Second-day road log: From Cuba to Counselor, Lybrook, Nageezi, Barrel Springs, Fossil Forest, Blanco Trading Post and return to Cuba

Thomas E. Williamson, Spencer G. Lucas, Adrian P. Hunt, Larry N. Smith, and Barry S. Kues

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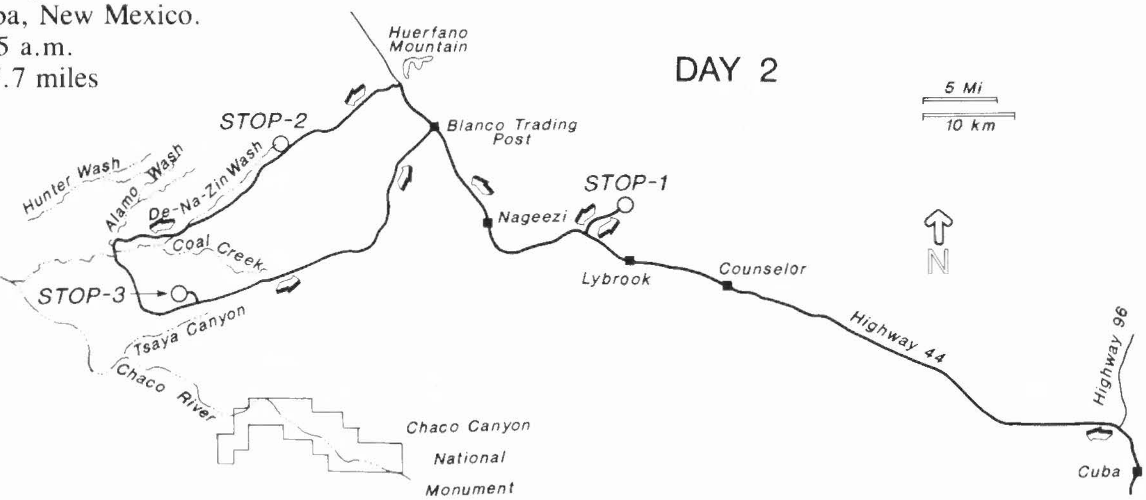
SECOND-DAY ROAD LOG, FROM CUBA TO COUNSELOR, LYBROOK, NAGEEZI, BARREL SPRINGS, FOSSIL FOREST, BLANCO TRADING POST AND RETURN TO CUBA

THOMAS E. WILLIAMSON, SPENCER G. LUCAS, ADRIAN P. HUNT, LARRY N. SMITH
and BARRY S. KUES

FRIDAY, OCTOBER 2, 1992

Assembly point: Parking lot of Frontier Motel and Cafe, Cuba, New Mexico.
Departure time: 7:45 a.m.
Distance: 187.7 miles
Stops: 3



SUMMARY

Today's route traverses a portion of the central San Juan Basin and focuses on the stratigraphy, sedimentology, paleontology and economic geology of the uppermost Cretaceous (Lewis Shale, Pictured Cliffs Sandstone, Fruitland and Kirtland Formations) and lower Tertiary (Ojo Alamo Sandstone, Nacimiento and San Jose Formations) strata exposed in this portion of the basin.

At Stop 1, we examine a long-standing mapping error that appeared on Dane and Bachman's (1965) and Clemons' (1982) geologic maps of New Mexico, where the contact between the Paleocene Nacimiento Formation and the overlying Eocene San Jose Formation was incorrectly mapped. We will also discuss the lithologies of the Escavada Member of the Nacimiento Formation. From Stop 1, we continue west toward Huerfano Peak and turn south to De-Na-Zin Wash. Stop 2, for lunch, is at the parking area overlooking the badland exposures of the Nacimiento Formation of the De-Na-Zin Wilderness Area. Here we will discuss the Cretaceous-Tertiary boundary. After lunch, we continue south to the Bisti badlands. Stop 3, our last stop, is at the Fossil Forest. Here we discuss the coal resources and fossil flora and fauna of the Upper Cretaceous Fruitland and Kirtland Formations. After Stop 3, we return north to the main highway and travel southeastward back to Cuba.

Mileage

0.0 **Turn right** and proceed north on NM-44. **0.1**

0.1 At 3:00 to right, low gray beds are Paleocene Nacimiento Formation in front of Nacimiento uplift. **0.5**

0.6 At 1:00, note latest Paleocene–early Eocene Cuba Mesa Member of San Jose Formation above Nacimiento Formation (Fig. 2.1). This is Baltz's (1967) reference section of the Nacimiento Formation–Cuba Mesa Member contact and the base of the type section of the Cuba Mesa Member. Note channelized nature of the Cuba Mesa Member in the 130-ft-high cliff where paleochannels are oriented toward the south.

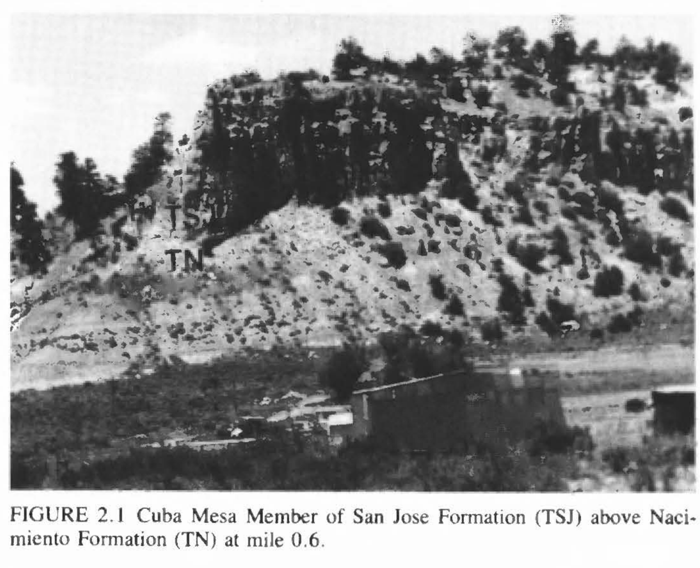


FIGURE 2.1 Cuba Mesa Member of San Jose Formation (TSJ) above Nacimiento Formation (TN) at mile 0.6.

At 9:00, note slight angular unconformity between the Nacimiento Formation and the base of the Cuba Mesa Member, where beds of the Nacimiento are truncated to the south. **0.5**

1.1 Lignites in the Nacimiento Formation on the right contain plant fossils. **0.1**

1.2 Road crosses Nacimiento Formation–San Jose Formation contact; road will now pass through three 120-ft-thick sandstones of Cuba Mesa Member for next 2.2 mi. **0.9**

2.1 Outstanding outcrop of Cuba Mesa Member sandstones in roadcut to right displays at least three paleochannel cross sections (Fig. 2.2). **0.7**

2.8 Cross San Jose Creek. **0.6**

3.4 Junction with NM-96 to La Jara; continue straight on NM-44. **0.3**

3.7 Roadcuts in San Jose Formation, Cuba Mesa Member. Road will now climb above the Cuba Mesa Member and into the Regina Member. The Regina Member is dominated by colorful mudstones interbedded with thin siltstones and fine-grained sandstones deposited in alluvial floodplain settings. **0.4**

4.1 Good view at 3:00 of San Jose Creek valley and San Jose Formation. Note Regina Member forming ridges along Continental Divide. **0.9**

5.0 Dirt road to right enters Jicarilla Apache Reservation and gives access to San Jose Formation fossil beds there (cf. Lucas et al., 1981). **2.0**

7.0 Golden-brown sandstone on right in roadcut is an alluvial channel sandstone of the Regina Member of the San Jose Formation. These sandstones (in roadcuts next 0.7 mi) are identical in lithology to those in the Cuba Mesa Member, but cannot be traced into the main body of the Cuba Mesa Member. **2.1**

9.1 Crest of hill in somber mudstones and sandstones of the Regina Member. Coarse-grained channel sandstones are replaced laterally by floodplain mudrocks. Much of the Quaternary alluvium along drainages is cut by arroyos along which modern yellowish brown soils and similar, but buried (late Holocene?), soils are exposed. **3.0**

VEGETATION AND PLANT COMMUNITIES OF THE SAN JUAN BASIN

Paul J. Knight

Marron, Taschek and Knight, Ecotechnical Services, 4686 Corrales Road, Corrales, New Mexico 87048

The San Juan Basin includes portions of San Juan, McKinley, Rio Arriba and Sandoval Counties, New Mexico, as well as portions of Montezuma County, Colorado. The terrain varies from sparsely vegetated badlands to pine forested mountains to grasslands and brushland on the lower mesas. Erosion has played an important role in shaping the landscape of this semiarid region, exposing sandstone cliffs and cutting deep arroyos in the high mesas. San Juan County covers much of the northern half of the San Juan Basin, bordering Arizona, Utah and Colorado. The San Juan River flows from Colorado through the northern part of the basin and eventually empties into the Colorado River. Nearly 80% of the land is held by the Navajo Nation, and another large portion is federally owned.

The vegetation of the San Juan Basin is primarily an eastward extension of the Great Basin desert flora. The Great Basin Desert is dominated by low, semi-woody half-shrubs that often form large, rather monotonous stands. These shrubland communities are usually dominated by cold-tolerant xeric shrubs that are adapted to a predominantly winter rainfall pattern. However, other floristic assemblages, such as the southern Rocky Mountain flora and the New Mexico desert grassland, contribute considerable numbers of species to the San Juan Basin flora.

Fossil floras indicate that the northern part of the Great Basin was forested during the Miocene (Axelrod, 1983). As a trend toward drier weather continued, Axelrod estimated that precipitation gradually decreased, resulting in greater drought stress and warmth southward. Eventually, the increasing aridity led to the development of sclerophyllous shrub communities. The flora of the Great Basin has two major ancestral sources. One is related to the east Asian deserts and semideserts. This is characterized by the presence of species such as *Ephedra* (Mormon tea) and *Atriplex* (saltbush). The second group of plants that contribute to the Great Basin flora occur in the Mohave and northern Sonoran Desert region. These include shrubs such as *Chrysothamnus* (rabbitbrush), *Erigonum* (wild buckwheat) and *Teradymia* (horsebush) (Axelrod, 1983).

Aspect and substrate play major modifying roles in the composition of plant communities. The communities on the northern exposures of canyons and mesa slopes are often quite different from those found on western or southern aspects. However, at the same aspect and elevation,

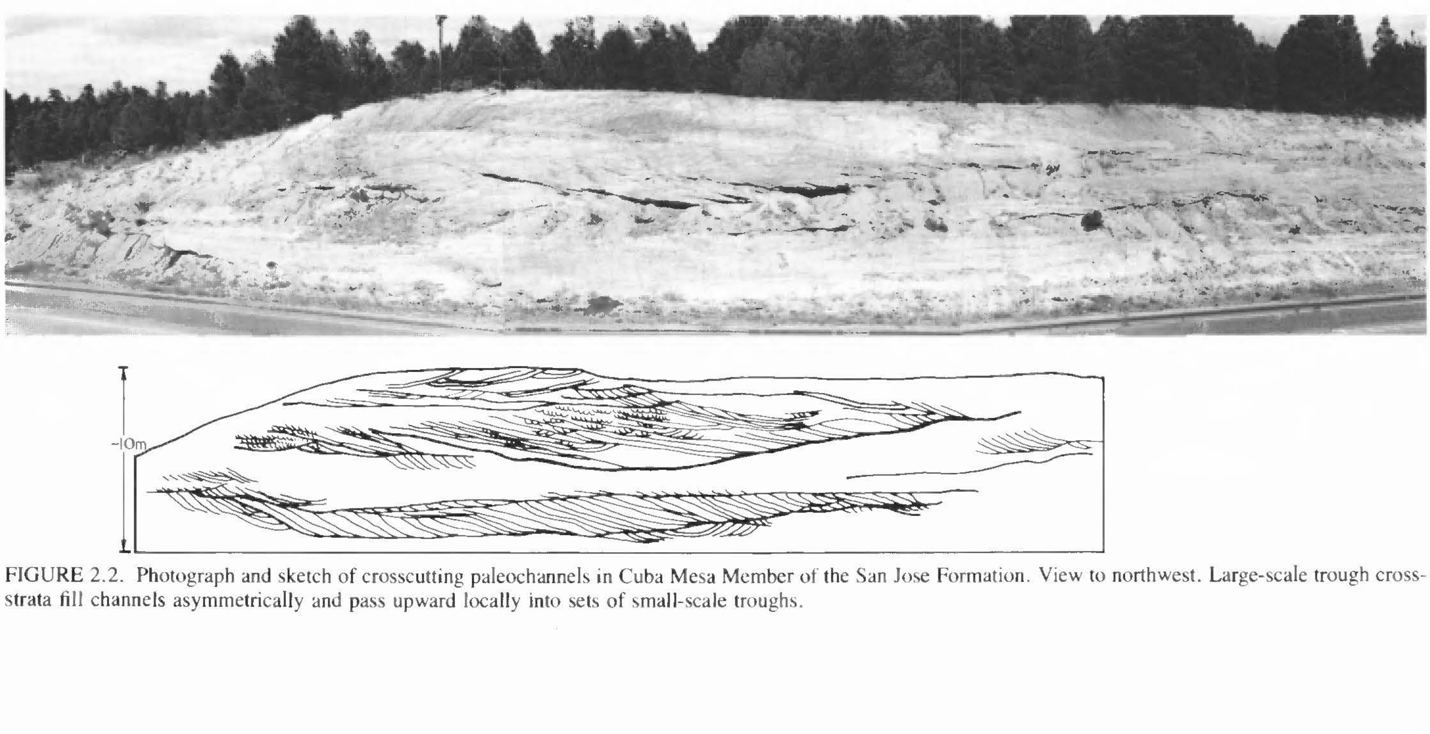


FIGURE 2.2. Photograph and sketch of crosscutting paleochannels in Cuba Mesa Member of the San Jose Formation. View to northwest. Large-scale trough cross-strata fill channels asymmetrically and pass upward locally into sets of small-scale troughs.

plant communities can change rapidly from bunch grass to sagebrush or even saltbush just by changes in soil composition. Consequently, in areas of complex geology with pronounced variation in topography and soil types, the mixture of plant communities can become quite complex.

