN BASIN, NEW MEXICO-COLORADO

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Wood et al. (1941) proposed a succession of North American land-mammal "ages" (LMAs) to encompass Cenozoic time. These LMAs are biochronological units—intervals of geologic time that correspond to the duration of a "fauna" (i.e., an assemblage zone of mammalian fossils). As such, LMAs are not ages in a formal stratigraphic sense; they lack stage stratotypes. Therefore, to call them ages is misleading, though the term LMA is well entrenched in the literature and will probably not be abandoned. Wood et al. (1941) named five LMAs that they thought were of Paleocene age; three were based on mammalian fossil assemblages from the San Juan Basin—Puercan, Torrejonian and Tiffanian (Fig. 3.3).

The Puercan was based on fossil mammals from the lowest part of what is now called the Nacimiento Formation. These fossils came from major drainages that feed the Chaco River south of Farmington—Betonnie Tsosie, Kimbeto, De-Na-Zin Arroyos and the West Fork of Gallegos Canyon (Lucas, 1984; Williamson, 1996). Cope (1875) had first used the name "Puerco marls" to refer to strata later named the Nacimiento Formation and the term "Puerco fauna" to refer to fossil mammals from these strata. By the time of Wood et al. (1941), two "formations," each with a distinctive mammalian fauna, were included in the Nacimiento Group—Puerco (lower) and Torrejon (upper) Formations (e.g., Gardner, 1910; Reeside, 1924; Matthew, 1937). Puerco and Torrejon, however, really were not mappable lithostratigraphic units (formations), so Simpson (1948) recommended using them only as biochronologic (faunal) terms to refer to the two temporally-successive mammalian assemblages in a single lithostratigraphic unit, which he termed Nacimiento Formation.

The younger assemblage provided the basis for the Torrejonian LMA; fossils were found over a broad outcrop belt extending from tributaries of the Animas River north of Aztec southward through Kutz Canyon and Kimbeto Arroyo to Arroyo Torreon (long misspelled "Torrejon" in the vertebrate paleontological literature) near Ojo Encino west of Cuba, New Mexico (Wood et al., 1941). The Tiffanian LMA was named for a much more limited assemblage of fossil mammals collected in the vicinity of Tiffany near Ignacio, Colorado. Most of these fossil mammals came from a single locality called "Mason pocket" in strata now assigned to the Animas Formation (Simpson, 1935).

Superposition of Puercan and Torrejonian mammals was easily demonstrated in the extensive badlands that ring the southwestern and western San Juan Basin. However, the precise stratigraphic relationship of the Tiffanian assemblage to the Puercan and Torrejonian assemblages has never been fully understood, so the younger age of the Tiffanian was inferred by its more evolutionarily "advanced" mammals.

Today, magnetostratigraphy and a more extensive knowledge of Paleocene mammals throughout the Western Interior confirms that the temporal succession Puercan-Torrejonian-Tiffanian is correct. Furthermore, the Dragonian LMA of Wood et al. (1941) has been abandoned as an equivalent of the early part of the Torrejonian (Tomida and Butler, 1981; Schoch and Lucas, 1981; Archibald et al., 1987; Lucas et al., 1997). The Paleocene-Eocene boundary is within the early part of the Wasatchian LMA, not at the Clarkforkian-Wasatchian boundary (Lucas, 1997).

The San Juan Basin thus provides an indispensable standard for the mammalian biochronology of the Paleocene. Indeed, the distinctiveness of the Paleocene mammals from the San Juan Basin led Matthew (1937) to argue for the recognition of the Paleocene as an Epoch distinctive from the Eocene, and helped win worldwide recognition of the Paleocene (Simpson, 1981).

45.6 Ditch Canyon. **0.6**

46.2 Enter village of Cedar Hill. Note badlands developed in Nacimiento Formation to W in Cox Canyon. **5.0**

51.2 County Road 2800 to right. Across river extensive Nacimiento Formation badlands in Tucker and Bohannon Canyon. Terraces to left. **2.7**

53.9 Junction with NM-173; left leads to Navajo Lake State Park; enter Aztec, elevation 5590 ft; population 6000 plus. An All-American City of 1963. Aztec was founded in 1879 and named for the ruined pueblo nearby. Archeologists thought these ruins represented a northern branch of the Aztec Indians, but they record a settlement built by the Anasazi people as part of the Chacoan culture. **1.1**

NAVAJO LAKE STATE PARK

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Navajo Lake State Park, comprising one of the largest reservoirs in the state, is in the Four Corners Region of northwestern New Mexico, 25–30 mi east of Bloomfield via US-64, NM-511, and NM-527 (Fig. 3.4). Over a half million people visited the lake in 1996. Navajo Dam was built in 1958–1962 for flood control and to provide water to the Navajo Indian Irrigation Project, one of the many projects of the basinwide Colorado River Storage Project (CRSP), established in 1956. The Navajo Indian Irrigation Project, established in 1962, provides water for approximately 110,000 acres of farmland on the Navajo Reservation. The dam traps water from the San Juan, Piedra and Los Pinos Rivers, Sambrito Creek and La Jara Creek. The dam consists of an earth- and rock-filled structure that extends 3648 ft across the river and is 402 ft high at an elevation of 6085 ft. In the reservoir area, five cemeteries, 4 mi of Colorado state highway, and 6.5 mi of railroad were relocated. A 30-megawatt hydroelectric power plant is operated at Navajo Dam since 1987 by the City of Farmington. When full, the reservoir covers 15,610 acres.

Navajo Lake has four developed recreational sites: San Juan River, Pine River and Sims Mesa in New Mexico and Arboles in Colorado (Fig. 3.4). The U.S. Bureau of Land Management also operates the Simon Canyon Recreation Area along the San Juan River. The Miller Mesa State Waterfowl Area, administered by Navajo Lake State Park, lies along the lake in northern New Mexico.

Recreational activities include hiking, picnicking, camping, swimming, fishing, boating, sailing and water skiing. Camp and picnic sites are along the lake as well as along hills and mesas above water level. Launching ramps for boats and a marina (Fig. 3.4), electrical hookups, showers, drinking water, and handicapped facilities are available. Airstrips are near or at both the New Mexico and Colorado sites. The New Mexico State Park Office is located at the Pine River Recreation Area; a visitors center is

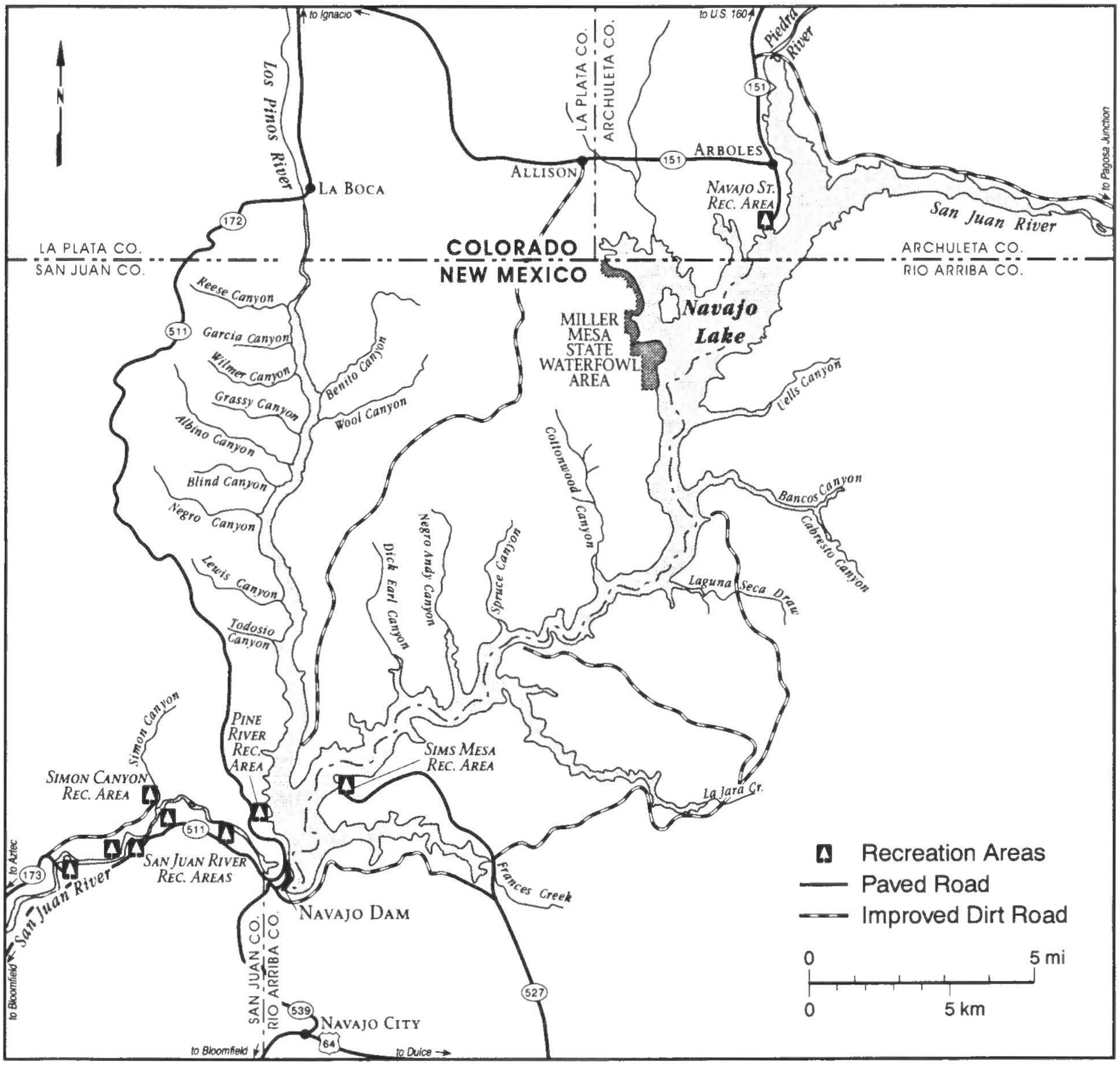

FIGURE 3.4. Location map of Navajo Lake State Park, showing recreational sites.

also at the Arboles Site in Colorado. The lake is stocked by the State Game and Fish Department with small- and large-mouth bass, catfish, crappie, bluegill, and trout. The San Juan River, downstream of the dam, is known as the Miracle Mile and is famous for some of the best trout fishing in the Southwest. All of the water is open to the public. Sandy beaches are separated by rocky beaches and offer a diversity appreciated by both swimmers and fisherman. Coves abound and offer solitude even during busy holiday weekends.

Piñon pine, juniper, mesquite, cholla, prickly pear and yucca cover the hillslopes and mesas surrounding the lake, and various wild flowers are common. Cottonwood and poplar trees are found along the river valleys. Falcons, mountain bluebirds, quail, dove, ducks and geese are plentiful. Upland bird and waterfowl hunting is allowed within the park boundaries along the San Juan River. A few bald eagles and peregrine falcons inhabit the area as well. Antelope, elk and mule deer roam the countryside; big game hunting is allowed outside park boundaries. A few mountain lions and bear roam the adjacent hills.