Four general vegetation types are common within the San Juan Basin. These include sagebrush/scrubland, pinyon and juniper woodland, grasslands and badland-lowland areas dominated by saltbush or greasewood communities. In addition to the four general vegetation types described above, portions of the mountains along the edge of the basin support communities of ponderosa pine and Douglas fir, a variety of unique rimrock communities that are restricted to areas of exposed sandstone bedrock, and riparian communities along perennial streams and rivers.

The sagebrush communities are primarily moisture-controlled rather than soil dependent. They are found on well-drained loams, fine clays, or sandy soils, but always require at least 9 in. of annual precipitation. Typically, big sagebrush (*Artemisia tridentata*) dominates this association, often mixed with Bigelow sage, sand sage, black sage and occasionally fringe sage. The sagebrush communities support extensive and variable stands of forbs and grasses, and at higher elevations are often intermixed with pinyon-juniper woodland.

The grassland communities are quite variable in composition, depending upon the parent-soil type. Lowland areas of alkaline heavy soils are often dominated by alkali sacaton (*Sporobolus airoides*) associated with galleta (*Hilaria jamesii*), blue grama (*Bouteloua gracilis*) and sand dropseed (*Sporobolus cryptandrus*). Sandy soils are usually dominated by Indian rice grass (*Oryzopsis hymenoides*), sand dropseed, galleta, spike dropseed (*Sporobolus contractus*) and scattered blue grama. Fine-textured upland soils support blue grama, galleta, alkali sacaton and sand dropseed. Loamy soils favor extensive grama-galleta grass development. These communities can also contain high concentrations of shrubs, such as fourwing saltbush and Bigelow sagebrush.

Pinyon (*Pinus edulis*) and juniper (*Juniperus monosperma*) woodlands extend in one form or another from east-central New Mexico across northern Arizona to Nevada. Their general distribution appears to follow the area of overlap of the winter and summer precipitation patterns. Pinyon-juniper woodland requires higher levels of annual precipitation than does the sagebrush, grassland or badland communities. As such, it would normally be found at higher elevations or in areas that are sheltered. Juniper dominates the lower elevations of pinyon-juniper woodland. It is significantly more drought tolerant and often grades into grassland communities, creating a savanna-like condition. Pinyon occurs in the middle to upper ranges of the community. As the density of pinyon and juniper trees increases, the grasses generally decrease. Pinyon-juniper woodland is often found on north-facing slopes or on top of sandstone mesas within the San Juan Basin.

The badlands and lowland areas of the San Juan Basin generally support low-density communities of xeric shrubs and forbs. Many of the rare plants of the basin are found in this habitat type. Dependent upon the type and consistency of the clay substrate, the community coverage can vary from zero to 30%. The most common shrubs are saltbush. There are several perennial forbs that persist in badlands, but in general, annuals or biennials supply the greatest diversity. These annual species are totally moisture-dependent, and in dry years they do not develop. The badland communities are some of the most interesting and least predictable of those in the study area. The saltbush and greasewood vegetation types usually occur in saline or alkaline lowlands, often along large drainages where storm water runoff accumulates. This community type usually has low species diversity, with alkaline-tolerant grasses, such as alkali sacaton, desert saltgrass and galleta often present. Forbs such as Russian thistle (*Salsola kali*), pepperweed (*Lepidium montanum*) and goosefoot (*Chenopodium* spp.) also occur on these sites.

The classification scheme used in this treatment is based on the Brown et al. (1979) system. It has been modified to include the shift in biomes encountered in New Mexico. The vegetation map (Fig. 2.3) of the New Mexico portion of the San Juan Basin was abstracted from figures presented by Cully and Knight (1986). The raw data for these maps were compiled from several sources: field studies by the New Mexico Natural Resources Department botanical staff; the 1978 Soil Conservation Service (SCS) map of the potential vegetation of New Mexico, compiled by Donart et al. (1978); Dr. Sandy Dick-Peddie's map of the current vegetation of New Mexico; and the Morain et al. (1977) map of vegetation and land use in New Mexico produced by the Technology Application Center in Albuquerque.

12.1 Continental Divide (note historical marker to left). View at 12:00 of persistent channel sandstone in Regina Member of the San Juan Formation. **1.2**

13.3 Enter Jicarilla Apache Reservation. Highway now within relatively flat "Largo Plains" physiographic region of Baltz (1967) of the central San Juan Basin (Fig. 2.4). The extensive Quaternary valley fill in the Jicarilla Apache Reservation has not been analyzed to date. **2.2**

15.5 Road to left to oil well. **2.1**

17.6 Mile marker 82; outcrops at 9:30–12:00 of candy-striped mudstones, siltstones and sandstone of Regina Member. Dark yellowish-orange sheet sandstones represent throughgoing channels during Regina Member deposition. **3.5**

21.1 Highway to right (NM-537) leads to Dulce, center of the Jicarilla Apache Reservation; continue straight on NM-44. From 9:00–12:00, Regina Member mesas and ridges form skyline. **5.5**

26.6 Cross Largo Canyon Arroyo. Ledges of tan sandstone downstream are of Cuba Mesa Member, San Jose Formation. **2.7**

29.3 Crest of hill; view at 1:00–2:00 of Cuba Mesa Member sandstone (at base) overlain by Regina Member mud-sand sequence. **1.1**

30.4 Leave Jicarilla Apache Reservation. **1.9**

32.3 Crest hill; Counselor ahead; Regina Member exposures along road. Note margin of sheet sandstone in Regina Member on right (Fig. 2.5). **1.0**

33.3 Counselor Trading Post and Boarding School. Counselor was named for Jim Counselor, the owner of the trading post established here in 1930. Counselor had begun to trade with the Indians in 1916, and ultimately established several trading posts in Navajo country (Pearce, 1965). **0.3**

33.6 Canyon Largo drainage ahead. **0.2**

33.8 Counselor Chapter House of Navajo Nation on right. **0.8**

34.6 Enter Rio Arriba County. Roadcuts in Cuba Mesa Member; the floor of Escrito Canyon, which we will cross soon, is in this unit. Mileage marker 100. Entering Lybrook Field. This field, discovered in 1957, has produced 3,000,309 BO through 1990 from the Cretaceous (Coniacian) Tocito Sandstone, a series of tidally influenced inner-shelf sand riges (Kofron, 1987; Nummedal et al., 1989). Most Tocito lentils are surrounded by marine shales and provide major stratigraphic traps for oil in the San Juan Basin (Fig. 2.6). The field extends northeast to Stop 1. **1.8**

36.4 Cross Escrito Canyon. **0.9**

37.3 Road curves right; view at 10:00 toward radio towers is of Cuba Mesa Member (lower sandstone cliff) overlain by the Regina Member of the San Jose Formation. **1.0**

38.3 Enter Lybrook; natural gas refinery on right. Lybrook is named for a family of homesteaders who arrived from North Carolina in 1918 and established sheep and cattle

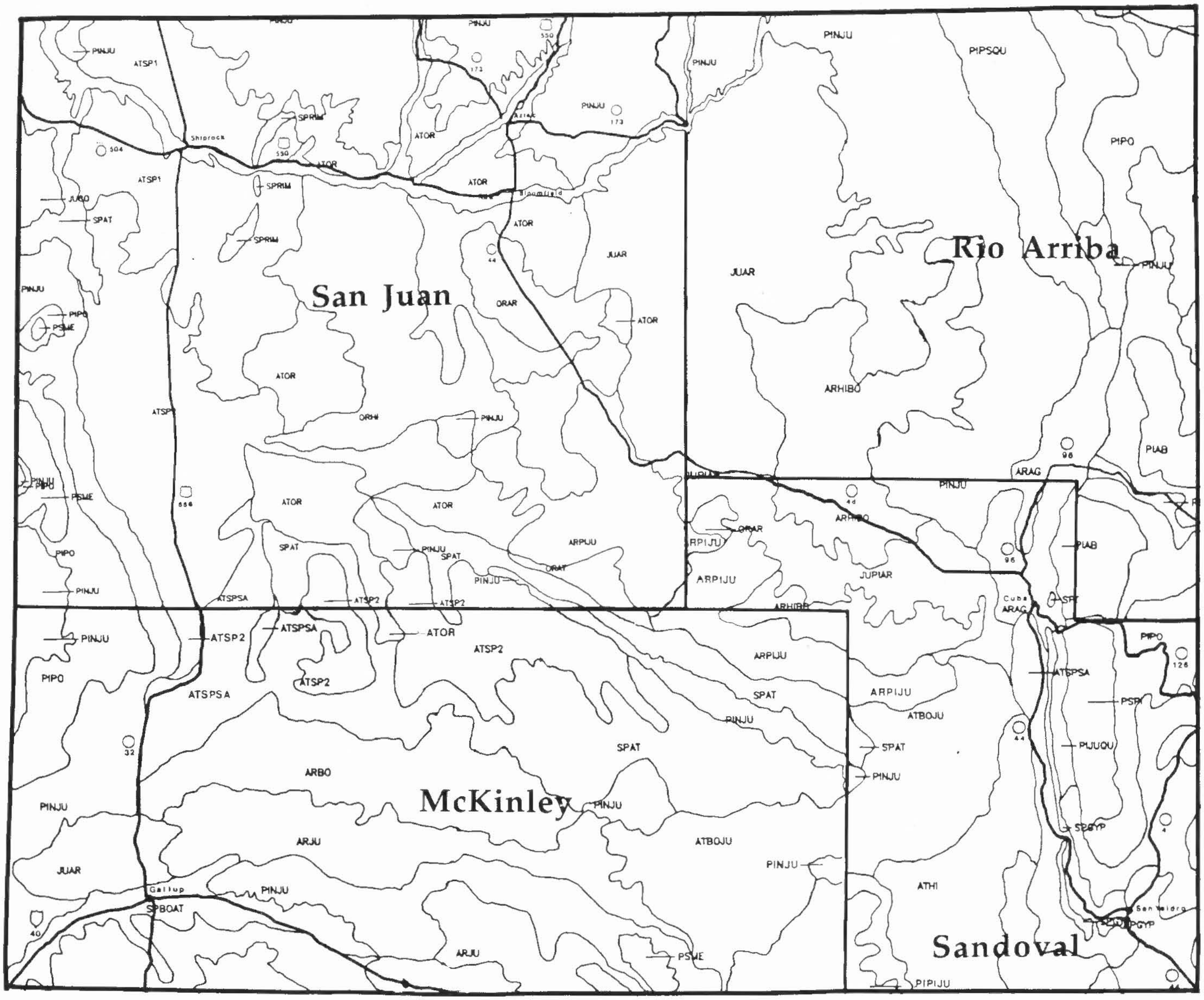


FIGURE 2.3. Plant communities and association in the San Juan Basin. ARBO—*Artemisia tridentata* and *Bouteloua* spp.; big sagebrush and blue grama grass (Association level). ARHIBO—*Artemisia tridentata, Hilaria jamesii* and *Bouteloua gravilis;* big sagebrush, galleta grass, and blue grama with western wheatgrass and rabbitbrush inclusions (Series level; DSH, NRD). ARJU—*Artemisia tridentata* and *Juniperus monosperma;* big sagebrush, oneseed juniper, and western wheatgrass (Association level). AROR—*Artemisia tridentata* and *Oryzopsis hymenoides;* big sagebrush and Indian rice grass (Association level). ARPIJU—*Artemisia tridentata;* big sagebrush with western wheatgrass, galleta grass, dropseeds, occasional pinyon pine, and juniper (Association level). ATBOJU—*Atriplex confertifolia, Bouteloua* spp. and *Juniperus monosperma;* shadscale, grama grasses, and oneseed juniper, with sand dropseed and fourwing saltbush (Association level). ATHI—*Atriplex* spp. and *Hilaria jamesii;* various species of saltbush and galleta grass, with alkali sacaton and black greasewood (Association level; NRD, DSH). ATOR—*Atriplex* species and *Oryzopsis hymenoides;* big sagebrush and Indian rice grass (Association level). ATSP1—*Atriplex* spp., including *A. cuneata* and *A. corrugata,* and *Sporobolus airoides* (Association level). ATSP2—*Atriplex* spp. but not including *A. cuneata* and *A. corrugata* and *Sporobolus airoides;* various saltbush species with alkali sacaton, galleta grass, threeawn grass, blue grama grass, sand dropseed and Indian rice grass (Association level). ATSPSA—*Atriplex canescens, Sporobolus airoides* and *Sarcobatus vermiculatus;* fourwing saltbush, alkali sacaton and black greasewood (Association level). HIORJU—*Hilaria jamesii, Oryzopsis hymenoides* and *Juniperus monosperma;* galleta grass and Indian rice grass occur with blue grama, sideoats grama and threeawn. JUAR—*Juniperus monosperma* (in northwestern areas sometimes *J. utahensis*) and *Artemisia tridentata;* oneseed juniper (sometimes Utah juniper) and big sagebrush (Association level). JUCO—*Juniperus utahensis* and *Cowania stansburiana;* Utah juniper and cliffrose (Association level). ORAR—*Oryzopsis hymenoides* and *Artemisia tridentata;* Indian rice grass and big sagebrush, with dropseed, galleta grass, threeawn grass, blue grama grass, and inclusions of western wheatgrass and rabbitbrush (Series level). ORAT—*Oryzopsis hymenoides* and *Artemisia tridentata;* Indian rice grass and big sagebrush (Series level). ORHI—*Oryzopsis hymenoides* and *Hilaria jamesii;* Indian rice grass and galleta grass with Mormon tea, blue grama grass, sand dropseed grass, threeawn grass, broom snakewood and occasional big sagebrush (Series level). PINJU—*Pinus edulis* and *Juniperus monosperma;* pinyon pine and oneseed juniper with little appreciable woody understory; may include ponderosa pine at higher elevations (Series level). PIPIJU—*Pinus edulis* and *Juniperus monosperma;* pinyon pine and oneseed juniper with little appreciable woody understory; may include ponderosa pine at higher elevations (Series level). PIPO—*Pinus ponderosa;* dominated by ponderosa pine with some Douglas fir and pinyon pine, grassy understory includes Arizona fescue and mountain muhly (Association level). PSME—*Pseodotsuga menziesii* and *Pinus ponderosa;* Douglas fir and ponderosa pine (Association level). RIHI—Riparian; human impacts, including agriculture levee building and dams have changed much of this habitat. SPAT—*Sporobolus airoides* and *Atriplex* spp.; with occurrences of western wheatgrass, blue grama and rabbitbrush (Series level). SPBOAT—*Sporobolus airoides, Bouteloua gracilis* and *Atriplex* spp.; alkali sacaton, blue grama saltbush species (Series level). SPRIM—Special area; The Hogback. A massive rimrock outcrop representing the easternmost extension of the Arizona strip flora; includes species such as *Cercocarpus intricatus, Artemisia spinescens* and *Astragalus desperatus*.