Pottery, spear points and ruins of shallow pit-houses attest to Native Americans occupying the area as early as 3000 B.C. Numerous petroglyphs and pictographs, mostly of the Pueblo Period (A.D. 700–1050) occur along Los Pinos Creek and lower San Juan River Canyon where the steep, vertical cliffs laid close to now-abandoned village sites (Schaafsma, 1961). About A.D. 1050, the area was abandoned by humans, probably due to drought and erosion.

Ancestors of the Navajo, Ute, and Apache Indians migrated into the Southwest about A.D. 1550 (Schaafsma, 1962). The Navajos and Utes settled in the Four Corners region of New Mexico, Arizona, Utah, and Colorado, whereas the Apaches settled in eastern and southern New Mexico and southern Arizona. The Jicarilla Apaches settled in north-central New Mexico near Chama. Through contact with the Pueblo Indians and Spanish settlers, the Navajos and Utes became more dependent on farming and grazing, but they continued to raid neighboring communities. The Spanish and Mexicans perpetuated these raids by attacking and enslaving the Navajos and Utes (Strawn, 1967; Young, 1968).

General Stephen Kearney conquered New Mexico in 1846 for the United States and promised to end hostilities with the Indians. Peace treaties were signed with chiefs of the Navajos and Utes, but all were broken. Fort Defiance was established in eastern Arizona in 1851. The Tuni Cha outpost was established near Sheep Springs, south of Farmington, in 1853, but closed in 1858 (Giese, 1991). The Chuska Valley camp was established in 1858, but closed that year when a peace treaty with the Navajo Indians was signed. In 1860, Fort Fauntleroy, named for Department Commander Colonel Thomas Fauntleroy, was established at the site now occupied by Fort Wingate. The peace treaty was short lived and Fort Defiance was abandoned in 1861. The garrison was transferred to Fort Lyon (formerly Fort Fauntleroy), but was abandoned in December 1861 when the garrison was transferred to Fort Craig near Socorro to meet the Confederate Army, which had invaded New Mexico.

The defeat of the Confederate forces at Glorieta Pass, east of Santa Fe, allowed General James Carleton to transfer troops into the Navajo country to subdue the Indians. A new fort, Fort Wingate, was established in 1862 at San Rafael, south of Grants. In 1863, Colonel Kit Carson and about 800 men were ordered to pursue the Navajos. Carson was unable to engage the Navajos in major battles, but he did wipe out their economic base by burning fields and hogans and slaughtering livestock. By the end of a severe winter, the Navajos were defeated; in March 1864 they began a 300-mi journey to the Bosque Redondo Reservation at Fort Sumner in eastern New Mexico (Young, 1968; Bahti, 1968). In 1868, the Navajos were allowed to return to their homeland.

With the Indians subdued, northwestern New Mexico was settled by Hispanic and Anglo farmers. Bloomfield was established in 1878 and Farmington in 1879. Milt Virden and others laid out the townsite and named the town Farmington, since the area was known as a farming town (Julyan, 1996). San Juan County was established in 1887 and named for the San Juan River. Oil and gas were discovered in the area in the 1940s and an important industrial economy developed.

Sandstones forming the shoreline and adjacent cliffs and interbedded shales around Navajo Lake belong to the Eocene San Jose Formation. The San Jose Formation is fluvial in origin and represents the last preserved period of Laramide deposition (Smith, 1992). It was deposited along high energy, low-sinuosity streams and on adjacent muddy floodplains. The formation consists of (in ascending order) the Cuba Mesa, Regina, Ditch Canyon, Llaves and Tapicitos Members (Smith, 1992).

Special thanks to the state park personnel for discussions and information on the history of the park. The New Mexico Bureau of Mines and Mineral Resources Cartography Department drafted the figures.

55.0 Intersection with NM-544 to left; continue west on US-550 toward Farmington. **0.6**

55.6 Bridge over Animas River, and turnoff to Aztec National Monument Ruins; proceed ahead on US-550. **0.9**

56.5 Leaving Aztec; note terrace gravels along San Juan River to right. **3.2**

59.7 San Juan River Valley to left; bluffs across river to south expose Upper Cretaceous Kirtland Formation. **0.7**

60.4 Flora Vista post office on right. Founded in 1884, Flora Vista was a small farming and ranching community that is now part of the Farmington-Aztec-Bloomfield urban area. **1.0**

61.4 Farmington city limits. Founded in 1879, the original name was "farming town" but was later condensed to one word. The Navajo called this place *tó* ("water") *tá* ("among"), meaning "a place among the rivers." The San Juan, Animas and La Plata Rivers join here. **2.9**

64.3 Turn right onto Piñon Hills Road to bypass downtown Farmington. **0.9**

65.2 Ojo Alamo Formation crops out in roadcuts on right. **2.1**

67.3 Road to left goes to world-famous (no exaggeration!) Piñon Hills Golf Course; continue straight. **1.3**

68.6 Traffic light at 30th St. **Turn right** and continue to W. **0.9**

69.5 Descend into valley of Farmington Glade. Chuska (from *Ch'oshgai*, "white worm") and Lukachukai (from *ok'aach'egai*, "horizontal white streak of reeds") Mountains (10:30–11:00), Shiprock (12:00), and Carrizo Mountains (1:00) in distance. The valley fill is 20 ft of Holocene alluvium, which Ward (1990) correlated with the Naha and Tsegi alluvia (6–0.7 ka) of Hack (1941). **0.3**

69.8 On the left, the Four Corners Regional Airport sits on the Q4d terrace of Ward (1990), correlated to the Lower Florida Gravel (late Sacagawea Ridge) of Richmond (1965) and Bald Mesa terrace, which has been dated at 300 ka (M. L. Gillam, cited in Ward, 1990). The airport terrace is 200 ft above the San Juan River (Ward, 1990). **0.6**

70.4 Descend into valley of La Plata River. The La Plata, Animas, and San Juan Rivers have cut younger channels and floodplains into the Naha and Tsegi Alluviums, whereas most of the smaller, intermittent tributaries below Farmington (such as the Glade) have not. **0.6**

71.0 Cross La Plata River. Ojo Alamo Formation cliffs cap the east wall of the valley. The terraces in the less prominent west wall are cut in the underlying weaker Farmington Member of the Kirtland Formation. *Dibé nitsaa* (La Plata Mountains) in the distance at 3:00. **0.2**

71.2 Cross La Plata Highway (NM-170). Continue straight on County Road 6480, climbing through roadcuts in the Farmington Member. **0.8**

72.0 Aggregate quarries in terrace gravels of Martin Mesa on the right and left. **0.8**

72.8 Road descends from Martin Mesa. Note, from 10:30 to 1:00, the Hogback monocline (10:30), Four Corners Power Plant, Twin Mounds and Ship Rock (1:00). Piñon Mesa to right has Ojo Alamo Formation cap above slopes of Kirtland Formation. Reeside (1924, pl. 1) originally mapped only two stratigraphic units at Piñon Mesa, the McDermott Formation overlain by the Ojo Alamo Sandstone. As Reeside (1924, p. 25) noted, "beds of purely andesitic debris do not occur west of La Plata River in New Mexico, though sandstone, shale, and conglomerate with a notable amount of andesitic material in them mark the McDermott formation clearly in the region north of the San Juan River." Thus, Reeside (1924, p. 61) reported 40+ ft of McDermott Formation unconformably overlain by 190 ft of Ojo Alamo Sandstone. On the north side of Piñon Mesa, Reeside reported as much as 165 ft of McDermott Formation.

Hayes and Zapp (1955), however, offered the following observations on the stratigraphy in this and adjoining areas:

> ...at Pinon Mesa...the Kirtland Shale is succeeded by 60 to 100 ft of banded sandy shale and thin beds of sandstone that differ from the underlying Kirtland shale only in the presence of scattered chert pebbles in the sandstone and local lenses of tuffaceous sandstone. These beds are overlain with irregular contact by approximately 200 ft of cliff-forming conglomeratic sandstone. Reeside (1924) assigned the lower pebbly and tuffaceous beds to the McDermott formation and the overlying sandstone to the Ojo Alamo sandstone, which he considered genetically distinct from the McDermott formation and unconformable with it...
>
> Considerable effort was expended during this investigation in an attempt to establish and trace a precise upper contact of the Kirtland shale, to be drawn at the lowest occurrence of pebbles, or megascopically identifiable andesitic detritus. Careful tracing of beds in areas of continuous exposures revealed that the stratigraphic horizon at which these materials appear is not constant, that the beds are lenticular, and that lithologies common in the Kirtland shale recur above the lowest coarse clastics. The upper contact of the Kirtland shale is therefore transitional and arbitrary.

These observations, as well as the work of Barnes et al. (1954) and O'Sullivan et al. (1972) have supported assignment of the strata at Pinyon Mesa and adjacent areas north of the San Juan River in New Mexico that Reeside (1924, pl. 1) mapped as McDermott Formation to the Kirtland Formation (also see Lehman, 1985). As Fassett and Hinds (1973, p. 24) put it:

> In the Pinyon Mesa area, beds of tuff ranging in thickness from thin laminae to beds several feet thick and thicker sandstone beds which contain abundant andesitic debris occur in the uppermost Kirtland; these beds are in what Reeside (1924) originally called the McDermott Formation.

It is well worth considering how similar Reeside's McDermott at Pinyon Mesa is to the McDermott we saw at Stop 1.

At Pinyon Mesa, biostratigraphic control of the Cretaceous-Tertiary boundary is very poor. To our knowledge, the only biostratigraphic data relevant to placement of this boundary are dinosaur fossils reported by Kues et al. (1977, p. 146, 264). The fossils are indeterminate hadrosaur remains from the lower exposures of the Kirtland west of Pinyon Mesa in sec. 25, T30N, R5W. **0.6**

73.4 Cross Locke Arroyo. **0.9**

74.3 Cross Dain Arroyo. **0.2**

74.5 Pass under powerline. Twin Mounds, on left, are the remnants of a terrace about 550 ft above the San Juan River. They are shown as remnants of the Q2 terrace on the map by Ward (1990). M. L. Gillam (personal commun., 1996) estimated their age as 1.1 Ma (early Pleistocene) by comparison with the Hood Mesa terrace upstream. **0.5**

75.0 At crest of hill, Mesa Verde is visible at 2:00. **0.2**

75.2 Junction with County Road 6200. Continue straight. **0.3**

75.5 Cross Coolidge Arroyo, named after O. J. Anderson's favorite president. Outcrops of Farmington Member of Kirtland Formation visible in the arroyo. **0.8**

76.3 Enter greater Kirtland. Founded about the turn of the century, Kirtland originally was a fruit-farming community. **0.7**

77.0 Junction with County Road 6483; continue straight. **0.5**

77.5 View of the 1614-megawatt San Juan generating station at 1:00. The minemouth plant is operated by Public Service Company of New Mexico (PNM). It is supplied by the adjoining San Juan Mine and by the La Plata Mine 20 mi to the northeast. Both surface mines are operated by BHP Minerals in the Fruitland Formation. **0.4**

77.9 Intersection with County Road 6500. **Turn left**. Note badlands of Kirtland Formation to right in Hutch Canyon. **0.3**

78.2 Pigging station on natural gas pipeline on right; Western Gas Resources (formerly operated by El Paso Natural Gas) sweetening plant in the distance. Flare Hill, behind the plant, is the Q4d terrace of Ward (1990). M. L. Gillam (personal commun., 1996) suggests that Flare Hill, at about 330 ft above the river, is closer in height to Ward's Q3c, which is overlain by an ash bed dated at about 660 ka (hence, this terrace is about 670–710 ka). **1.0**

79.2 Traffic light at intersection with US-64; **turn right** to proceed west. **1.2**

80.4 Outwash gravels visible in Stevens Arroyo along the highway. This is the Q5 terrace of Ward (1990), correlated to the Bull Lake terraces of Richmond (1965). The larger clasts are principally quartzite, granite, dacite, and andesite, with some amphibolite, mobilized by Pleistocene glaciers in the San Juan and La Plata mountains. Proceeding downstream along the San Juan River, we encounter progressively lower, younger terraces. **0.8**

81.2 County Road 6675 (left) goes to Fruitland. **0.8**

82.0 Coal beds to right are in the Fruitland Formation. This was lush coastal plain some 68–70 Ma, but with proper aging the vegetative debris was transformed into fuel which now provides lighting for cities such as Phoenix and Los Angeles. The Fruitland Formation is the youngest coal-bearing unit in the San Juan Basin; the coal in the Fruitland field varies from high-volatile B bituminous to subbituminous A, with the higher rank found northward near the New Mexico-Colorado line, reflecting the influence of the San Juan volcanic field and the La Plata intrusive complex. Mean ash content of the coal ranges from 18 to 22%, definitely high ash (Hoffman, 1996).

Upper Cretaceous nonmarine strata exposed along the south bank of the San Juan River west of Farmington include the type sections of the Fruitland and Kirtland Formations of Bauer (1916, p. 274). These strata yield extensive fossil assemblages dominated by dinosaurs. In the San Juan Basin, the Fruitland Formation is as much as 550 ft thick and consists of interbedded sandstone, shale, mudstone, siltstone and lignitic to bituminous coal (Fassett and Hinds, 1971; Lucas, 1981; Hunt and Lucas, 1992). The Fruitland conformably overlies and intertongues with the Pictured Cliffs Sandstone and is conformably overlain by the Kirtland Formation (Fig. 3.5). Fruitland deposition took place on a delta plain (Lucas and Mateer, 1983).

The Kirtland Formation is as much as 1950 ft thick and consists of interbedded sandstone, mudstone, siltstone and

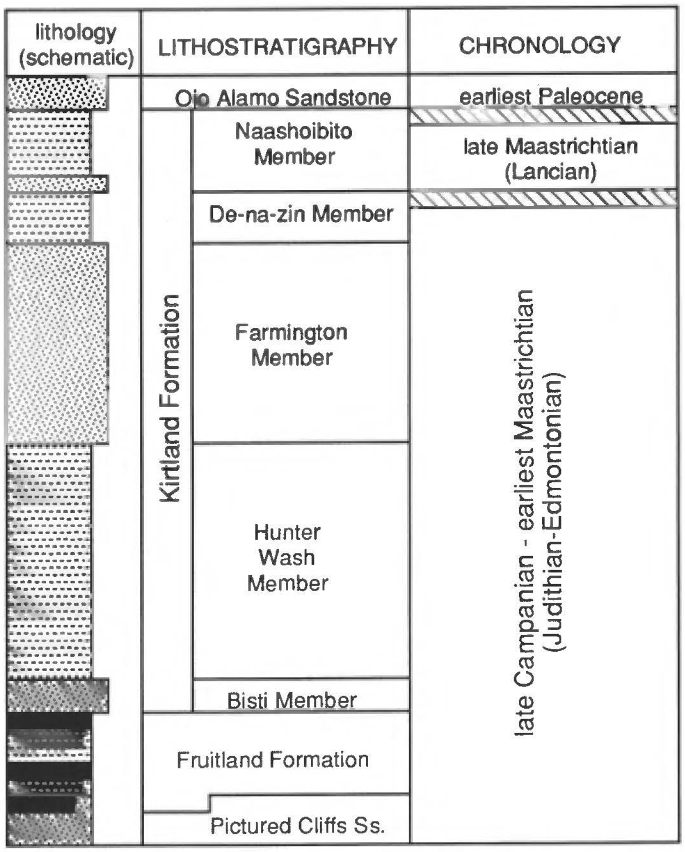

FIGURE 3.5. Summary of nonmarine Upper Cretaceous stratigraphy and chronology in the San Juan Basin.

minor shale. Lignitic to bituminous coal is limited to relatively thin, discontinuous beds near the base of the formation. Indeed, Bauer's (1916) initial recognition of the Fruitland and Kirtland as distinct formations was largely based on the abundant coal in the Fruitland (it is the economic unit from which most coal in the San Juan Basin is mined) and virtual absence of coal in the Kirtland.

Bauer (1916) divided the Kirtland Formation into three members and included its uppermost strata in the Ojo Alamo Sandstone. Baltz et al. (1966) and Hunt and Lucas (1992) redefined the Kirtland Formation and identified five members. The Bisti Member is a thin (up to 40 ft thick) sheet of sandstone. The Hunter Wash Member is up to 1250 ft thick and consists of green and gray siltstone, mudstone, thin, lenticular crossbedded sandstone, thin (<3 ft thick) carbonaceous mudstones and coals and rare, thin airfall volcanic ashes. The Farmington Member is up to 455 ft thick and is mostly sandstone and conglomerate with minor beds of mudstone and siltstone. The De-Na-Zin Member is up to 100 ft of mudstone, siltstone and minor sandstone, and the Naashoibito Member is as much as 100 ft thick and consists of interbedded sandstone, mudstone, siltstone and minor conglomerate. Kirtland deposition took place in a wide array of fluvial environments, mostly on meanderbelt floodplains (Lucas, 1981; Lehman, 1985). The Ojo Alamo Sandstone (sensu Baltz et al., 1966) disconformably overlies the Kirtland Formation.

The age relationships of the Fruitland and Kirtland Formations have been determined by their fossil content, their inferred relationships to ammonite biostratigraphy of the underlying and in part laterally equivalent Lewis Shale and Pictured Cliffs Sandstone, magnetostratigraphy and radioisotopic dating. These data indicate that the Fruitland Formation and lower Kirtland Formation (up to the Farmington Sandstone Member) are definitely of late Campanian age (Hunt and Lucas, 1992). The age of the Farmington and De-Na-Zin Members of the Kirtland Formation probably also is late Campanian based on magnetostratigraphy and radioisotopic ages (Fassett and Steiner, this volume), but these strata may also range into the earliest Maastrichtian. The Naashoibito Member produces fossil mammals and dinosaurs that indicate a Lancian (late Maastrichtian) age (Hunt and Lucas, 1992). This indicates there probably was a substantial hiatus (= much of Maastrichtian time) between the Naashoibito and De-Na-Zin Members of the Kirtland Formation (Fig. 3.5). **0.1**

82.1 Gas Man service station on the right is built on spoil from the former Smouse drift mines, which operated from 1926 to 1954 (Nickelson, 1988). **0.1**

82.2 Diversion dam in San Juan River and water intake station for PNM generating station visible on left. **0.5**

82.7 On the right are ruins of the Silva slope mine, which last produced coal in the late 1960s (Nickelson, 1988). All of the small abandoned mines in this area are now included within BHP's coal lease, and many of the old underground workings have been daylighted by the San Juan surface mine, which now extends southward almost to the highway. **0.2**

82.9 Just past unimproved County Road 6763, the highway enters the Pictured Cliffs (on right) and follows them for the next 1.1 mi (Fig. 3.6). The cliffs were named for the locally abundant petroglyphs. This is the type section of the marine-regressive Pictured Cliffs Sandstone, 200 to 250 ft thick; here it has abundant *Ophiomorpha* traces but very little lower shoreface sandstone. It is capped by a veneer of outwash gravel. **1.3**

84.2 Traffic light at junction with County Road 6800, which leads north to the San Juan Generating Station (Fig. 3.7). Turn right and proceed north. **0.3**

84.5 Badlands to left of road are developed in sandy, upper part of the Lewis Shale. **2.6**

FIGURE 3.6. Characteristic outcrop of the Upper Cretaceous Pictured Cliffs Sandstone in its type area.

FIGURE 3.7. Aerial view to north of San Juan generating plant. Open-pit mine is visible at far right, to east of plant.

87.1 **STOP 2,** San Juan Generating Station (Fig. 3.8), parking lot at visitor center on left; pull in and park. The San Juan Generating Plant is operated by the Public Service Company of New Mexico. It consists of four coal-fired pressurized units, the first two of which were completed and went on-line in 1972. Unit one is rated at 360 MW, unit two at 350 MW, and units three and four are each rated at 544 MW. Total gross MW rating is 1798. All units have state-of-the-art pollution control equipment installed to remove particulate material and to reduce and control SO_2, CO, and NOx emissions (see following minipaper by Anderson).

The coal is supplied from two sources. The main source is the San Juan Coal Company mine which lies immediately to the east of the plant and produces a high-ash coal from the Fruitland Formation. The other source is the La Plata Mine, located approximately 22 miles to the northeast, and supplies approximately 30% of the fuel needed to fire the plant. The La Plata also produces from the Fruitland Formation (see following minipaper by Hoffman). After Stop return to US-64. **2.9**

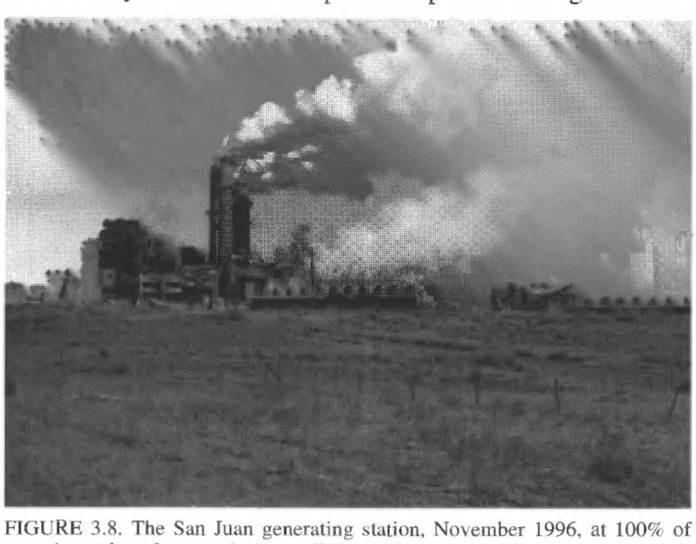

FIGURE 3.8. The San Juan generating station, November 1996, at 100% of capacity; a lot of steam, but very little smoke.