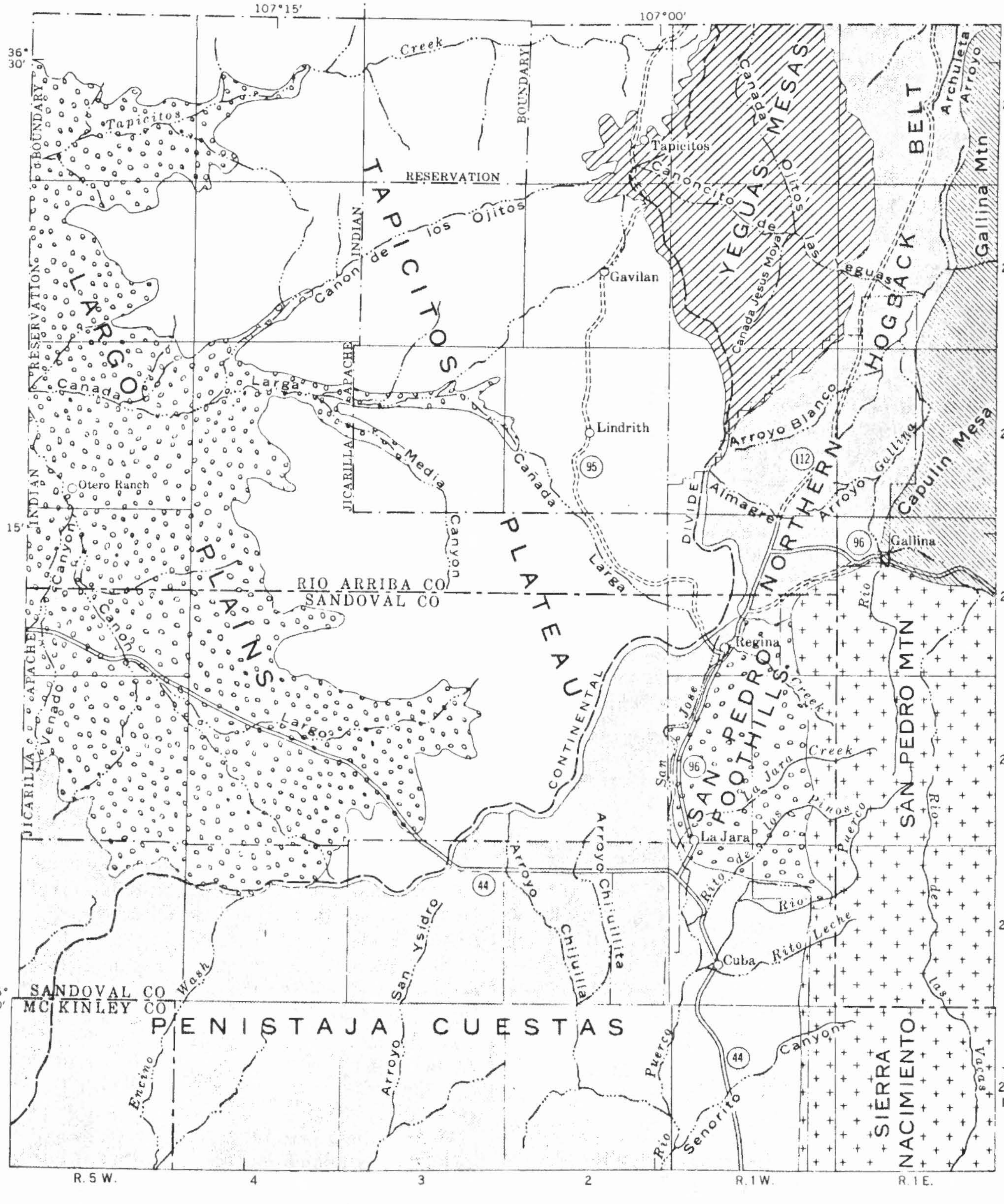


FIGURE 2.4. Physiographic index map of east-central part of San Juan Basin and adjacent region, New Mexico (from Baltz, 1967).

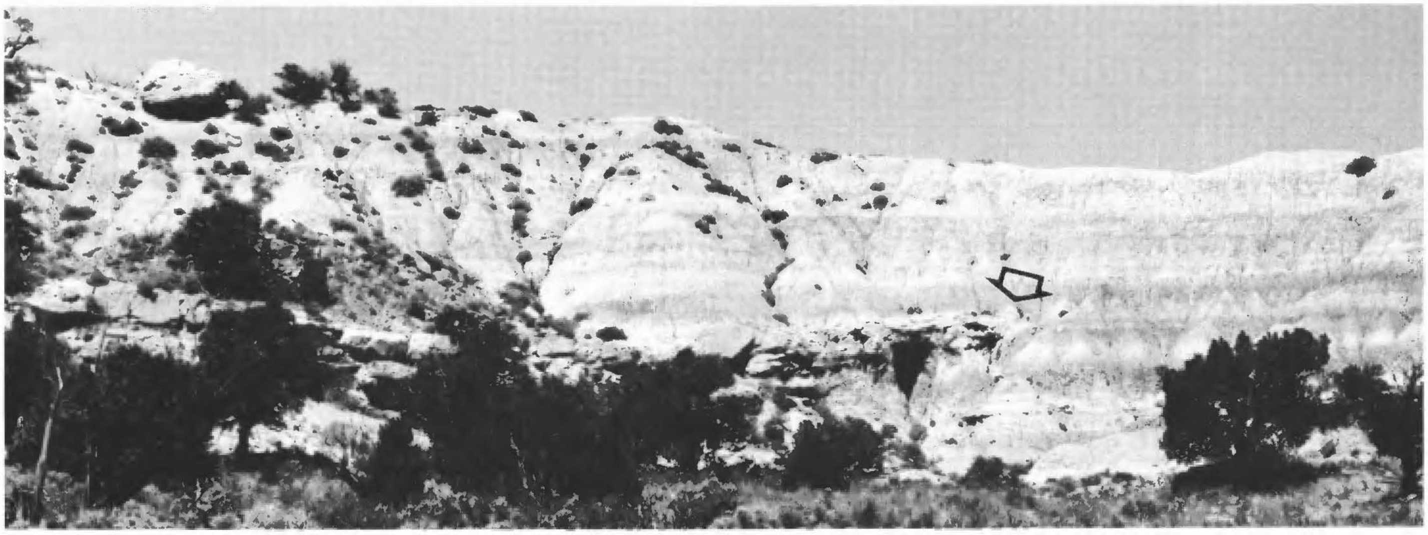


FIGURE 2.5. View west-northwest of lateral pinchout (arrow) of Regina channel sandstone into floodplain strata of sandstone (light color) and mudrocks (dark color). Exposure is 60 ft high.

ranches (Pearce, 1965). The Gas Company of New Mexico later built a refinery here, and the present small community mainly services the refinery. **0.8**

39.1 Lybrook store on left; Cuba Mesa Member on right. **0.3**

39.4 Dirt road to right. Note bluff to right exposing Regina Member. Road is on Regina Member. **0.3**

39.7 Crest of hill; sandstone on both sides of road is Regina Member sandstone, mistakenly mapped as Cuba Mesa Member by Dane and Bachman (1965). **0.3**

40.0 Escrito Trading Post on left. **0.2**

40.2 Roadcut on right of Cuba Mesa Member. Road is in Cuba Mesa Member next 1.5 mi. **0.5**

40.7 Road drops below Cuba Mesa Member into Paleocene Nacimiento Formation. **2.3**

43.0 Road to right (sign reads "Bannon Energy, South Blanco Creek Plant"). **Turn right,** cross cattle guard, go straight. **0.1**

43.1 Road forks, stay right. **0.1**

43.2 Road forks, stay left. **0.1**

43.3 Cattle guard. On right, upper Nacimiento Formation (silcrete-laden Escavada Member) is well exposed; continue straight past church on left. **0.1**

43.4 Road forks, bear right. **0.4**

43.8 Bannon Energy Corporation compressor station; **STOP 1** to discuss sheet-like geometry and pinchout into the basin center of the Cuba Mesa Member of the San Jose Formation, Nacimiento Formation silcrete beds and the Lybrook and Escrito oil fields. This canyon has excellent outcrops of the upper Nacimiento Formation, Escavada Member, an especially thin and friable Cuba Mesa Member sandstone overlain by variegated, reddish Regina Member mudrocks and fine sandstones (Fig. 2.7). The yellowish-orange sandstone capping the mesa east of the stop had been mapped previously as the basal San Jose Formation (Dane and Bachman, 1965; Clemons, 1982). The upper sandstone is regionally continuous and may be a tongue of the Cuba Mesa Member of the San Jose Formation.

The Nacimiento Formation is here represented by the Escavada Member, mostly a white to tan conglomeratic sandstone. The member is composed of coarse-grained sandstone, conglomerate and conspicuous silcretes (see accompanying minipaper). Paleocurrents in the Escavada Member of the Nacimiento Formation (Fig. 2.8) and in the Cuba Mesa Member of the San Jose Formation indicate northwest-to-southeast paleoslope in this region, consistent with regional drainage elsewhere in the Paleocene Ojo Alamo and Eocene San Jose Formations (Sikkink, 1987; Smith and Lucas, 1990). Paleocurrent directions have only been obtained from the conglomerates of the Escavada Member to date.

After stop, retrace route to NM-44. **0.9**

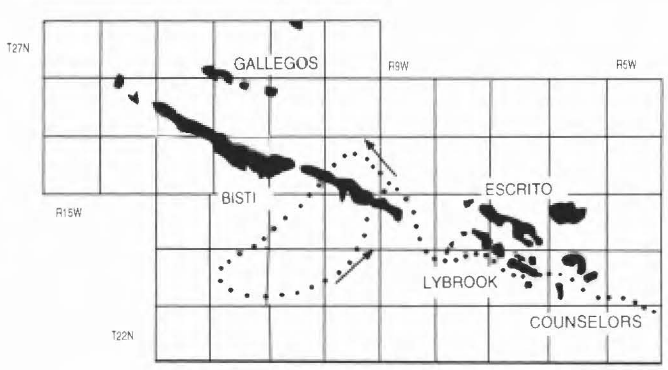


FIGURE 2.6. Map of Tocito oil fields in the central San Juan Basin.

SILCRETES OF THE PALEOCENE NACIMIENTO FORMATION

Thomas E. Williamson[1], Laura J. Crossey[1] and Spencer G. Lucas[2]

[1]Department of Geology, University of New Mexico, Albuquerque, New Mexico 87131-1116;
[2]New Mexico Museum of Natural History, 1801 Mountain Road NW, Albuquerque, New Mexico 87104-1375

The Nacimiento Formation is a mudrock dominated, nonmarine deposit of Paleocene age. Facies are indicative of a variety of lacustrine and typical alluvial floodplain deposits, including point bar, crevasse splay and proximal and distal floodplain. One of the more distinctive

FIGURE 2.7. Nacimiento Formation (TN), overlain by San Jose Formation (TSJ) at Stop 1.

facies present in the Nacimiento Formation has been interpreted as pedogenic silcrete (Rains, 1981). Pedogenic silcretes require special climatic conditions for their formation, and therefore their presence in the Nacimiento Formation may indicate the existence of specific climatic conditions during the Paleocene in northwestern New Mexico.

Silcretes are usually defined as a product of surficial or near-surface, low temperature cementation and/or replacement of detritus with silica.

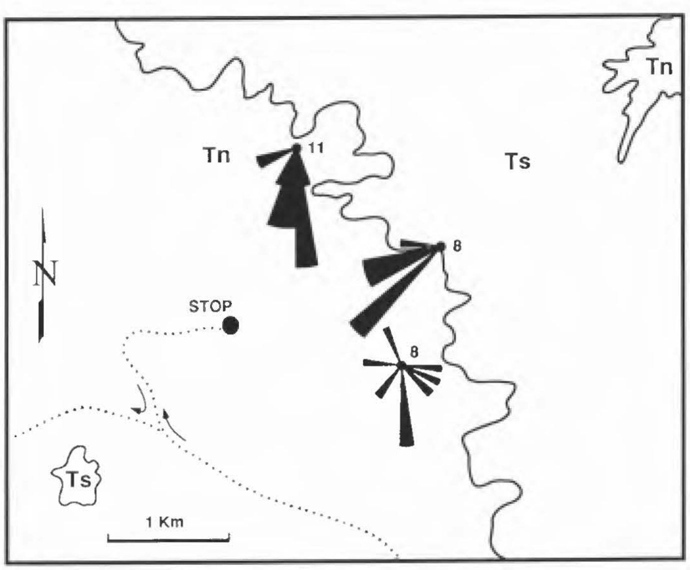


FIGURE 2.8. Geologic map and paleocurrent rose diagrams of Cuba Mesa and Escavada Members near Bannon Energy plant.

The term silcrete was first coined in order to describe widespread silicified horizons in Australia and has now been applied to similar facies in South Africa, Europe and North America. The silcretes of the Nacimiento Formation are quite distinctive and show similarities to and differences from silcretes reported elsewhere.

Silcretes of the Nacimiento Formation are extremely hard and highly resistant units normally ranging in thickness from 2–3 cm up to about 0.3 m (Fig. 2.9B–C). The bases of these units tend to be irregular, whereas the tops are relatively planar. These silcretes, though thin, may have a wide lateral extent. The thicker silcretes are generally more extensive than thinner silcretes, which tend to pinch out laterally and are nodular. Rains (1981), in his study of silcretes of the Nacimiento Formation, reported that he could correlate a single 0.3-m-thick silcrete bed between De-Na-Zin and Tsosie Washes, a distance of about 40 km. The Nacimiento silcretes never cut across bedding, though they have been observed to bifurcate (Rains, 1981). Rarely, several closely spaced silcretes may coalesce into one thicker silcrete (Rains, 1981). The silcretes are never seen as thin units of silicification within thicker sandstone bodies but are usually intercalated with mudstones and/or siltstones. However, some silcretes are near underlying or overlying sandstones that lack extensive silicification and distinctive silcrete textures.