POLLUTION CONTROL AND ABATEMENT AT COAL FIRED GENERATING PLANTS

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The products of combustion in a coal-fired generating plant are the particulate and gaseous components in the exhaust (stack) gas stream, plus the inorganic-incombustible material left as residue in the combustion chamber, called bottom ash. The particulates entrained in the rising gas stream are called fly ash and consist for the most part of relatively low density, small diameter (<100 m), siliceous spherules. Although fly ash is important from an environmental standpoint, specifically with respect to visibility reduction in areas where no significant deterioration of air quality is permitted, generally 20% of the particulate matter remains behind as bottom ash. With high-ash coals (18–22%) such as those burned in the San Juan Plant, bottom ash removal becomes a problem. Total daily consumption of coal at the plant is approximately 20,000 tons. Thus nearly 4000 tons of bottom and fly ash are generated daily along with all the electricity. The bottom ash plus the collected flyash is hauled back to the mine; the fly ash (particulate matter) is quite effectively removed from the stack gas stream by the use of electrostatic precipitators. One potential use of this low-density material is feed material for cinder block, but the economics and feasibility have not been thoroughly investigated as yet.

Of the gaseous pollutants, sulfur dioxide (SO_2) is perhaps the most significant. All coal contains sulfur in various chemical forms; the arbitrary dividing line between high and low sulfur coal is 1%. The coal supplied to the San Juan Generating Plant is low sulfur by this standard. The problem with this definition of low sulfur is that it does not relate sulfur content to energy content (BTU) of the coal. In recognition of this problem the Environmental Protection Agency adopted (1971) regulations which state that fossil fuel fired steam generating units may not discharge gaseous effluent containing more than 1.2 lb of SO_2 per million BTU heat input (New Source Performance Standards). Low sulfur coal then becomes any coal which can meet the regulations, and is in essence compliance coal. Under this more relevant definition the coal supplied to San Juan is not low sulfur, or compliance coal, and scrubber technology had to be installed in order that the plant operate in compliance with Federal and State regulations, although State regulations are more stringent than Federal regulations. Since airborne sulfur compounds are the primary culprit implicated in the phenomena we have come to know as acid rain (SO_2 hydrolysis to sulfuric acid), sulfur removal from stack gases is an important part of complying with air quality regulations. At present the San Juan generating plant employs methodology developed by the British, called the Wellman-Lord process. This consists of a fine spray of alkaline solution injected into the gas stream, which results in the removal of most of the sulfur compounds (known collectively in the trade as SO_x). Currently the recovered sulfur is converted to a salable by-product, sulfuric acid, but the acid recovery system is complicated and expensive to operate. To improve upon this the plant is now in the midst of a significant modification that will allow more efficient removal of stack gas SO_x. A limestone-forced oxidation process will supplant the old Wellman-Lord approach on all four units by 1999. In the new process, a fine mist of water and limestone ($CaCO_3$) is sprayed into the absorber module resulting in the precipitation of anhydrite ($CaSO_4$), as follows:

$$CaCO_3 + SO_2 + heat®CaO + SO_2 + CO_2 \, -$$
$$CaO + SO_2 + ½O_2 ® CaSO_4{}^{-}$$

Thus the burning of coal must be viewed as more than simply a means by which modern society derives electrical energy; it also is an effective means of mobilizing sulfur, *and* liberating carbon trapped millions of years in sedimentary rocks. While not normally considered to be a pollutant, during the combustion process carbon is partially oxidized by combining with an oxygen molecule to form the poisonous, odorless, gas called carbon monoxide (CO), an unsaturated compound. Coal-fired generating plants, such as the San Juan Plant, closely monitor the CO in their stack emissions for two reasons: high CO indicates improper combustion and hence a waste of fuel, and they want to keep the release of this gas to an absolute minimum.

Another product of combustion are the nitrogenous compounds known collectively as NO_x. In higher concentrations one of these compounds (NO_2) may produce a brownish plume that is commonly and mistakenly attributed to particulate matter (dust). Coal is not the major source of nitrogen, the air is. The production of NO_x during combustion is directly related to temperature; the higher the combustion zone temperatures, the more nitrous oxide (or NO_x) is produced. This may be effectively dealt with by designing combustion chambers to operate at lower temperatures (or with no hotspots), without compromising the efficiency of the plant, and thus produce less NO_x. This is accomplished by staged combustion in which ultimately all the heat energy is delivered, but at lower temperatures and with a larger heat exchanger.

COAL MINES IN THE VICINITY OF FARMINGTON, NM

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Very little mining, except for small, temporary pits opened by the local Navajos for home heating fuel, was done before 1953 in the Navajo coal field, south of the San Juan River (Fig. 3.9). Utah Construction and Mining became interested in the coal on the Navajo Reservation in the early 1950s, obtaining an exploration permit in 1953 and a permit to mine from the Navajo Nation in 1957. In 1958 the company obtained a permit for water use. Arizona Public Service Co. (APS) became interested in the resource and negotiated with the Navajo Nation for a power plant site. APS signed a contract with Utah International to supply coal and water to the power plant in 1960. The Four Corners power plant was constructed and became operational with three units, a total capacity of 560 MW, in 1963. By 1966 two additional units had been built, bringing the total capacity to 2038 MW, and Utah Construction reached full production at the Navajo mine (Nickelson, 1988). In 1986 Utah International was acquired by BHP Minerals, Inc., present operators of the Navajo mine who hold the leases for the northern two thirds of the Navajo field. A 35-year contract between the Navajo mine to supply the Four Corners Power Plant expires in 2004, but there is a 15-year extension option (BHP, 1996). This contract is with a consortium of utilities including APS, Public Service Company of New Mexico, Salt River Project, Tucson Electric Power and El Paso Electric.

The Navajo, the largest open pit coal mine in New Mexico, is a dragline operation, mining up to nine seams in the Fruitland Formation. The mining sequence has proceeded southward from the power plant and an 18 mi rail line is used to transport coal from the newest pits in Area 3. The average quality of coal from the mine is 8750 BTU/lb, 22% ash, 0.75% sulfur, and 13% moisture. Production capacity is 9 million tons/year and current reserve estimates for the Navajo mine are 1 billion tons.

Small coal mines in the Fruitland coal field (Fruitland Formation outcrops north of the San Juan River) were opened in the 1890s and early 1900s to supply fuel for domestic use (Nickelson, 1988, p. 126). Very little large-scale mining took place in the Fruitland field before 1958. At that time, exploration projects were started that resulted in some of the present large strip-mining operations.

Most of the surface-minable resources of the Fruitland field are within the lease areas of the San Juan mine and the La Plata mine (San Juan Coal Co., subsidiary of BHP Minerals). Public service company of NM (PNM) and Western Coal Company's San Juan strip mine north of the San Juan River began "stripping" operations in late 1972. By 1977, Utah International began contract mining at the San Juan mine and in 1980 PNM sold its assets to Utah International (Nickelson, 1988). In 1986 San Juan mine became a part of BHP and is operated by the San Juan Coal Co., a wholly-owned subsidiary of BHP. San Juan mine is the main supplier of coal to the adjacent 1614 MW San Juan Generating Station. The principal owners of this power plant are PNM (46%), Tucson Electric Power (19%) and seven municipal utilities (35%) such as the city of Anaheim.

Two major coal seams in the Fruitland Formation are mined at San Juan. The mine employs both draglines and truck and shovels in their operation. In 1985 the stripping ratio increased to a point where pre-stripping was necessary. Deep leases at the southern end of the original mine lease were acquired in 1983 and are being evaluated for mining. Estimated recoverable reserves are 176 million st and production capacity is about 4 million st/year. San Juan coal averages 9,375 BTU/lb, 21.4% ash, 0.9 sulfur and 10.3% moisture.

The La Plata Mine operated by San Juan Coal in the northernmost Fruitland area, near the Colorado-New Mexico border, was permitted in January 1986 and had its first shipment of coal in August of that year. The La Plata mine produces coal from four coal seams varying from 6 to 30 ft thick (BHP, 1996). This mine is the only mine in New Mexico that uses trucks and front-end loaders exclusively for removal of overburden and coal because of the high-angle dip. Coal from the mine is trucked 22 mi on a special haul road to the San Juan power plant and blended with coal from the San Juan mine. Coal from this mine is high in ash (26%), averaging 9500 BTU/lb, 0.75% sulfur and 7% moisture. Average production is 1.5 to 2 million st/year. Recoverable reserves for the La Plata mine area are 73 million st.

90.7 Junction with US-64; **turn right** and proceed west. After turning note the many small aggregate pits developed in Pleistocene terrace gravels of the San Juan River Valley. **0.1**

90.8 Highway descends from the lowest terrace (Q6b of Ward, 1990) into Jewett Valley, an agricultural area developed on the younger alluvium of the floodplain. Pass under power lines. **0.2**

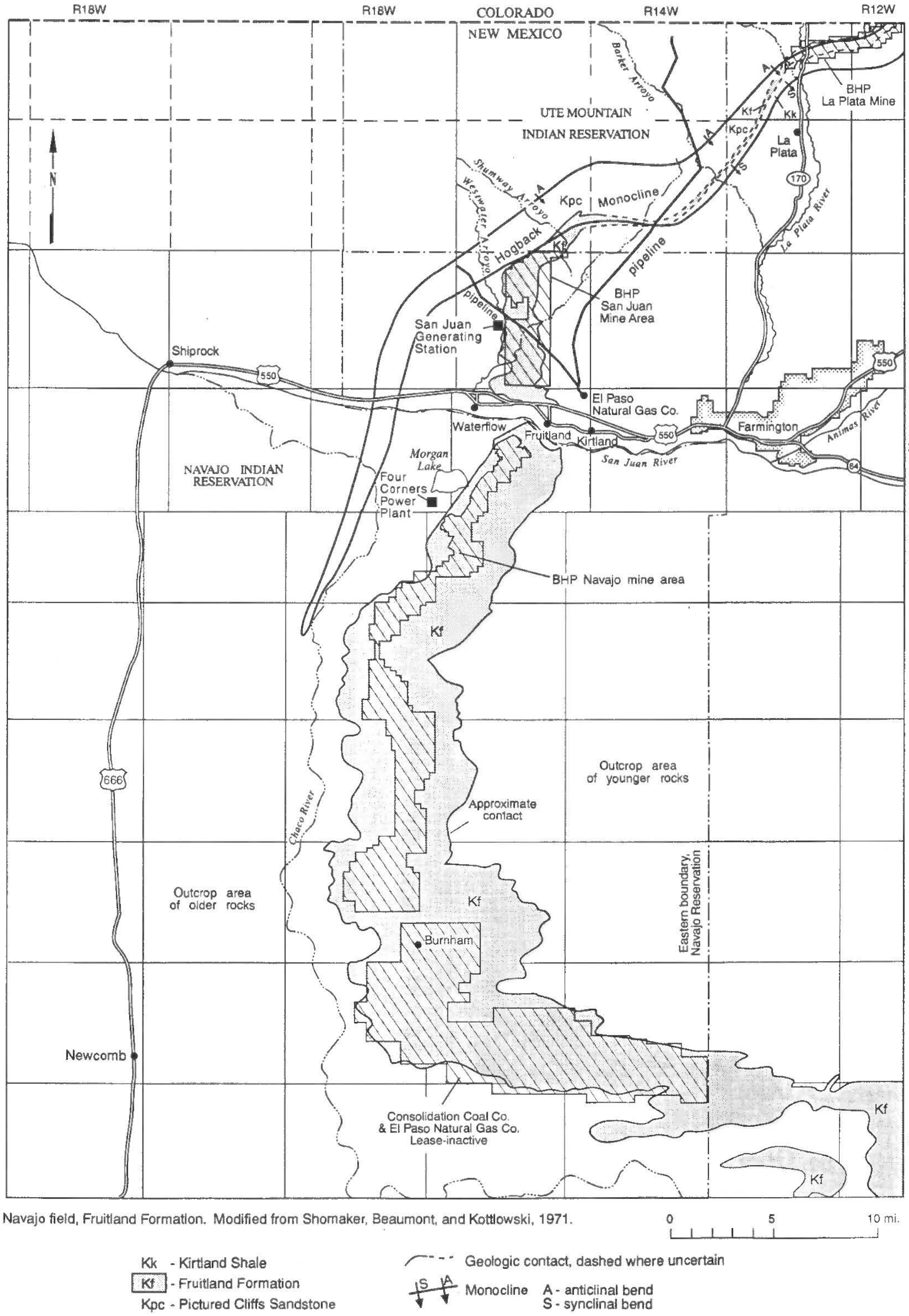

FIGURE 3.9. Map of the Navajo coal field.

91.0 Cross Shumway Arroyo. **0.2**

91.2 *Tsé taak'aan* ("rock ledge slanting into water"), the Hogback monocline, fills the near horizon from 11:00 to 2:00. This is the northwestern structural boundary of the San Juan Basin. From here only the cap of Cliff House Sandstone, uppermost unit in the Mesaverde Group, is visible. **0.5**

91.7 Pass under power line. **0.3**

92.0 County Road 6893, on right, leads north to oil wells and a pass in the Hogback. Continue straight ahead on US-64. **0.4**

92.4 Waterflow Post Office on right. **0.7**

93.1 The flat tops of the highest peaks in the Chuska Mountains, visible through the gap at 11:00, are the remnants of

Oligocene minette sills associated with the Navajo volcanic field. **0.3**

93.4 The stacks of the 2000-megawatt Four Corners power plant of Arizona Public Service are visible at 9:00. This plant is supplied by BHP's Navajo Mine, at one time the largest surface coal mine in the United States. Active and reclaimed pits, not visible from here, extend for more than 12 mi south of the plant, along the strike of the Fruitland Formation outcrop upsection from the Hogback. **0.7**

94.1 Hogback historical marker on right provides a concise geological description of this locality. **0.4**

94.5 Milepost 32. Three terraces, at heights above the river of about 50 ft, 180 ft and 240 ft; (elevations from M. L. Gillam) are visible across the San Juan from 10:00–11:30. The lowest terrace has been correlated to the Pinedale terrace of Richmond (1965) by several workers (Weide et al., 1979; Strobell et al., 1980; Ward, 1990; M. L. Gillam, personal commun., 1996). The next highest terrace, the Q5 of Ward (1990), has been dated at late Bull Lake by that author and at early Bull Lake by Weide et al. (1979). M. L. Gillam (personal commun., 1996) has correlated the highest terrace with the Farmington Airport terrace and estimates its age at about 400 ka (middle Pleistocene). This impressive exposure of Quaternary geomorphology was immortalized by John Shelton in his classic work, *Geology Illustrated* (1966), and is sometimes still seen as an illustration in introductory geology textbooks. **0.5**

95.0 Enter the Hogback monocline and the Navajo Nation. As we descend through the Mesaverde Group the units in order are, the Cliff House Sandstone, the carbonaceous Menefee Formation, and at the base of the hogback, the Point Lookout Sandstone (Fig. 3.10).

Notice: Persons wishing to conduct geological investigations on lands of the Navajo Nation, including the stops described in this guidebook, must first apply for and receive a permit from the Navajo Nation Minerals Department, P.O. Box 1910, Window Rock, AZ 86515, or (520) 871-6587. **0.1**

95.1 Carbonaceous shales, mudstones, and sandstones of the Menefee Formation crop out on the right (Fig. 3.11). **0.4**

95.5 Immediately past Milepost 31, **turn right** (north) through cattle guard onto old coal mine road (watch for debris). Coal mine road follows closely the top of Point Lookout Sandstone, here dipping approximately 26–30°E. Uppermost sand unit is commonly bleached and highly crossbedded and may represent a distributary channel sandstone (Fig. 3.12). **1.9**

97.4 Note clinker and tonsteins to right in Menefee Formation. **0.2**

97.6 **STOP 3**, at crest of hill. Here we have the opportunity to examine the Upper Cretaceous section consisting of the Point Lookout Sandstone, a regressive, littoral sandstone which prograded into the Western Interior Seaway to end a major depositional cycle recorded by the Mancos Shale; the overlying Menefee Formation, composed of carbonaceous shales and coal, and fluvial channel and overbank (floodplain) deposits); and the relatively thick, Cliff House Sandstone, associated with the last major transgression of the Seaway (Fig. 3.13).

The Point Lookout consists of as much as 53 ft of fine- to very-fine-grained quartzose sandstone with a wide variety of sedimentary features (ripple marks, flat to low angle crossbedding, small-scale scour surface, and small, calcareous-sandstone concretions). Body fossils are not common at this locality, but impressions of inoceramid

FIGURE 3.10. Aerial view of Hogback monocline.

FIGURE 3.11. Outcrops of Menefee Formation capped by cuesta-forming Cliff House Sandstone at Hogback monocline.

FIGURE 3.12. Light colored, cross-bedded sandstone at top of Point Lookout Sandstone.

shells have been noted and trace fossils are abundant. Most of this section could be assigned to a lower shoreface depositional environment based on the fine-grained, flat-bedded aspect. The slightly coarser grain size and crossbedding in the upper part indicates that it was deposited in a higher energy environment where wave and current action were major factors. This type of environment is generally described as upper shoreface characteristic of water depths less than 30 to 60 ft, although wave base is relative, not an absolute depth. Other depositional environments are represented along depositional strike both to the northwest and southeast.

Studies have shown (Cumella, 1983) that the Point Lookout contains more lithic fragments than some of the older littoral sands associated with regressive episodes along the western margin of the seaway, e.g., the Gallup

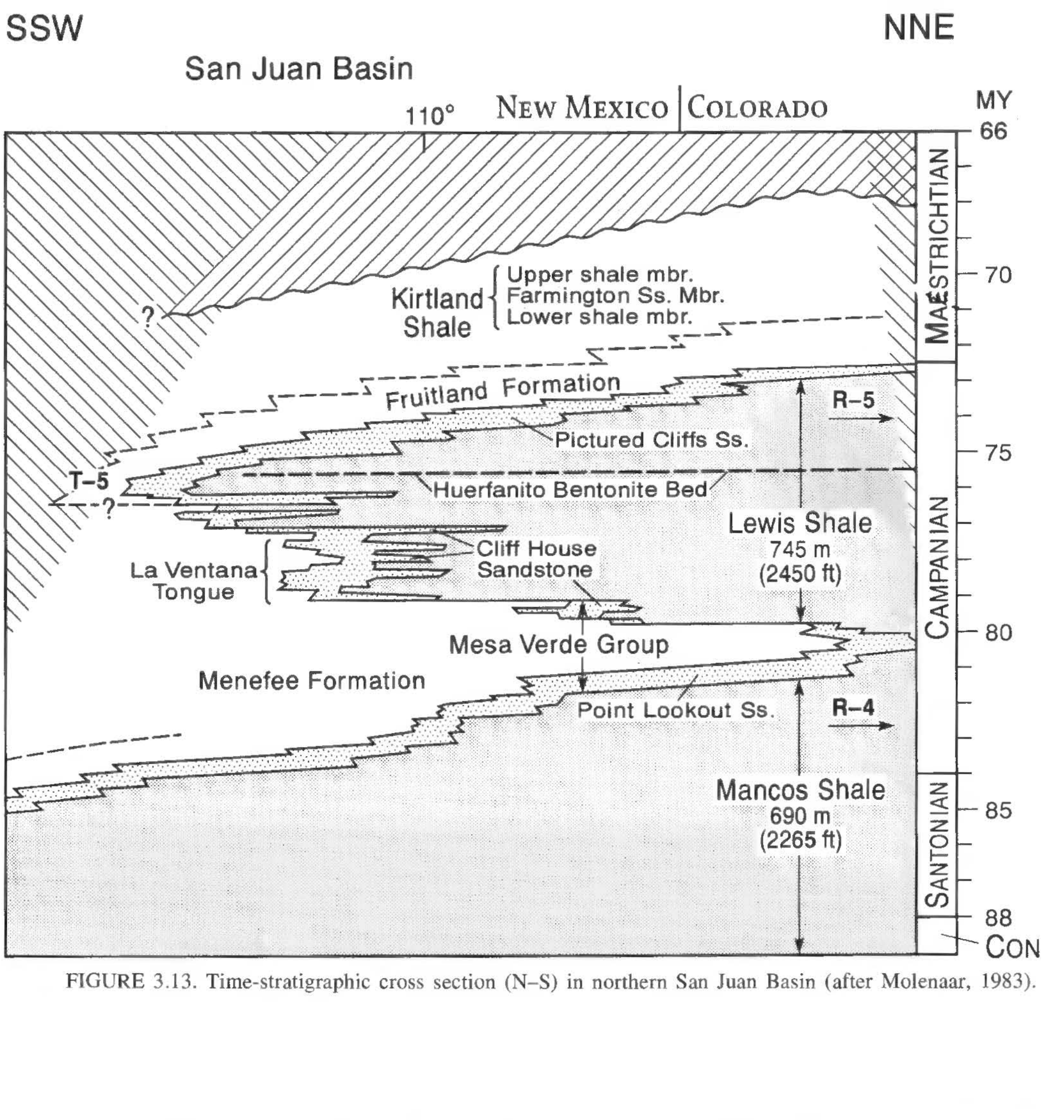

FIGURE 3.13. Time-stratigraphic cross section (N–S) in northern San Juan Basin (after Molenaar, 1983).

Sandstone. Source terrains were implied to be in southeastern Arizona, whereas farther northward, the source area for prograding sand bodies was considered to be the Sevier orogenic belt.