Nacimiento Formation silcrete beds tend to have a granular texture on a fresh surface. Typically, where fresh, they are light gray (N 7) and weather a pinkish gray (5 YR 8/1) and dark yellowish orange (10 YR 6/6). They tend to break into cubic blocks that litter surrounding slopes. A silcrete horizon is often identified from a distance by the apron of orange debris extending down-slope. Silcretes of the Nacimiento Formation often exhibit structures that resemble small burrows and rhizoliths (Fig. 2.9E). We have observed two different types of structures. The first are cylindrical voids, about 0.8 cm in diameter and

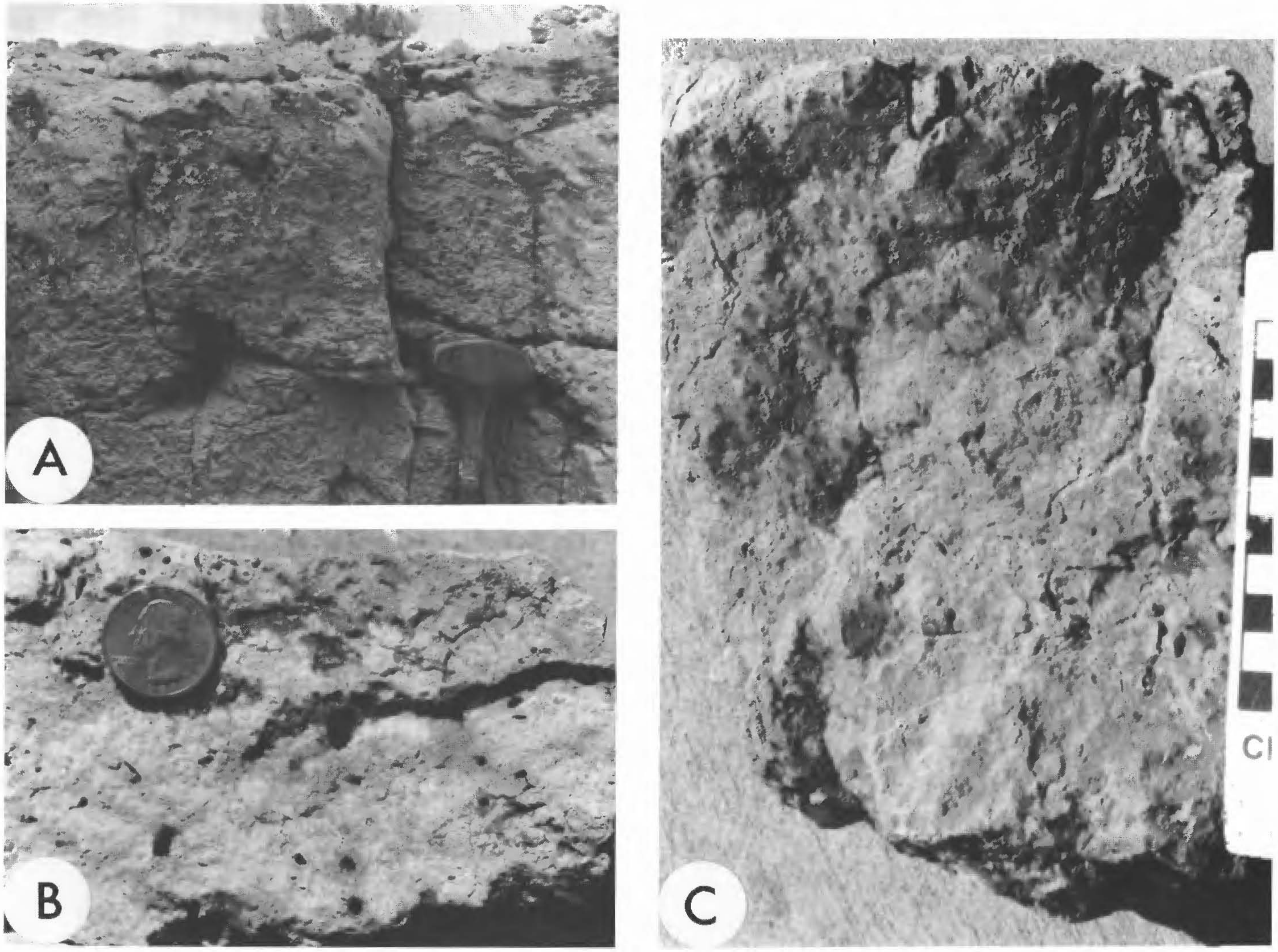


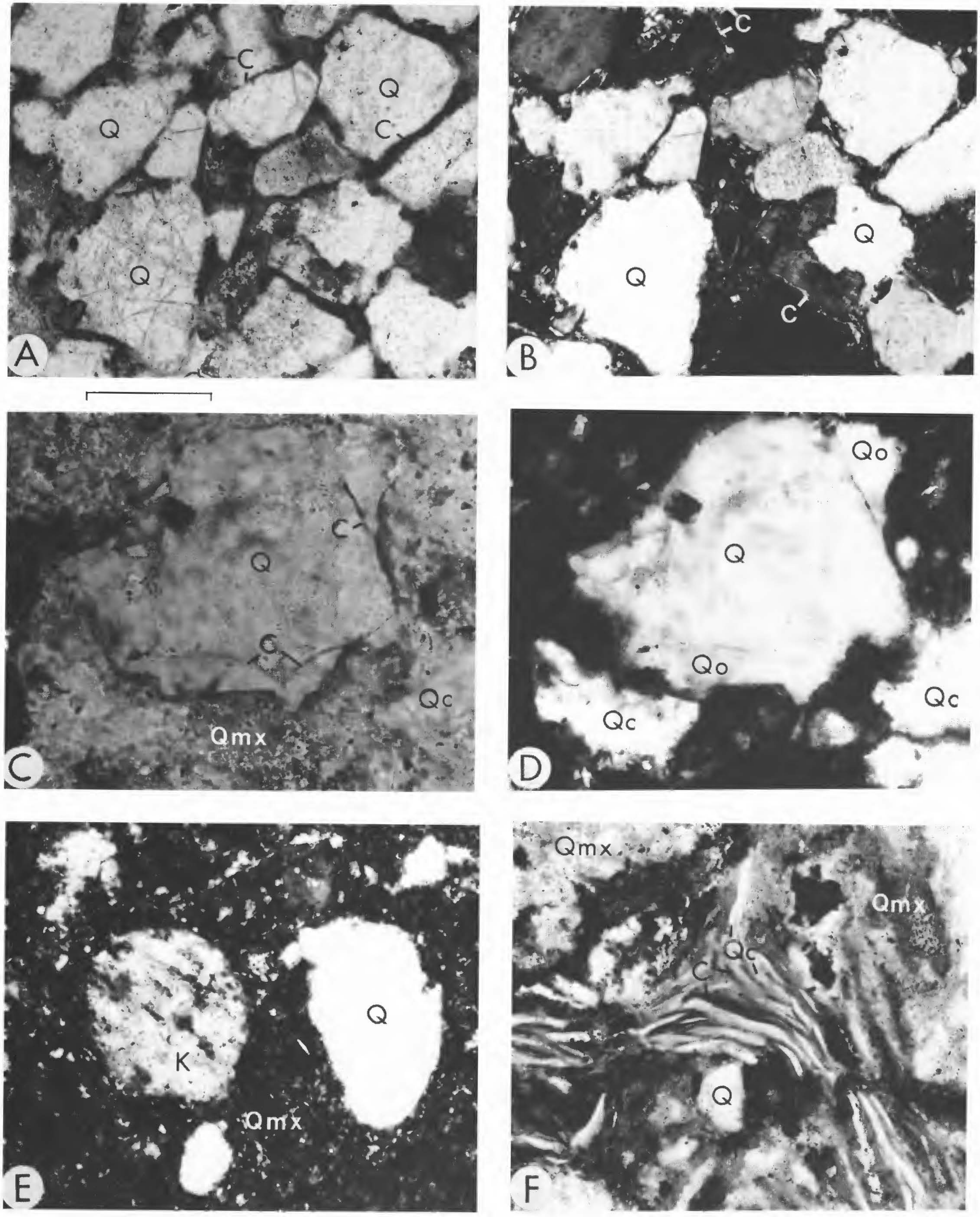
FIGURE 2.9. Silcrete from the Nacimiento Formation. A, Silcrete forming resistant bench in badland exposure of Nacimiento Formation. B, Top surface of silcrete showing openings to vertically oriented, burrow-like structures and sinuous, horizontal burrow-like structure leading to opening. C, Silcrete in profile view showing vertical burrow-like (b) and rhizolith-like (r) structures.

of constant width. They may be highly sinuous, but generally are vertically oriented and do not appear to bifurcate. They appear to be more highly concentrated near the top of a silcrete bed. These structures most closely resemble burrows made by a wide variety of arthropods, including insects and spiders (Ratcliffe and Fagerstrom, 1980). The second type of structure also appears as cylindrical voids, but is thinner (about 0.2 cm in diameter) and dendritic. These structures are generally vertically oriented and can extend entirely through a silcrete, branching into finer structures downward. They closely resemble root tracings.

Rains (1981) found that silcretes were petrographically nearly identical to typical sandstones of the Nacimiento Formation in framework-grain composition. However, the main differences were in the composition of the cement. Typical Nacimiento Formation sandstones contain a clay matrix (Fig. 2.10A–B). Petrographic analysis indicates that Nacimiento Formation silcretes consist of fine- to medium-grained sandstones with extensive silica cementation (Fig. 2.10E). The rock appears to be matrix supported, and matrix comprises as much as 33–65% of the rock (Rains, 1981). Predominant framework grains are detrital quartz with minor amounts of potassium feldspar and trace amounts of other minerals or lithic grains. Matrix is composed primarily of microcrystalline quartz (Fig. 2.10C, D, E), with some megaquartz cement and quartz overgrowths (Fig. 2.10C, D, F). Framework quartz grains often show overgrowths with an irregular contact with surrounding matrix (Fig. 2.10C–D). The matrix often fills embayments and fractures within framework grains, suggesting that the cement is replacive.

Silcretes of the Nacimiento Formation show many similarities and differences from silcretes described from other parts of the world. Briefly, silcretes have been described from Australia (Twidale and Milnes, 1983; Thiry and Milnes, 1990, and sources therein), South Africa (Summerfield, 1983a, and sources therein), France (Thiry and Millot, 1986, and sources therein), the Middle East (Khalaf, 1988), Canada (Leckie and Cheel, 1990), Texas (Murray, 1990), Nebraska and Wyoming (Hunt,

FIGURE 2.10. Photomicrographs of a sandstone and silcretes from the Nacimiento Formation. A–B, Sandstone between two silcrete horizons in plane light (A) and under crossed nicols (B); sandstone is composed of predominantly quartz framework grains (Q) and clay matrix (C). Note orientation of clays parallel to detrital grain surfaces. Scale bar is 0.2 mm. C–D, Silcrete in plane light (C) and under crossed nicols (D). The framework quartz grain (Q) in silcrete has clay rims (C) and quartz overgrowths (Qo). Note also microcrystalline quartz matrix (Qmx), embayed outline of quartz grain and nearby patch of quartz cement (Qc). Scale bar is 0.05 mm. E, Silcrete (crossed nicols). Framework grains of potassium feldspar (K) and quartz (Q) are floating in microcrystalline quartz matrix (Qmx). Again note embayed outline of quartz grain. Microcrystalline quartz crystals are approximately 6 μm across. Scale bar is 0.1 mm. F, Silcrete (plane light) with microcrystalline quartz matrix (Qmx), framework quartz grains (Q) and enlarged position of cutan composed of clay (C) infilled with quartz cement (Qc). Scale bar is 0.1 mm.


C
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1990) and throughout the Rocky Mountain region of North America (Gassaway, 1991).

Generally, silcretes from other areas differ in a number of macro- and micro-structural features. Classical silcretes from Africa and Australia, for example, often are far thicker and more extensive than silcretes observed in the Nacimiento Formation, reaching thicknesses of several meters and forming extensive caprock on mesas. However, many of these also contain similar structures such as vertically oriented burrow-like structures, and are similar in microscopic details. Thiry and Millot (1986) and Thiry and Milnes (1990) described several examples of silcretes from the early Tertiary of France and from classical localities of South Australia. They observed complex vertical profiles in many of these silcretes, indicating varied, complicated, and long histories of formation. These silcretes often contain opal in addition to microcrystalline quartz. Silcretes from the Nacimiento Formation, by contrast, are relatively homogenous upon petrographic examination and lack opal. Thiry and Milnes (1990) suggested that the presence of microcrystalline quartz rather than opal indicates relatively low silica concentrations in ground waters. Opal precipitation generally requires high silica concentrations. Alternatively, opal may have been present originally but later altered to more stable minerals such as quartz. The single example of a silcrete from the Eocene of Canada differs by occurring as zones of nodular silcretes rather than as continuous silicified horizons, and is composed almost entirely of massive, microcrystalline quartz rather than as a sandstone with a microcrystalline quartz matrix. In short, silicified units that have been referred to as silcretes vary widely and therefore probably formed under somewhat different conditions.

Many workers have suggested that the presence of silcretes indicates that particular climatic conditions prevailed during their formation. Silcrete formation in present environments of South Africa requires seasonal or cyclic wet-dry climates, shallow water tables, stable land surfaces, and minimal erosion (Summerfield, 1983; Thiry and Milnes, 1990). However, Twidale and Harris (1977) suggested that silcretes may also form under warm and humid to subhumid environments. Gassaway (1991), for example, suggested that silcrete formation in widely scattered regions throughout the world during the early Tertiary indicates that there was a synchronous climatic event. The presence of reactive volcanic glass in the parent strata may also play a role in silcrete formation (Rains, 1981; Hunt, 1990).

Thiry and Milnes (1990) argued the importance of distinguishing between silcretes that form during soil formation and those that form during deeper burial as ground-water silcretes. Pedogenic silcretes form under the direct influence of the prevailing climate, whereas ground-water silcretes are somewhat insulated from the prevailing climate. Pedogenic and ground-water silcretes can be distinguished by distinctive suites of micro- and macro-structures and fabrics.