An interesting aspect of the Point Lookout is the seaward (northeastward) stratigraphic rise of the unit. In prograding across the San Juan Basin, a distance of approximately 130 mi, the Point Lookout rises stratigraphically about 1200 ft (Molenaar, 1977, 1983). Although the gradient is not uniform across this distance, the average does come out to 9.2 ft/mi. The gradient is very similar for the younger Pictured Cliffs Sandstone (Fassett, 1977), which does not crop out in the Hogback. But what do these figures represent? Obviously a seaward paleoslope existed prior to the onset of shoreline regression (progradation of Point Lookout sand body). What that slope was we do not know; but we envision that seaward from the littoral zone, offshore silty mudstones, and farther out, mud/shale were being deposited on this paleoslope. Further, global sea level was *not* falling (long term eustatic curve from Haq et al., 1988), and that in order for progradation to occur the vertical space (accommodation space) between the sea floor and sea level had to be filled in; only then could the paleoshoreline regress. This seaward-thickening wedge of sediment (Mancos Shale) accounts for the stratigraphic rise described by Molenaar (1977; 1983). Importantly, stratigraphic rise will be greater in such cases—regression driven by sediment supply with little or no eustatic change—than in the case of falling sea level (forced regression). For greater detail and discussion of the role of relative sea level change and localized sea floor subsidence see Posamentier et al. (1988).

Conformably overlying the Point Lookout is the slope-forming, carbonaceous, Menefee Formation, named for exposures on Menefee Mountain east of Mesa Verde National Park, by Collier (1919). The Menefee consists of as much as 1000 ft of lenticular crossbedded sandstone, mudstone, carbonaceous shale and coal (Fig. 3.14). This sequence was deposited in fluvial and paludal environments in deltaic and lower coastal plain settings developed behind the regressing paleoshoreline. The unit has been divided into a lower, Cleary Coal Member and the overlying Allison Member. Locally, mainly northward, an upper coal member has been recognized.

The coal in the Menefee Formation is within the Hogback coal field. This field is a NNE-trending area of Menefee and Cliff House that extends some 6 mi to the north of our present location to the north edge of T30N. Numerous small, underground mines are present immediately north of this vantage point and follow the outcrops of lower Menefee coal off to the northeast for nearly 3 mi.

According to reports of the Territorial Mine Inspector, the Hogback field was opened in 1907 to provide fuel for the Indian Agency at Ship Rock, 8 mi to the west. Previously, the agency had utilized coal mined from the Dakota Formation along the San Juan River, but this was low rank, high ash coal that would hardly burn. Here at the hogback locality the coal was of much better rank and quality. The initial mining took place in a 6-ft-thick bed and was called the San Juan mine (Nickelson, 1988). The land upon which it was located was originally public domain, but an act of Congress in 1936 extended the Reservation boundary a

FIGURE 3.14. Professor Steven Semken points to a tonstein in a coaly sequence in the lower part of Menefee Formation.

short distance to the east to provide the Navajo people easy access to this important fuel source. Navajo coal miners immediately opened numerous small mines or pits. By the 1950s the mining of coal from this area became so popular the Navajo Tribal Government felt it necessary to maintain some control of the activity and began issuing permits (Nickelson, 1988). Mining continued for another 20 years, the last of the Hogback mines closing in 1976. More and better housing with gas heating systems was partly responsible for the closing of the mines.

The prominent sandstone, which forms the crest of The Hogback immediately north of US-64, is the Cliff House Sandstone. Although McCubbin (1982) assigned the section exposed here to the La Ventana Tongue of the Cliff House, a unit named and recognized in the southeastern San Juan Basin, this is a long distance across which to correlate a member rank unit in the subsurface. However, the two localities lie along depositional strike and both represent beach, littoral, and/or lagoonal deposits along the western margin of the epeiric seaway. Perhaps further supporting the correlation is that similar to the type La Ventana, the local unit consists of a thick, vertical build-up of sandstone that terminates upward in what was an apparently rapid transgression.

Aside from the correlation and nomenclature of subunits within the Cliff House, the section so well-exposed here is an interesting one. As the measured section (Fig. 3.15) illustrates, the Cliff House is locally divided into three easily recognized units, in both a sedimentologic sense and from a mapping perspective. The lower unit consists of siltstone and sandstone in a coarsening-upward sequence as much as 48 ft thick. The base contains sufficient carbonaceous material to color it black, and probably represents reworking of paralic peat swamp deposits as the seaway transgressed the coastal plain. The coarsening upward aspect of the remainder of the section suggests shoaling upward in a regressive, progradational portion of an overall marine transgression, an interpretation consistent with that of McCubbin (1982) and Molenaar (1983).

The medial part of the section includes as much as 240 ft of fine-grained deposits—mudstone, shale, siltstone—with relatively thin beds of fine-grained, flat-to-low-angle-

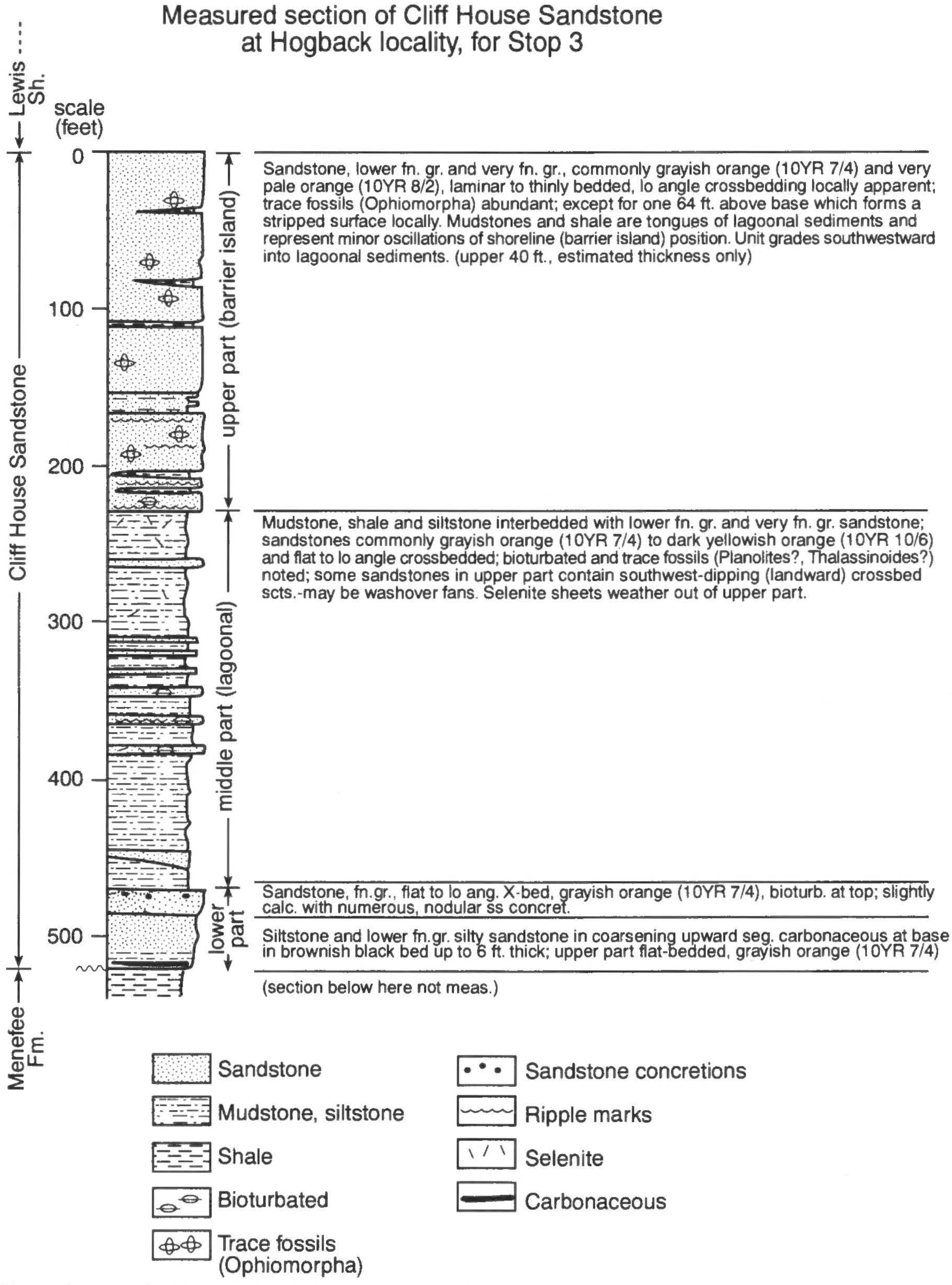

FIGURE 3.15 Measured section of Cliff House Sandstone in S½ SW¼ sec. 28, T30N, R16W, San Juan County, New Mexico; section is approximately 1 mi NE of Stop 3. (Section measured by O. J. Anderson and S. C. Semken.)

crossbedded, commonly bioturbated sandstone. Inasmuch as the entire unit appears to be lagoonal, based upon vertical and lateral relationships to barrier island deposits and the observations of McCubbin (1982), the thin beds of fine-grained sandstone likely represent washover fans deposited by storm channels cut through the barrier beach complex. The entire unit appears to thicken and become carbonaceous in a landward (SW) direction within 8 to 10 mi of this locality. The thickening comes at the expense of the overlying sandstone, and the carbonaceous matter represents influence from the mainland beach and associated paralic swamps.

The upper part of the Cliff House is a fine-grained, relatively thin-bedded sandstone, which forms the crest and dipslope along the east side The Hogback. This sandstone unit is as much as 229 ft thick (uppermost 40 ft estimated) and contains numerous trace fossils, mainly *Ophiomorpha*. Several thin mudstone and shale beds are present within the sandstone and represent intertonguing with laterally adjacent depositional environments. Given that this relatively thick sandstone unit grades landward (SW) into carbonaceous sediments, the sand body likely represents vertical build-up in a barrier island setting (McCubbin, 1982). This interpretation is supported by both outcrop and subsurface data. The Lewis seaway eventually transgressed the barrier island system and reached a maximum landward position some 20 mi SW of here. The youngest fossils reported from strata associated with this transgression are *Baculites perplexus* Cobban, which is consistent with an early late Campanian age. No diagnostic body fossils were found during the measurement of the local section.

After stop, turn around and retrace route to US-64. **2.1**

99.7 Junction with US-64; **turn right** and proceed W toward Shiprock for optional Stop 4. Contact between Point Lookout Sandstone and Mancos Shale is immediately east of the power line, on right. From here to the town of Shiprock the route will be on outwash terraces and floodplains cut into the upper Mancos Shale. For those who thirst for more Upper Cretaceous stratigraphy and are quizzical about the Gallup Sandstone, we are stratigraphically above it as well as some 12–15 mi seaward (northeastward) of the last vestiges of strata associated with the Gallup regression and lowstand (see following minipaper by Hart).