Pedogenic silcretes often show illuviation structures that imply alternating episodes of leaching and deposition of interstitial silica, and periods of infiltration of water with silica-rich solutions. Ground-water silcretes often preserve sedimentary structures, and their horizontal disposition suggests a close relationship to the ground-water table (Thiry and Milnes, 1990).

Silcretes of the Nacimiento Formation contain structures strongly resembling insect burrows and rhizoliths, indicating that these units probably did exist at or near the surface for a significant time. The timing of silicification relative to these structures has not yet been determined. Also, their sometimes great lateral extent, conformity to bedding planes and association with particular lithologies strongly suggest that they are of pedogenic rather than strictly ground-water origin. William R. Dickinson of the University of Arizona loaned us thin sections used in Rains' (1981) study.

44.7 Intersection with NM-44, **turn right** and proceed north. **0.4**

45.1 Enter San Juan County. Good view of Escavada Member of Nacimiento Formation at 10:00, capped by tan Cuba Mesa Member of San Jose Formation (Fig. 2.11). **0.8**

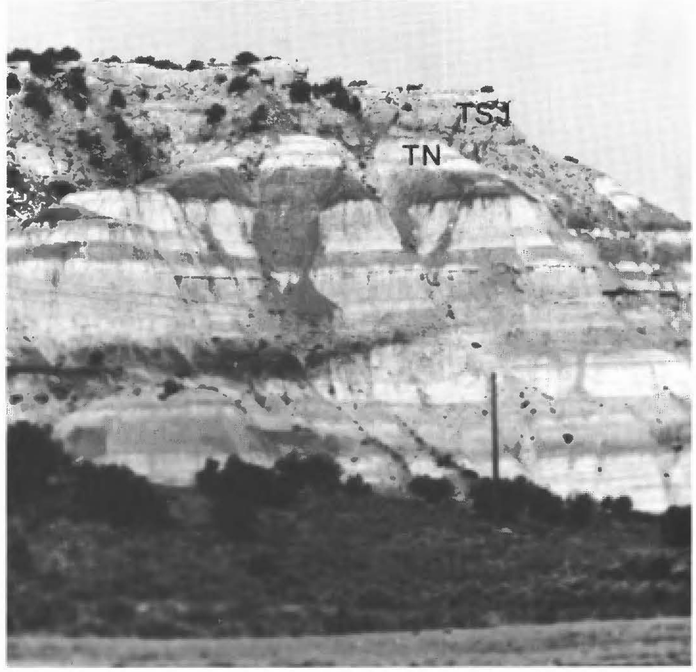

FIGURE 2.11. Cuba Mesa Member of San Jose Formation (TSJ) above Escavada Member of Nacimiento Formation (TN) at mile 45.1.

45.9 Curve in road. **0.3**

46.2 Road passes through gap in Escavada Member outcrop. Road is now in this unit next 1.5 mi. **1.4**

47.6 Crest of hill. Entering Chaco River drainage at crest of hill. For the next 20 mi we will be crossing the drainage divide between the northern tributaries to the Chaco River (a large, ephemeral tributary to the San Juan River) and north-flowing streams that directly flow to the San Juan. Note that the sand-dominant San Jose Formation does not crop out in the headwaters of the northern tributaries of the Chaco River northwest of this region. View ahead is of Escavada–Ojo Encino Member (of Nacimiento Formation) contact. Top of Ojo Encino Member is black mudstones and red-white variegated intervals. **0.4**

48.0 Badlands to right well display Ojo Encino and Escavada Members (Fig. 2.12). **2.1**

50.1 44 store on right (Thriftway); badlands at 10:00 devel-

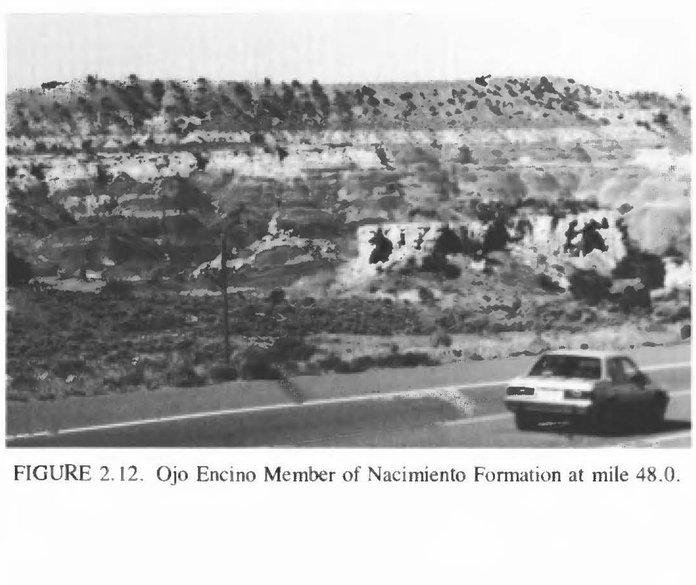

FIGURE 2.12. Ojo Encino Member of Nacimiento Formation at mile 48.0.

oped in Ojo Encino Member. The red-green intervals are extremely fossiliferous with Torrejonian (early Paleocene) vertebrates. **0.8**

50.9 Note channel sandstones in upper Nacimiento Formation in roadcut on right and ridge to left. **0.3**

51.2 Cross upper reach of Kimbeto Wash. **0.9**

52.1 Nacimiento Formation variegated beds (Ojo Encino Member) to right. **0.8**

52.9 At crest of hill, Nageezi Chapter on right; re-enter Blanco Wash drainage, exiting Chaco River drainage. **0.4**

53.3 Road to Chaco Canyon and Negeezi post office to left, Huerfano ahead at 12:00. Nageezi is a name probably derived from the Navajo nayi'ze, meaning squash. The post office was established in 1941. **0.9**

54.2 Road curves left. Huerfano at 12:00, Angel Peak at 1:00 in distance with San Juan Mountains visible in the distance (on a clear day). **1.6**

55.8 San Juan County Road 7776 to left. **1.7**

57.5 Crest hill, roadcuts to right in thick Nacimiento Formation sandstone. El Huerfano ahead is capped by San Jose Formation (Cuba Mesa Member) over Nacimiento Formation (Escavada Member). **3.6**

61.1 Blanco Trading Post and NM-57 on left. Blanco Trading Post (Spanish, white) is at the intersection of NM-44 and NM-57, the main route into Chaco Canyon from the east. Pearce (1965) attributed the name to a "prominent outcropping of rhyolite in adjacent hills." There is, however, no rhyolite in the vicinity; the name most likely refers to the white to light gray sandstones of the Nacimiento Formation. **3.0**

64.1 Road to Dzilth-Na-O-Dith-Hleh boarding school to right. **0.8**

64.9 Huerfano. The trading post of El Huerfano takes its name from the large isolated mesa to the east (Spanish, orphan). This is a sacred place to the Navajo, who call it dzil naodili, where Changing Woman raised her sons Monster Slayer and Child Born of Water, the twin war gods of the Navajo. The trading post was established in the 1930s. **0.2**

65.1 **Turn left** on San Juan County Road 7500, cross cattle guard. **0.6**

65.7 Road to left, continue straight on main dirt road. **0.7**

66.4 Intersection, veer left and stay on main road. **0.2**

66.6 Cattle guard. **0.2**

66.8 Road forks; stay right (left fork is San Juan County Road 7515). **0.6**

67.4 Road to right, continue straight, crossing Gallegos Canyon, which flows directly into the San Juan River. **0.3**

67.7 Cattle guard. **1.0**

68.7 Road passes under powerline. **0.6**

69.3 Cross head of fork of Gallegos Canyon, entering Bisti oil field. Bisti field, discovered in 1955, has produced 37,786,331 bbls of oil through 1990 from the Tocito Sandstone, second only to Horseshoe field at 38,665,832 bbls, another Tocito pool. Bisti field has produced an average of 860 BOPD since 1977, totaling only 4.1 MBO during its declining production. **0.6**

69.9 Road and pump station to right. **0.3**

70.2 Intersection with San Juan County Road 7520 to Navajo Miracle Church on right; continue straight. **0.6**

70.8 Road to left, continue straight. **0.6**

71.4 Road to right; continue straight. **0.2**

71.6 Pass under powerline; road enters from left. **0.2**

71.8 Cattle guard. **0.6**

72.4 Road forks; take San Juan County Road 7500 to left (not 7510 to right!). **0.1**

72.5 Crest of ridge reveals panoramic view with Chuska Mountains on skyline and Bisti and De-Na-Zin badlands in foreground. **0.9**

73.4 Road enters from right; veer left. **0.4**

73.4 Large wash to right is De-Na-Zin, exposing lower part of Nacimiento Formation. Road now begins traverse of Split Lip Flats, a name probably derived from the bodily effects of the persistent winds that sweep this plain much of the year. **0.4**

74.2 Road to left; continue straight. **1.1**

75.3 Road forks; **go right. 0.2**

75.5 Good view at 3:00 of lower Nacimiento Formation badlands in De-Na-Zin Wash. **0.9**

76.4 Turn right on small dirt track at sign that says "De-Na-Zin Wilderness Area." Park in Bureau of Land Management parking area. **STOP 2.** Walk approximately 0.5 mi north to Barrel Springs overlook to discuss the Cretaceous-Tertiary boundary.

Note stabilized eolian dunes near upper edge of badlands. Sandy eolian sediment throughout the Chaco dune field supports a distinctive flora including Indian rice grass (*Oryzopsis hymenoides*). Sandy sediment reduces runoff on these low gradient, alluvial geomorphic surfaces, protecting underlying shale from erosion. Where wind and water erosion strips the sandy mantles, badland erosion results, especially in areas with high local relief. The principles involved in producing and maintaining geomorphically stable landforms can be applied to land reclamation design in the strippable coal belts of the San Juan Basin (Wells, 1983; Wells and Jercinovic, 1983).

In the San Juan Basin, vertebrate fossils have long been the primary basis for locating the Cretaceous-Tertiary boundary (Brown, 1910). Only in the past two decades have other chronological tools (principally palynology and paleomagnetism) been applied in this area. Here, in De-Na-Zin and Alamo Wash (Figs. 2.13–2.15), fossil vertebrates of Late Cretaceous and early Paleocene age are found in unambiguous stratigraphic superposition.

Late Cretaceous fossil vertebrates of the Alamo Wash local fauna (Clemens, 1973) occur in the Naashoibito Member of the Kirtland Formation in the headlands of Alamo Wash. These fossils are present as low as the basal conglomerate of the Naashoibito Member and as high as 10 ft below the base of the Ojo Alamo Sandstone (Lehman, 1985, fig. 3). This fauna is dominated by turtles and hadrosaur and ceratopsian dinosaurs. Dinosaurs, particularly *Torosaurus* (a ceratopsian), *Alamosaurus* (a sauropod), and cf. *Tyrannosaurus*, as well as the multituberculate mammals *Essonodon browni*, *Mesodma formosa* and the marsupial *Alphadon marshi* (Lehman, 1984; Flynn, 1986) indicate a Lancian (Maastrichtian) age assignment for this fauna (Lehman, 1981, 1985; Flynn, 1986; Lucas et al., 1987).

The Paleocene vertebrate fossils in De-Na-Zin Wash occur in the Nacimiento Formation. This mammal-dominated assemblage forms the basis of the Puercan land-mammal "age" (Wood et al., 1941), one of the earliest

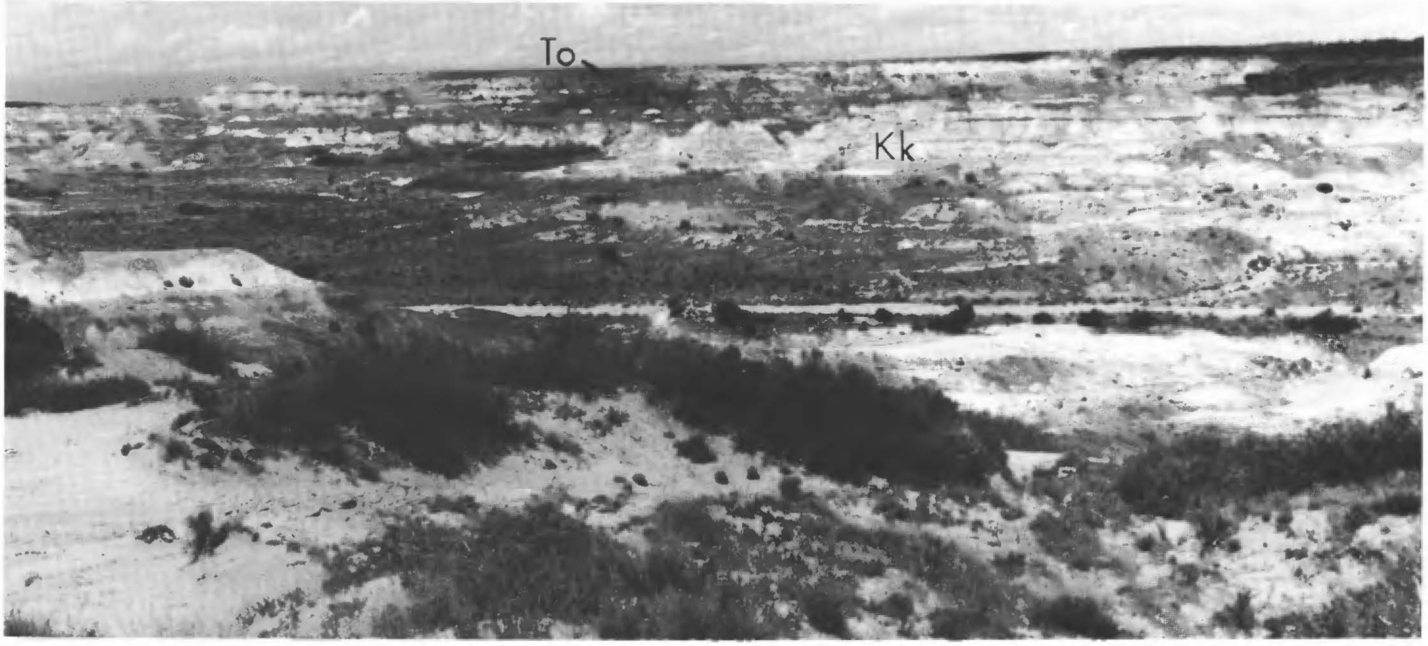

FIGURE 2.13. Cretaceous-Tertiary boundary (K/T) in De-Na-Zin Wash between Naashoibito Member of Kirtland Formation (Kk) and Ojo Alamo Sandstone (To).

biochronologic units of Cenozoic age. In De-Na-Zin Wash, two relatively thin zones produce fossils of Puercan "age." The lowest zone is about 15 ft above the base of the Nacimiento Formation in a red-banded muddy siltstone. This zone, which is sparsely fossiliferous in De-Na-Zin Wash but much more productive in exposures in Kimbeto and Betonnie Tsosie Washes to the east, is usually referred to as the *Ectoconus* zone (Sinclair and Granger, 1914) or the *Hemithlaeus* facies (Van Valen, 1978). The second zone occurs in a "doublet" of red-banded silty mudstone with occasional, black manganese bearing, channel sandstones, about 75 ft above the base of the Nacimiento Formation. This zone is much more productive than the lower zone in this area and yields the large multituberculate mammal *Taeniolabis*. This zone is often referred to as the *Taeniolabis* zone (Sinclair and Granger, 1914; Lucas, 1984a, b). In the San Juan Basin, *Taeniolabis* is found at only one other collecting area, the West Fork of Gallegos Canyon (Lucas, 1984a, b). *Taeniolabis* has never been recovered from the *Ectoconus* zone. De-Na-Zin Wash is the only location where the two fossiliferous zones yielding Puercan age mammals are in direct superposition.

Above the *Taeniolabis* zone are approximately 170 ft of "barren" (lacking vertebrate fossils) strata (William-

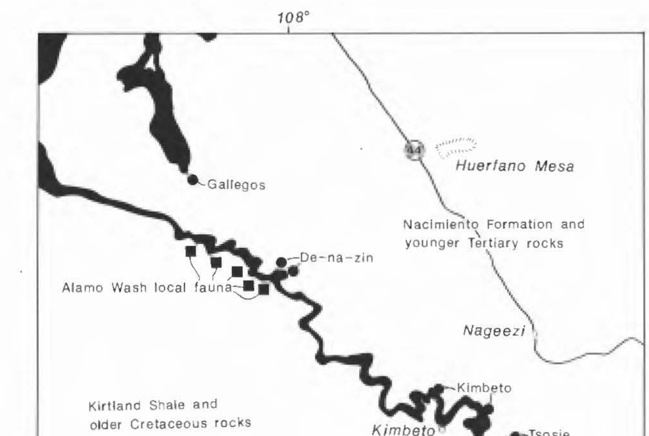

FIGURE 2.14. Part of the west-central San Juan Basin showing localities of Alamo Wash local fauna (latest Cretaceous dinosaurs, and so forth) and Puerco fauna (earliest Paleocene mammals and so forth). Geology modified from Fassett and Hinds (1971).

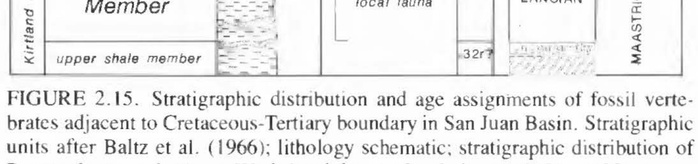

FIGURE 2.15. Stratigraphic distribution and age assignments of fossil vertebrates adjacent to Cretaceous-Tertiary boundary in San Juan Basin. Stratigraphic units after Baltz et al. (1966); lithology schematic; stratigraphic distribution of Puerco fauna and Alamo Wash local fauna after Lehman (1981, 1985), Lucas (1984a, b) and from unpublished data; magnetostratigraphy after Lucas et al. (1982); see text for correlation of land-mammal "ages" and stages. Note that Bugcreekian and Mantuan land-mammal "ages" are not indicated here because of a lack in the San Juan Basin of vertebrates that represent these biochrons.

son and Lucas, 1991a, b). Above this "barren interval," near the head of De-Na-Zin Wash, is a thin interval of fossiliferous strata that yields typical Torrejonian mammals, including *Periptychus carinidens* (Sinclair and Granger, 1914). These strata also yield turtle, gar and champsosaur fossils.

The Nacimiento Formation strata exposed in De-Na-Zin Wash are fairly typical of its basal Arroyo Chijuillita Member (see Williamson and Lucas, this volume). In De-Na-Zin Wash, the Arroyo Chijuillita Member attains a thickness of approximately 250 ft and is overlain by the Ojo Encino Member, the base of which is visible to the northeast, at the head of the wash. Typically, the Arroyo Chijuillita Member is somewhat variegated near its base but is dominated by thick units of black mudstone (Williamson and Lucas, 1992). This mudstone weathers into wide benches of low relief and has the characteristic "popcorn" surface texture of swelling clays. The mudstone composing these units lacks bedding but locally contains numerous slickensides. Slickensides in mudstones are often attributed to soil-forming processes (Retallack, 1983; Bown and Kraus, 1981, 1983, 1987), suggesting these units may be paleosols. The dark coloration is probably due to organic material. Where these mudstones are fossiliferous they often produce large numbers of gar scales, turtles and crocodilians, suggesting that they were deposited in "swampy" environments. Several very extensive silcretes are exposed near the base of the Nacimiento Formation. Rains (1981) correlated the lowest silcrete exposed in De-Na-Zin Wash with a prominent silcrete exposed in Betonnie Tsosie Wash, a distance of about 40 km (see minipaper accompanying Stop 1).

After stop return to main dirt road. **0.1**

76.5 Turn right and continue west. Road is still on Split Lip Flats. **0.5**

77.0 Road begins descent from Ojo Alamo Sandstone–defended flats to a late Pleistocene alluvial surface cut on Cretaceous Kirtland Formation and mantled by late Pleistocene and Holocene alluvial and eolian sands. **0.7**

77.7 Cattle guard. **1.6**

79.3 Stabilized dunes of Chaco dune field on right and left are mostly east-northeast-oriented detached arms of parabolic dunes (see Smith, this volume). **0.9**

80.2 Road to right; stay on main road. **0.5**

80.7 Cattle guard. **0.8**

81.5 At 10:00, Fruitland-Kirtland formations in badlands at divide between the broad Coal Creek valley before you and Tsaya Wash beyond; Chacra Mesa at 11:30; Chuska Mountains at 12:00–2:00. **1.5**

83.0 Cattle guard; at 9:00, low badlands are Fossil Forest area. **1.6**

84.6 Cattle guard. **0.5**

85.1 Road bed on red Fruitland Formation "clinker." **0.6**

85.7 Bridge over Coal Creek. **0.6**

86.3 Road crests hill; view at 3:00 of low Fruitland Formation badlands, mostly coals, carbonaceous shales and "clinkers." Road passes through these badlands next 0.5 mi. **0.8**

87.1 Fruitland Formation coal beds both sides of road. **2.8**

89.9 Stop sign, cattle guard, intersect paved NM-371, **turn left.** Outcrops to right are of coal- and "clinker"-bearing Fruitland Formation. **1.9**

91.8 San Juan County Road 7650 to left (unpaved); view ahead (before turn) is of Cretaceous Cliff House Sandstone within Tsaya Canyon. **Turn left** on 7650 and cross cattle guard to proceed up Tsaya Wash to the east-northeast. **0.1**

91.9 Pavement ends. **0.5**

92.4 Low escarpment at 10:00 is Pictured Cliffs Sandstone. Road is on covered Lewis Shale. **0.6**

93.0 Pretty Rock (Tsaya) at 12:00 is capped by Pictured Cliffs Sandstone over Lewis Shale (slope former) above Cliff House Sandstone which floors Tsaya Wash at this location (Fig. 2.16). The Lewis Shale is very thin here because its pinchout occurs 2–3 mi to the southwest, near the present Chaco River. At the mouth of Tsaya Canyon, the transgressive Cliff House Sandstone nearly merges vertically with the regressive Pictured Cliffs Sandstone (Fig. 2.17). **1.2**

94.2 Pictured Cliffs Sandstone to left with Fruitland Formation coal and "clinker" beds overlying it. **1.1**

95.3 Sandstone forming ridge to left with dwellings is Pictured Cliffs Sandstone. **0.8**

96.1 Badlands at 9:00–9:30 are Fruitland Formation. **0.4**

96.5 Cattle guard. Note lack of dramatic downcutting in this drainage in comparison to De-Na-Zin, Alamo, Coal Creek and Ah-shi-sle-pah drainages. Tsaya Wash has essentially not entranched its upper valley since the late Pleistocene, unlike these other drainage basins. **0.3**

96.8 Black Lake at 2:00 is a natural playa that was dammed between the 1930s and 1960s for stock watering. Foster (1913) noted "remarkable carbonaceous deposits" in the lake when it was full of water during early surveys of the coal resources of the San Juan Basin. **1.4**

98.2 Road to left heading northwest; **turn left** before road crests low hill. **0.4**

98.6 Road passes through stabilized dunes of late Pleistocene and Holocene age. Dunes of these ages occur near local baselevel only in Tsaya Wash and along Split Lip Flats. Elsewhere, late Pleistocene dunes occur on surfaces that are above badland watersheds. **0.4**

99.0 Road passes in front of stock dam. **1.2**

100.2 Pass through playa blowout; lake below with Kirtland

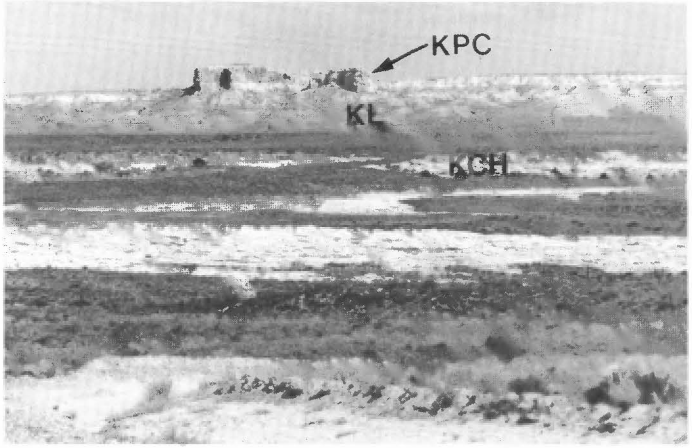

FIGURE 2.16. Pretty Rock is formed in Pictured Cliffs Sandstone (KPC) above thin Lewis Shale (KL) which overlies Cliff House Sandstone (KCH).

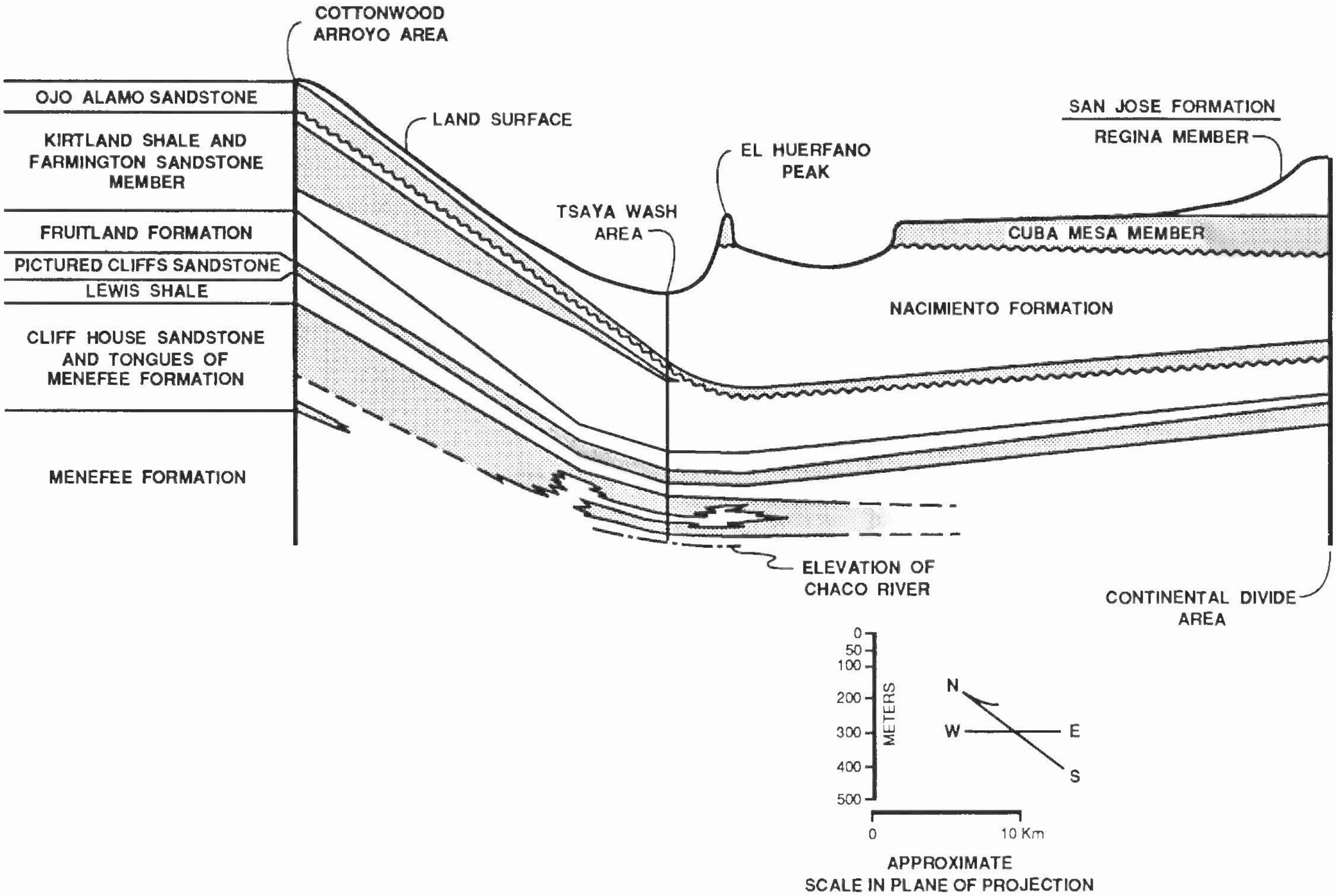

FIGURE 2.17. Fence diagram of Cretaceous and Paleogene strata exposed in the De-Na-Zin, Tsaya and Coal Creek drainage basins. The Lewis Shale pinches out near Chaco River, where the transgressive Cliff House and regressive Pictured Cliffs sandstones merge.