101.9 *Tsé bit´ á í* ("Rock with wings", or Ship Rock) visible at 10:30. This is part of the Oligocene Navajo volcanic field of lamprophyric necks and dikes that extends in an arc from the vicinity of Zuni northward to the Four Corners, then northwestward to the Monument upwarp. Ship Rock is 1640 ft high and consists mostly of minette tuff-breccia with a high percentage of comminuted wallrock. It contains abundant xenoliths of granitoid and mafic basement, and sedimentary rocks from the Plateau cover, but few ultramafic xenoliths. Three minette dikes extend approximately radially from Ship Rock. Minette from the prominent south dike was dated at 26.4±0.6 My by Laughlin et al. (1985), using the K-Ar method on phlogopite phenocrysts. **0.8**

102.7 Milepost 28. Red Jurassic sandstones exposed in the Beclabito dome are visible at the base of the Carrizo Mountains at 11:30. The highway descends from the youngest (Q6) terrace to the undifferentiated Naha and Tsegi Alluviums, here about 3–2 ft thick, in the floodplain (Ward, 1990). **0.1**

THE TOCITO SANDSTONES: VALLEY-FILLS, OFFSHORE BARS OR LOWSTAND SHOREFACES?

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Linear sand bodies of the Cretaceous Western Interior Seaway, such as the Turonian Cardium Formation (Alberta Basin), the Campanian Shannon Sandstone (Powder River Basin) and the Coniacian Tocito Sandstone (San Juan Basin) are currently the subject of considerable debate in sequence stratigraphic circles. At issue is whether these sandbodies formed as offshore bars (Fig. 3.16A), lowstand shorefaces (Fig. 3.16B) or valley fills (Fig. 3.16C). Each of these depositional models implies a different interplay of tectonic activity, relative sea-level change and depositional processes (i.e., different ways in which foreland basins fill), and each predicts a somewhat different distribution of sedimentary facies within the component sandbodies. These deposits can form important hydrocarbon reservoirs, so determining their origin is crucial for exploration and development activities to proceed in the most efficient and economical fashion.

The Tocito Sandstone consists primarily of medium- to coarse-grained sandstones and mudstones (McCubbin, 1969; Jennette and Jones, 1995; Valasek, 1995). Subsurface mapping and outcrop work show that the Tocito forms isolated, elongate sand bodies (typically 5 km across by 20–30 km long) that trend NW–SE. Paleocurrent directions measured in outcrop also trend NW–SE. These trends are approximately parallel to the shoreline trends defined for the underlying Gallup Sandstone (late Turonian). The Tocito sand bodies rest on a regional erosion surface and typically are encased in marine mudstones (Mancos Shale). More than 100 m of erosion exists at the base of the Tocito. The top of the formation is marked by a sharp lithologic transition from sandstone to marine mudstones.

Many workers, since the mid-1950s, have interpreted the Tocito, Shannon and other linear sand bodies as "offshore bars" or "sand ridges" (Fig. 3.16A; see Tillman, 1985 for a discussion of the application of this model to the Tocito). This explanation invokes the action of nearly shore-parallel currents (possibly controlled or influenced by sea floor bathymetry) to form shoreline-supplied sand into elongate ridges on the continental shelf. The erosion surface underlying the Tocito is currently thought to have been produced essentially subaerially during lowstand. One of the major problems with this explanation is mechanistic: how is medium to coarse sand (some formations are even conglomeratic) transported 10s of km from the contemporaneous shoreline, then formed into ridges?

Approximately 10 years ago, new interpretations regarding the Western Interior Seaway began appearing. The importance of relative sea level change with respect to shallow marine depositional systems became apparent, and some "offshore bars" (Cardium, Shannon) began to be reinterpreted as "lowstand shorefaces" (Fig. 3.16B; e.g., Plint, 1988). During

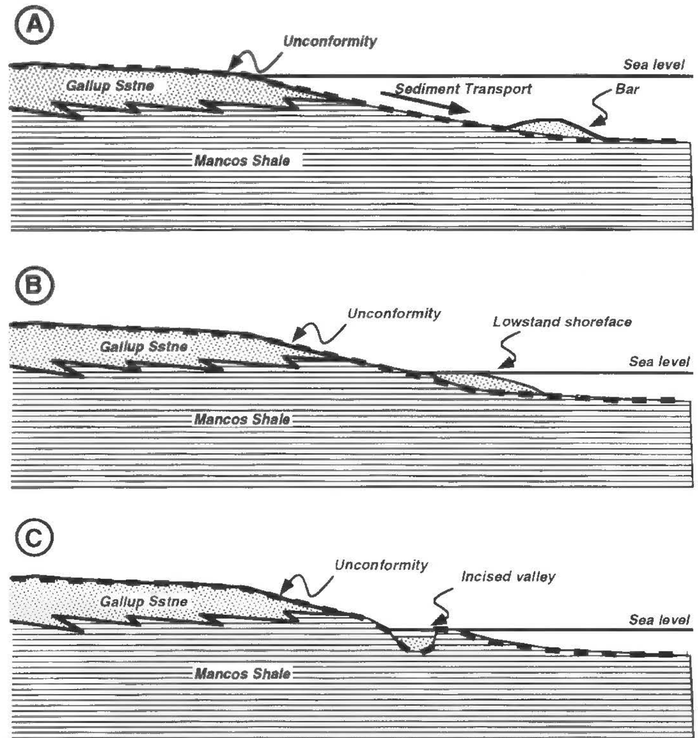

FIGURE 3.16. Three possible models for formation of Tocito Sandstone.

low stands of sea level, the shoreline moved 10s to 100s of km towards the center of the basin (the exact distance would be a function of the amount of sea level drop and sea floor slope). At such times, shoreline erosion could have incised elongate "bevels" into exposed offshore deposits; these bevels or "notches" were ultimately backfilled by shoreface deposits. This proposal helps to explain why these sand bodies are parallel to other shoreline indicators. The southeast paleocurrents could be the product of longshore currents in the surf zone (upper shoreface). It also helps to explain the generation of the regional unconformity that underlies the sand bodies. Previously, the Tocito Sandstone has not been interpreted as a lowstand shoreface sandstone.

The most recent interpretations of the Tocito Sandstone (Jennette and Jones, 1995) suggest that the formation is composed of incised valley-fill deposits (Fig. 3.16C). This interpretation has also been extended by other Exxon geologists to other linear sand bodies (e.g., Shannon). In this model, fluvial channels incise valleys into exposed shelf deposits during sea level lowstands. The orientation of the valleys parallel to other shoreline indicators is explained by reactivating NW–SE trending basement tectonic elements that constrain the rivers to flow in that direction (an idea originally suggested by McCubbin, 1969). During relative sea level rise, the incised channels would become estuaries and back-fill with sandy sediment. The paleocurrent directions indicate that the majority of the sediment was transported "down estuary." One of the major problems with this explanation is that the tectonic dip (up to the NW) needed to cause flows to the SE is at right angles to the dip (up to the SW) needed to cause other shorelines (e.g., Gallup) to prograde to the NE. Some record of this short-lived change in tilt should be preserved in the stratal record, but as yet none has been recognized.

The origin of the Tocito, Shannon and other linear sandbodies was debated at a SEPM Research Conference in 1995 but no consensus was reached. Why does the disagreement continue? Outcrops of linear sand bodies such as the Tocito tend to expose rocks that can be interpreted in a variety of ways. The elongate nature is defined in the subsurface, where subsurface data (cores, logs) can also be ambiguous. There are also no universally accepted good modern analogs for these units. Last, but certainly not least, scientific reputations are at stake.

The truth may lie in a combination of processes. For example, while Valasek (1995) recognized some estuarine deposits in the Tocito, he contended that the bulk of the formation consists of sands that were reworked during transgression into deposits somewhat akin to offshore bars. Similarly, it could be envisaged that lowstand shoreface sands could also be reworked by shelf currents during transgression into depositional bodies of mixed origin. Although reactivation of basement tectonic features might cause reorganization of drainage patterns, this type of movement might also help determine where shorefaces become incised during lowstands (Hart and Plint, 1993). In any event, linear sand bodies similar to the Tocito promise to be the source of rich debate in stratigraphic literature for many years to come.

102.8 Cross Hogback irrigation canal. **0.2**

103.0 Cross Eagle Nest Arroyo, which drains the marine and shoreface strata along the western slope of the Hogback. When flowing, this minor arroyo may represent the single largest contributor of salinity and dissolved solids to the lower San Juan River. The USGS has collected surface-water samples here containing total dissolved solids as high as 32,500 mg/L, whereas the San Juan River at the Hogback typically contains only 495 mg/L total dissolved solids (Thorn, 1993). **0.3**

103.3 Chimney Rock pinnacle, an erosional outlier of Mesaverde capped by Point Lookout Sandstone, is visible on the horizon at 3:00. **0.3**

103.6 Navajo Route 5031 leads north past the Hogback chapter house (against the terrace at 2:00) and on to the Horseshoe Gallup oil field. **0.2**

103.8 Note thin reddish-brown shelf sand unit in the upper Mancos Shale, exposed in the terrace on the right. **0.9**

104.7 Milepost 26. Elevated Hogback canal parallels the highway on right. **0.3**

105.0 Shelf sands hold up badlands topography in the upper Mancos Shale, on right. **0.7**

105.7 Milepost 25. The wide, flat- (sill-) topped mountain in the Chuska range visible at 10:30 is *Dzik´íhózhónii* (Beautiful Mountain). **0.5**

106.2 Enter Shiprock. Although it is not an incorporated town, it is the largest community in the Navajo Nation, with a population of about 10,000. It is also the largest Native American community in the United States. The locality was traditionally known to many *Diné* (Navajos) as *Tooh*, for the San Juan River. In 1903, Bureau of Indian Affairs agent William T. Shelton established a headquarters here and named it Shiprock for the prominent landmark 10 mi to the southwest. Navajos referred to Shelton as *Naat´aanii Nééz* (Tall Leader), and the community eventually came to be known by this name as well.

Historically an agricultural area, Shiprock grew with the establishment of a hospital and boarding school (now housing Navajo Community College), in 1912. It passed through a boom period in the 1950s and 1960s as the site of uranium-milling and helium-processing operations. The community is gradually emerging from the bust that followed, in its present role as the commercial, administrative, and educational center of the eastern Navajo Nation. **1.2**

107.4 Cross Baker Arroyo. Shiprock Trading Company on left. **0.2**

107.6 Milepost 23. Shiprock Chapter House on right. **0.2**

107.8 Traffic signal. Continue straight ahead on US-64. **0.2**

108.0 Traffic signal at junction with US-666. Continue straight ahead. Navajo Community College and Northern Navajo Medical Center to north. Shiprock flea market on left. **0.3**

108.3 Uranium-Mill Tailings Remedial Action (UMTRA) disposal cell is the gravel-covered pile visible atop the terrace at 9:00. Groundwater contamination in the terrace gravels and the alluvium of the floodplain beneath the cell is now being characterized in advance of possible remediation. **0.1**

108.4 Cross *Tooh* (San Juan River) on truss bridge. Shale and fine-grained sandstone of the lower part of the upper Mancos Shale exposed in the far bank of the river. After the bridge, the highway curves to the south. **0.5**

108.9 Traffic signal at junction of US-666 south and US-64 west, at Tsé Bit´aí shopping center. Continue straight ahead on US-666. Fairgrounds on left is the site of the Shiprock Navajo Fair, "the oldest and most traditional of Native American fairs," held the first week in October every year.