Formation slopes to south. **Turn left** on track across playa. **0.5**

100.7 Crest of hill; blowout below in lower Kirtland Formation. Road passes through dune field for next few miles. **0.2**

100.9 Low blowout (playa?) in Kirtland Formation. Note ironstone concretions. **0.6**

101.5 Kirtland Formation blowout again. **0.9**

102.4 Good view of lower Kirtland Formation badlands to right. **0.1**

102.5 Road curves right at fence line. **0.1**

102.6 Road curves left. **STOP 3** in lower Kirtland–upper Fruitland Formation badlands; walk to Fossil Forest. The Fossil Forest is the name given to the small area of badlands (Fig. 2.18) which expose exceptionally fossiliferous strata of the upper Fruitland Formation and the lower portion of the Hunter Wash Member of the Kirtland Formation (Hunt, 1984, 1991). These strata are of late Campanian–early Maastrichtian (Late Cretaceous) age. The Fossil Forest is named for a stump field of 40 stumps and 11 logs that were buried by a single flood event (Fig. 2.19; Hunt, 1991). Other logs and stumps are present, as well as fossilized roots and leaf compressions. Nonmarine molluscs are locally common.

The most conspicuous elements of the vertebrate fauna preserved in the Fossil Forest are numerous dinosaur bones, including several partial skeletons (Hunt, 1991). Early excavations in the Fossil Forest yielded the genoholotype skull of *Pentaceratops sternbergii* (Osborn, 1923). Other specimens have been excavated over the succeeding 60+ years (Wolberg et al., 1988; Hunt, 1991), including partial skeletons and cranial material of ceratopsians and hadrosaurs. Other dinosaurs represented here include tyrannosaurs and ankylosaurs. Several microvertebrate quarries in the area have produced diverse taxa, including mammals (e.g., Rigby and Wolberg, 1987), but the majority of specimens are undescribed.

Most mollusc fossils and microvertebrate specimens are found in fluvial channels (Hunt, 1991). Larger vertebrate specimens are divided roughly equally between channel and floodplain environments. Most plant fossils are found in poorly drained floodplain environments.

The majority of the Upper Cretaceous strata in the Fossil Forest were deposited by high sinuosity streams with a high suspended load (Hunt, accompanying minipaper). The floodplain was generally poorly drained, producing carbonaceous rock types including coal. This deposition was part of the northeastward regression of the epicontinental seaway during the late Campanian–

FIGURE 2.18. A, View of Big Badlands of the Fossil Forest, looking west from SE¼ SE¼ sec. 26, T23N, R12W. The Blue coal bed crops out in foreground. This 10-ft-thick bed is the highest minable coal in the Fruitland Formation. The top of the coal marks the contact between the Fruitland and the overlying Kirtland Shale. B, View of Big Badlands of the Fossil Forest, looking south from NW¼ SE¼ sec. 26, T23N, R12W. In the foreground is an outcrop of "clinker." This brick-red rock was formed when the Blue coal bed burned naturally over about 100 acres in section 26, baking or melting the overlying sediments. C, Upright petrified tree stump in NW¼ NE¼ sec. 23, T23N, R12W. Stump is about 3 ft tall and indicates burial in place rather than burial after transport (photographs by E. Heffern).

early Maastrichtian (Fig. 2.20). Two dissected geomorphic surfaces are evident in this area (Fig. 2.21), and the valley floor contains multiple Holocene fill terraces.

After stop, turn around and return to county road. **2.4**

SEDIMENTOLOGY OF A FOSSILIFEROUS FLUVIAL SYSTEM, FRUITLAND AND KIRTLAND FORMATIONS (LATE CRETACEOUS), FOSSIL FOREST AREA, SAN JUAN COUNTY, NEW MEXICO

Adrian P. Hunt

Department of Geology, University of New Mexico, Albuquerque, New Mexico 87131-1116

The Fossil Forest area of this report includes sections 13–15 and 22–24, T23N, R12W, San Juan County. The majority of the exposed strata in this area (e.g., Bauer and Reeside, 1921) represent the upper Fruitland Formation and the lower portion of the Hunter Wash Member of the Kirtland Formation (Upper Cretaceous; late Campanian–early Maastrichtian). Although only about 18 m of section are exposed, this area contains a rich paleofauna and paleoflora, including a fossil forest and numerous dinosaur bones (Hunt, 1984, 1991). Because of the paleontological importance of this area, a variety of detailed geological studies have been carried out in the Fossil Forest, including lithostratigraphy, magnetostratigraphy and taphonomy (Hunt, 1984, 1991; Wolberg et al., 1988; Heffern, this volume). This paper presents a preliminary sedimentological study of the area. Strata of the Fruitland and Kirtland Formations are exposed in a badland setting in the Fossil Forest and exhibit three-dimensional exposure, which is ideal for sedimentological study. The Fruitland and Kirtland represent nonmarine deposition as indicated by regional stratigraphic relationships, the presence of abundant nonmarine fossils (e.g., dinosaurs, *in situ* trees) and characteristically nonmarine rock types (e.g., coal).

The Fruitland-Kirtland formational contact passes through the Fossil Forest. Recent workers have utilized the highest, thick coal bed as the formational boundary (e.g., Fassett and Hinds, 1971; Strobell et al., 1985). However, C. M. Bauer, who named both formations, published many stratigraphic sections, showing that he intended the Fruitland to extend up to a persistent sandstone facies of brown-colored sandstones that is represented in the study area by ribbon sandstones described below (Bauer, 1916, pl. 45; Bauer and Reeside, 1921, pl. 22). I advocate use of the base of this easily recognizable sandstone as the formational contact in the northern San Juan Basin. This sandstone facies is not present in the southern basin and in that area the top of the stratigraphically highest, thick (>1 m) coal in the Fruitland Formation can be used as the formational contact.

Eight architectural elements of fluvial deposition are recognized in the Fossil Forest (Table 2.1). Over 70% of the rock volume is composed of generally fine-grained, extra-channel deposits (Hunt, 1984). Just under half of these strata are carbonaceous shale, coal or dark gray mudstone that were deposited in poorly drained floodbasin swamps. Rocks representing better-drained floodplain deposition contain approximately half of the dinosaur bones and more than three-quarters of the logs and stumps.

Two distinct channel morphologies are present. The most common channels are ovoid in plan view (up to 490×230 m) and up to 6 m thick. They are characterized by inclined heterolithic stratification (IHS), asymmetrical channels and channel fill, low angle-planar and trough crossbeds, upward fining, commonly associated crevasse-splay deposits, numerous vertebrate remains, including partial dinosaur skeletons, and fossil logs. These channels represent high sinuosity river channels with a low braiding parameter on the basis of IHS, asymmetrical cross section, common channel fill (abandoned channels) and common crevasse splays. The presence of sandy bedforms, lateral accretion products

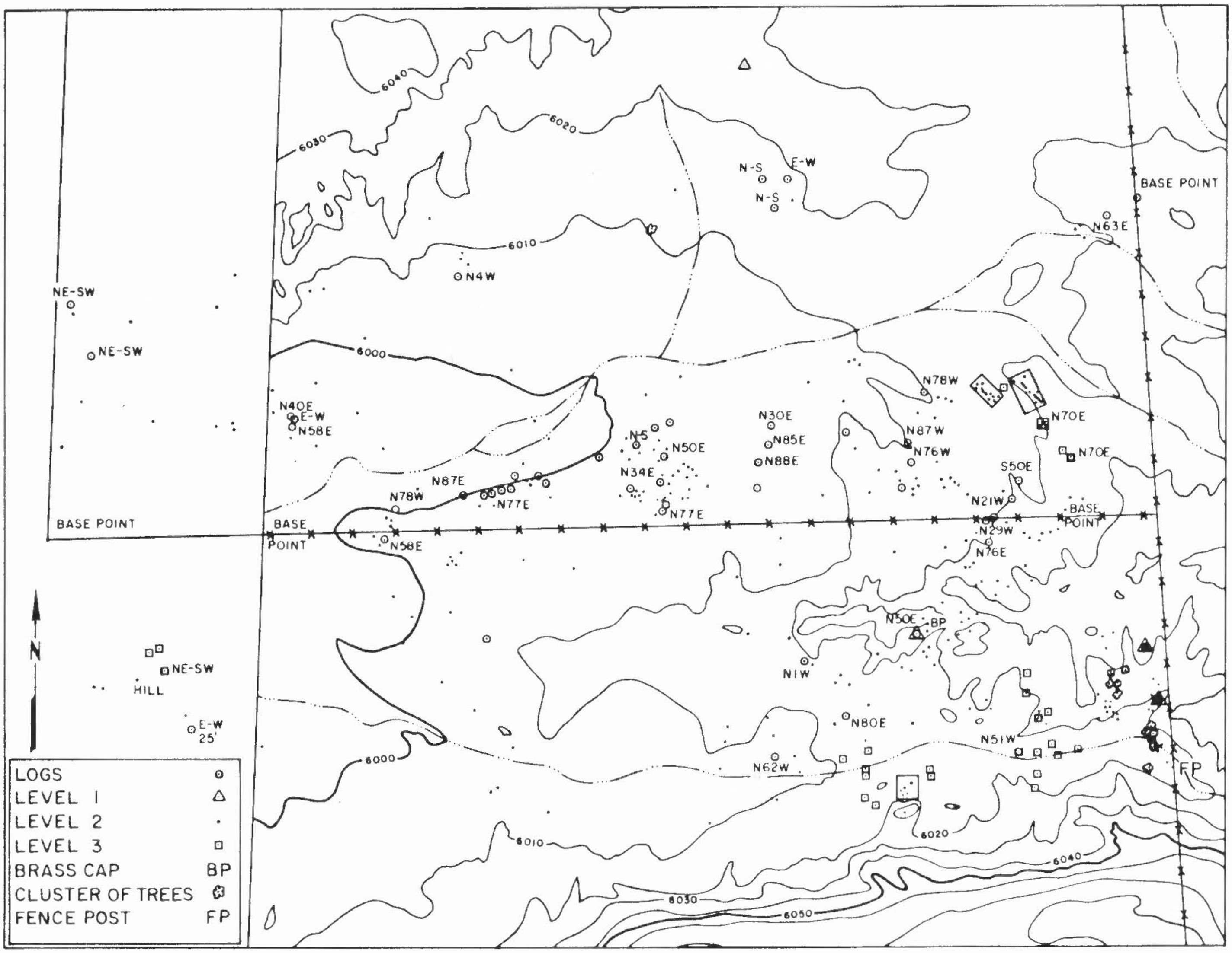

FIGURE 2.19. Distribution of stumps and logs in the Fossil Forest (from Wolberg et al., 1988).

and abundant overbank deposits indicates that the majority of deposition in the study area was by high sinuosity, suspended-load streams (Miall, 1985, fluvial style 7, table 3, fig. 13).

The second form of channel is represented by only two examples. These channels are characterized by a ribbon shape in plan view (up to 840 m × 110 m), lack of IHS, dominantly low-angle planar crossbeds, trough crossbeds, horizontal stratification and large, shallow scours. Deposition in these channels appears to have been dominated by the migration of transverse bars (planar crossbeds) and in part by longitudinal bars (planar crossbeds associated with horizontal stratification). These channels appear to represent low-intermediate sinuosity channels with a high braiding parameter and "Platte-type" macroforms (cf. Miall, 1985). These sandstones are restricted to the lower Kirtland Formation, whereas the lenticular sandstones (described above) are similar to channels throughout the upper Fruitland.

The ribbon channels are further characterized by ferruginous-stained upper portions after exposure to weathering. Utilizing lithostratigraphy, the interval characterized by these brown-capped ribbon sandstones can be correlated from north of the San Juan River in the north to Ah-shi-sle-pah to the south. These strata represent the Bisti Member (Hunt and Lucas, this volume). These sandstones can be recognized in the northeastern portion of the San Juan Basin in the subsurface and are reservoirs for gas. Preliminary analysis suggests that these sandstones represent deposition during initial downwarping of the San Juan Basin at about the Campanian-Maastrichtian boundary when increased gradients may have resulted in lower sinuosity channelforms (Hunt, 1983). This change in fluvial style in the lower Kirtland coincides with the preservation of the majority of the fossil vertebrates and invertebrates in the Fruitland-Kirtland (pre-Naashoibito Member) sequence (Hunt, 1991). Throughout the northwestern San Juan Basin, the majority of vertebrate and invertebrate fossils are found in a narrow stratigraphic interval below the Bisti Member (e.g., Clemens, 1973).

Depositional environments in the Fossil Forest area were dominated by high sinuosity streams, with a high suspended load, which were subject to frequent flooding. The floodplain was poorly drained, as indicated by the high carbonaceous content of overbank deposits. Three phases of deposition can be recognized in the Fossil Forest. First, the upper Fruitland is characterized by lenticular channels and poorly drained overbank environments (gray mudstones, carbonaceous shales) and is terminated by a 1-m-thick coal. Second, the lowermost Kirtland is characterized by lenticular channels, better-drained overbank environments, more crevasse-splay preservation of the majority of the fossil biota and is terminated by a very persistent carbonaceous shale. Third, the higher Kirtland is characterized by both lenticular and ribbon sandstones, better-drained overbank environments (dominantly olive-green sediments) and a slight increase in grain size of overbank deposits from mudstone to siltstone. These three intervals can be recognized over a large portion of the northwestern San Juan Basin.