The Tsé Bit´aí shopping center on the west side of US-666 near the junction with US-64 was the site of a former U.S. Bureau of Mines helium processing plant. This plant was one of four built by the U.S. government during World War II to meet the increased demand for helium (The others were located at Amarillo, Texas, Excell, Texas, and Otis, Kansas). The Shiprock plant was completed in 1944, but was opened only on a trial basis and remained on stand-by status until 1952. At that time it went into production to meet the heavy demands of the Korean conflict. The plant had the capacity to process two to four mcf of gas per day. The gas originally came from government leased wells in the Rattlesnake field. Later, wells in the Hogback and Table

Mesa fields well were added. The gas from the Table Mesa field averaged 5.4% helium, but the other fields produced gas containing an average of only 0.5%.

Helium was separated from the other components by cooling the gas to a temperature below the liquefaction point of the ordinary constituents, but above that of helium. The helium having thus been concentrated to a purity of 98.2 to 99.5% by this method, was then passed over activated charcoal that had been cooled to the temperature of liquid nitrogen (195.8°C). The charcoal absorbed nearly all the remaining impurities resulting in a product with a purity of 99.995%. The helium produced at Shiprock was transported via underground pipeline to Gallup, New Mexico. At Gallup the helium was loaded into specially designed railroad tank cars. Rail transportation was discontinued in 1968 and the helium was then shipped by semi-trailers to various military and industrial plants.

Helium (the name comes from the Greek word "helios" meaning sun) is one of the inert gases; it is the second lightest gas known (0.177 g/l). These properties render it useful in a variety of applications. It has been used as a pressurizing agent for liquid fuel missiles and rockets and as a heat transfer medium in gas-cooled nuclear reactors. Other applications include usage in balloons and caissons, as an inert medium in shielded-arc welding, in growing transistor crystals, and in wind tunnels. In 1971 80% of the helium that was produced was purchased by Federal government agencies such as the Atomic Energy Commission, the Department of Defense, The National Aeronautic and Space Administration and the National Weather Service.

The Shiprock plant was operated by the Bureau of Mines until August, 1966, when it was transferred to the Bureau of Indian Affairs, which subsequently transferred it to the Navajo Nation. Air Reduction Company then leased the plant from the Navajos and operated it until September, 1969. It was next leased and operated by the Linde Division of the Union Carbide Corporation as a pilot plant in 1970 and 1971. The plant was abandoned in late 1971 and later demolished. **0.3**

109.2 Just past the fairgrounds, turn left onto Uranium Boulevard. **0.3**

109.5 Navajo Engineering and Construction Authority facility ahead is on the site of the former Kerr-McGee/Vanadium Corporation of America/Foote Minerals uranium mill, which operated from 1954 to 1968. The mill buildings, some encrusted with yellowcake (U_3O_8) dust, were removed in 1975. **Turn right** just before the gate. **0.1**

109.6 **Turn left** at first gravel road. **0.3**

109.9 **OPTIONAL STOP 4**. Shiprock UMTRA Site (Fig. 3.17), where we will discuss the local history and environmental impact of the uranium industry and view a remediated uranium mill site.

The Shiprock site, consisting of 230 acres, was located on the south side of the San Juan River on the Navajo Indian Reservation in what is now the center of the community of Shiprock, New Mexico.

The discovery in early 1949 of uranium-vanadium outcrops in the Salt Wash Member of the Morrison Formation in the Lukachukai Mountains of northeastern Arizona created interest in this area. Local Navajos, Dan Phillips and Kiley Black, made the original discoveries. F. A. Sitton of Dove Creek, Colorado, acquired leases in the mountains on December 20, 1949, and began mining in June 1950. During the summer of 1951, the Dulaney Mining Company of Cortez, Colorado began to map and sample all of the known mineralized exposures in the mountains.

In August 1951, the newly formed Navajo Uranium Company of Cortez, Colorado, acquired F. A. Sitton, Inc., and the Navajo leases. Richard O. Dulaney Jr. was the president of Navajo Uranium, and other officers were Edward Key and G. R. Kennedy. Navajo Uranium began mining in September, 1951.

Due to the success of locating new mineralized outcrops and the encouraging results of the initial drilling being done by the U.S. Atomic Energy Commission (AEC), officials of Navajo Uranium proposed to the AEC the construction of a 300-ton-per-day mill in Shiprock, New Mexico to process the Lukachukai ores and other ores in the Four Corners region. The mill proposal was not approved; but permission was given to construct an ore-buying station at Shiprock. The station was built by Navajo Uranium and was operated for the AEC by a contractor, American Smelting and Refining Company. The station began operating on January 17, 1952, and provided a market for all non-Vanadium Corporation of America (VCA) controlled ores in northeastern Arizona and northwestern New Mexico.

Early in 1952, Kerr-McGee Oil Industries, Inc., of Oklahoma City, Oklahoma, became interested in the Navajo Uranium Company's operations in the Lukachukais, and the potential of the area as indicated by Dulaney's maps and drilling being done by the AEC. In May, 1952, Kerr-McGee acquired the Navajo Uranium Company's holdings in the Lukachukai Mountains and the ore-buying station at Shiprock which had been leased to AEC. This marked the first time an oil company becoming involved in uranium exploration and mining.

On August 17, 1953, Kerr-McGee Oil Industries, Inc., Navajo Uranium Division, signed a contract with the AEC to produce uranium concentrates from the processing mill to be built at Shiprock, New Mexico, near the site of the AEC buying station. The mill was constructed at a cost of $3,161,000, and began operation in November 1954 at a

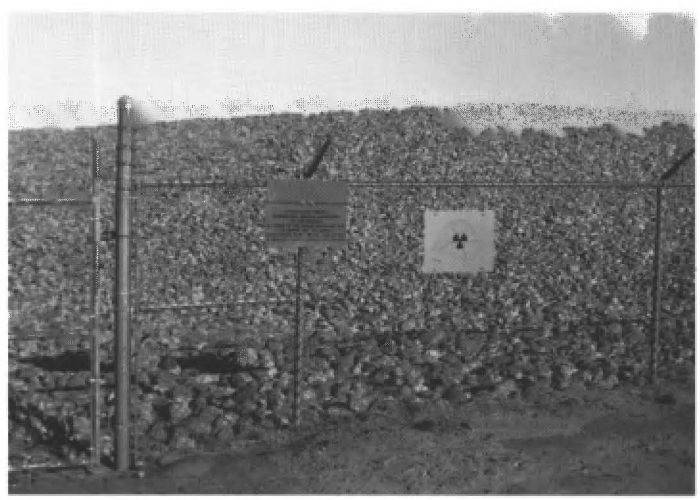

FIGURE 3.17. The Shiprock UMTRA site.

nominal capacity of 300 tons of uranium-vanadium ore per day. Later additions of equipment and process modifications increased the capacity to 500 tons per day.

On November 1, 1954, Kerr-McGee assumed the operation of the AEC ore-buying station. The AEC later sold the ore piles at the buying station to Kerr-McGee. This material amounted to 129,638 tons of ore averaging 0.28% U_3O_8 and 1.08% V_2O_5.

Ores for the Shiprock mill came from mines in the northern portion of the Navajo Indian Reservation, and other widely dispersed areas of the Colorado Plateau in Colorado, New Mexico, Arizona and Utah. After Vanadium Corporation of America assumed operation of the mill from Kerr-McGee on March 1, 1963, a portion of the Shiprock millfeed also consisted of dried slime concentrates and chemical precipitates produced by VCA's concentrating plants located at the Monument No. 2 mine in Monument Valley, Arizona.

Fifty-six percent of the ore fed to process at the Shiprock plant came from company controlled mines. Thirty-two percent was purchased from independent producers, and 12% was acquired from the AEC.

The original uranium-vanadium mill utilized an "acid cure" process to improve the recovery of vanadium from the relatively low-lime, high-vanadium ore. In this process crushed ore remained in a concentrated sulfuric acid solution for 6 hours or more to dissolve the vanadium and the uranium. There were materials handling problems with the initial mill design so the acid cure was abandoned in favor of conventional agitation leach in 1955. Concurrently, Kerr-McGee added a solvent extraction (SX) circuit to supplement the original fixed-bed ion exchange circuit. The SX circuit operated so well that eventually the operation of the ion exchange unit was discontinued.

The mill used conventional ore crushing, and grinding, followed by a two stage hot sulfuric acid leach with oxidant to solubilize both the uranium and vanadium. After liquid solids separation in classifiers and thickeners, the pregnant solution was treated by separate SX circuits to recover first the uranium, then the vanadium. Uranium recovery averaged about 95% for the life of the mill and vanadium recovery only 58%.

On March 1, 1963, the Shiprock mill was sold by Kerr-McGee Oil Industries, Inc., to the Vanadium Corporation of America (VCA). The sale also included Kerr-McGee's mines in the Lukachukai Mountains and the employee housing in Shiprock. The AEC issued VCA a new contract, effective January 1, 1963, to merge the Kerr-McGee and Durango contracts into a single one.

Vanadium Corporation of America was merged into Foote Mineral Company on August 31, 1967, and Foote continued the Shiprock milling operation until May of 1968 when operations ceased. Foote's lease on the millsite expired in 1973 and full control of the site reverted to the Navajo Nation.

During the seven years and four months the mill was operated by Kerr-McGee a total of 944,420 tons of ore was fed to process. The ore feed averaged 0.26% U_3O_8 and 0.88% V_2O_5. Kerr-McGee produced 4,559,473 lbs U_3O_8 in concentrate and shipped 4,524,236 lbs U_3O_8 to the AEC. Kerr-McGee also produced 5,914,212 lbs V_2O_5 in fused oxide, none of which was purchased by the AEC.

During the five years and two months that VCA and Foote operated the Shiprock mill, 582,767 tons of uranium-vanadium ore was fed to process. The millfeed averaged 0.23% U_3O_8 and 1.38% V_2O_5, and VCA-Foote recovered 2,863,423 lbs U_3O_8 and 14,544,316 lbs V_2O_5. VCA-Foote shipped 2,897,264 lbs U_3O_8 and no V_2O_5 to the AEC from Shiprock. The AEC purchased a total of 7,421,500 lbs U_3O_8, in concentrate, from the Shiprock mill at an average price of $9.18/lb.

Decontaminated portions of the western side of the millsite were used by the Navajo Engineering and Construction Authority for an earth moving training program which was begun in 1973 and continued until 1978. The millsite was reclaimed in 1985 under the Uranium Mill Tailings Radiation Control Act of 1978. The encapsulation of the tailings was completed in 1986. (Modified from Albethesen and McGinley, 1982 and Chenoweth, 1988).

End of Third-day Road Log. Retrace route to shopping center at Mile 108.9, and proceed as is your want or as the spirits may move you.