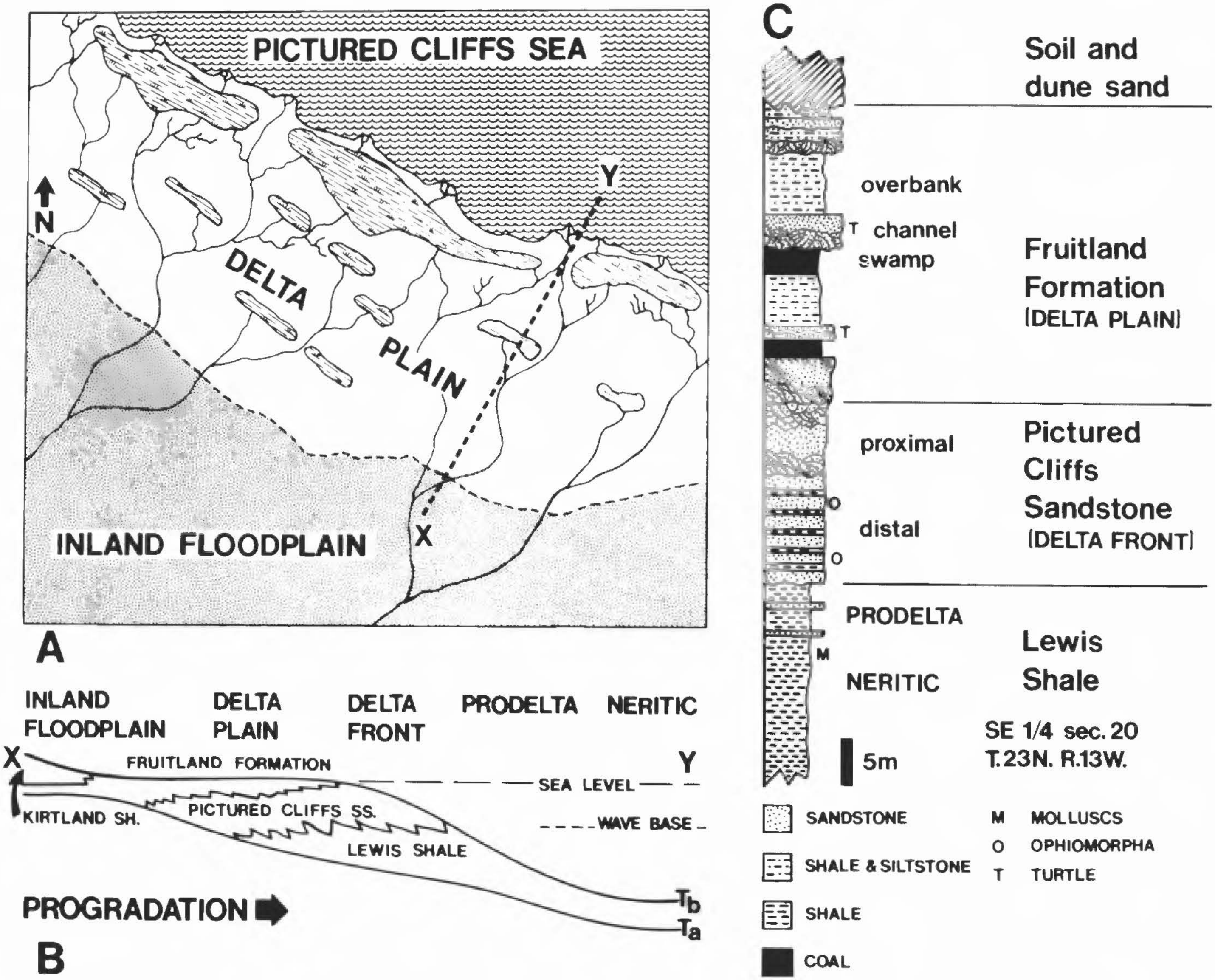

FIGURE 2.20. Depositional environments of the Lewis Shale, Pictured Cliffs Sandstone, Fruitland Formation and lower part of the Kirtland Formation. Diagrammatic paleogeographic map of part of northwestern New Mexico during the late Campanian, showing the environments of deposition of the rocks that now compose the Lewis Shale, Pictured Cliffs Sandstone, Fruitland Formation and Kirtland Formation (lower part). B, Diagram showing relationships of the Lewis Shale, Pictured Cliffs Sandstone, Fruitland Formation and Kirtland Formation (lower part) to a deltaic sedimentation model. C, Measured section of the Lewis Shale (upper part), Pictured Cliffs Sandstone and Fruitland Formation (lower part) at a locality in the western-central San Juan Basin, exemplifying the depositional environments depicted diagrammatically in A and B (from Lucas and Mateer, 1986).

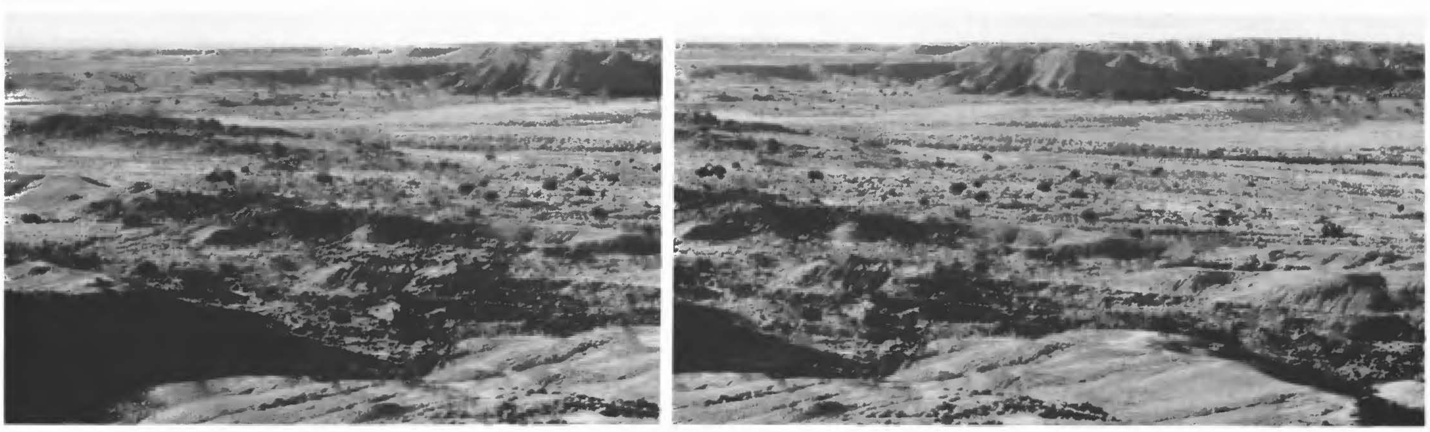

FIGURE 2.21. Stereo photo pair from the upper and central portions of Coal Creek. Two dissected geomorphic surfaces are evident in the background. In addition, the valley floor contains multiple Holocene fill terraces. Local badland topography is developed on the Kirtland Formation. Hills in the middle background are capped by the Farmington Member of the Kirtland Formation. The Ojo Alamo Sandstone crops out along the horizon on the right.

TABLE 2.1. Characteristics and interpretation of architectural elements from the Fossil Forest. Lithofacies after Miall (1978).

Element	Geometry	Lithology/(Lithofacies)	Interpretation
Clay-pebble conglomerate	Lenticular < 50 cm thick	Matrix supported, clay pebbles in poorly sorted sandstone, organic debris (Gm)	Channel lag
Lenticular sandstone	Ovoid in areal view, up to 490 m by 230 m, up to 6 m thick, lenticular	Medium-grained sandstone, trough and planar x-beds, IHS with width of 25 m and height of 5 m, fine up (St, Sr)	High sinuosity channel
Ribbon sandstone	Ribbon in areal view up to 840 m by 100 m, up to 6 m thick	Medium-very coarse grained sandstone, low angle planar x-beds, broad shallow scours, trough x-beds (Sp, St, Sl, Sc)	Low sinuosity channel
Interbedded sandstone/ siltstone	Tabular, up to 4 m thick, up to 10 m wide	Shaly sandstone, fines away from channel, siltstone, mudstone, low angle x-beds (Sl, Fl)	Proximal crevasse splay
Tabular sandstone	Tabular, up to 800 m wide, <1.5 m thick	Moderately sorted medium-grained sandstone, fine up, fine laterally, scour base, small-scale planar x-beds, ripples (Sl, Fl)	Crevasse splay
Carbonaceous beds	Tabular, < 1 m thick	Carbonaceous shale/ coal (C)	Floodbasin swamp
Interbedded sheet sandstone/ silt-mudstone	Tabular, up to 1000's sq m, <.5 m thick	Sandstone, siltstone, mudstone, ash, planar lamination, ripples, <u>Trypanites</u> (Fl, Fsc, Fcf, Fr)	Flood deposits
Lenticular interbedded sandstone-mudstone	Lenticular, up to 1.7 m thick, up to 10 m wide	Shaly sandstone with plant debris, interbedded gray mudstone (carbonaceous), lamination, ripples (Ss, Fl)	Channel fill

Wolberg (e.g., Wolberg et al., 1989; Bellis and Wolberg, 1989) argued that the presence of the mineral huntite in the Fruitland Formation of the Fossil Forest necessitates a modification of previous environmental reconstructions. By implication, huntite is proposed to be evidence of evaporitic conditions during Fruitland time. This hypothesis is contradicted by all sedimentological and paleontological data. Analysis of fossil-leaf floras and fossil tree-rings indicates a warm, humid, seasonal climate (Hunt, 1984, 1991). The diversity of the fossil biota in the Fruitland Formation (e.g., Lucas, 1981; Hunt and Lucas, this volume), particularly the presence of many aquatic vertebrates and the large number of megavertebrate herbivores (hadrosaurs, ceratopsians, ankylosaurs), argues against evaporitic conditions. In addition, there is no sedimentological evidence of aridity in Fruitland strata. Evaporites and coal are rarely found together. It is more parsimonious to believe that the conditions favoring formation of huntite in modern environments, of which there are few examples, are currently too poorly known to allow use of this mineral to predict past environments. The alternative is to discount all existing paleontological and sedimentologic evidence that indicates that evaporitic conditions did not exist during the time of Fruitland deposition.

MINERAL RESOURCES OF THE FOSSIL FOREST RESEARCH NATURAL AREA

Edward L. Heffern

U.S. Bureau of Land Management, P.O. Box 27115, Santa Fe, New Mexico 87502-7115

The Fossil Forest Research Natural Area (Fig. 2.22) lies in the San Juan Basin of northwestern New Mexico, about 35 mi south of the town of Farmington. The San Juan Basin Wilderness Protection Act of 1984 (the SJB Act) designated these 2770 acres in portions of sections 13, 14, 22, 23, 24, and 26, T23N, R12W, as a special area to be studied for paleontological and other values. Under the SJB Act, the BLM submitted recommendations for management of the Fossil Forest to Congress by October of 1992. The main reason this area was selected for special study was that it is both rich in fossil resources and coal resources, and the potential for coal mining could affect recovery of fossils.

About 111 million tons of coal in beds 2.3 ft thick or greater lie in place under the Fossil Forest at depths of 250 ft or less and with stripping ratios of 15:1 or less. The coal beds generally dip about one degree to the north and northeast. These surface minable coals are in the Upper Cretaceous Fruitland Formation. There are four main coal zones that occur within a stratigraphic interval of 110 to 140 ft. From lowest to highest, they are informally called the Green, Upper Green, Lower Blue and Blue coals.

The thickest and most economically important coals are the Upper Green and Blue. Individual coal beds are up to 15 ft thick (Fig. 2.23). Average total thickness of all coal beds is 22.7 ft, and average overburden is 139.9 ft, for an average stripping ratio of 6.2 ft of overburden to 1 ft of coal. This coal is subbituminous in rank, with high ash but low sulfur values. Core samples for individual coal beds show ash contents of 10 to 30% (average 21%), sulfur contents of 0.3 to 0.8% (average 0.5%) and ash-received BTU/lb heating values of 7300 to 9400 (average 8300). The analyses suggest that, in general, beds lower in the Fruitland Formation have slightly lower sulfur and ash contents and higher heating values than beds higher in the formation

The main fossil locations in the Research Natural Area appear to occur within a 100-ft-thick horizon immediately above the Blue bed (Fig. 2.23). This equates to the lowermost 100 ft of the Kirtland Formation. Much of this interval is covered by dune sand or alluvium; that which is exposed commonly exhibits badland topography.

All surface and mineral rights in the Fossil Forest are under federal ownership. The SJB Act, which designated the Fossil Forest study area, withdrew it from disposition under the mining laws and mineral leasing laws, subject to valid existing rights, and prohibited activities that would significantly disturb the land surface. Portions of four coal-preference-right-least applications (PRLAs) cover 2410 of the 2770 acres in the Research Natural Area (Fig. 2.22). These applications (NM 3752, 3753, 3754 and 3835) are currently held by Ark Land Company. The applications were filed in 1972 under authority of the Mineral Leasing Act of 1920. The applications thus predated the requirement in the 1976 Federal Coal Leasing Amendments Act to lease all coal tracts competitively, and predated the provision in the SJB Act to withdraw the area from mineral leasing. The applicants are entitled to a lease or other compensation if they can prove they found coal in "commercial quantities"—in other words, if they can prove they had valid existing rights. The long processing time frame is due to an ever-changing succession of laws, lawsuits, regulations and policy decisions, which have imposed additional requirements to process the applications.

There is no oil or gas production in the Fossil Forest. The nearest significant development is the Bisti field, approximately 10 mi north and east of the Fossil Forest, which produces oil from WNW-ESE-trending barrier-bar deposits in the Cretaceous Gallup Sandstone (Collins, 1978; Sabins, 1978). Two wells have been drilled in the Fossil Forest to Cretaceous targets, one in 1957 and one in 1971. However, both were dry and were later abandoned (U.S. Bureau of Land Management, 1986). These wells are in the SW¼ of section 23 and the SW¼ of section 26. Only one oil and gas lease (NM 55849) remains in the Fossil Forest. It overlaps 650 acres of the Fossil Forest and is held by Dugan Production Company. It will expire if production does not occur by 30 June 1993.

There are no current mining claims in the Fossil Forest. Uranium may be present in rocks of the Brushy Basin and Westwater Canyon Members of the Jurassic Morrison Formation, but these strata are about 5000 ft deep and are considered uneconomical to mine (Bielski et al., 1983). Iron carbonate and, less commonly, barite concretions occur in the shales and sandstones of the Fruitland and Kirtland Formations, but have little economic value.

There are no current mineral material sales or permits in the Fossil Forest. Potentially saleable minerals include petrified wood, sand and "clinker." Petrified wood occurs throughout the badlands of the Kirtland and Fruitland Formations. The greatest concentration is in the SW¼ SE¼ sec. 14 and the NW¼ NE¼ sec. 23, where 40 tree stumps and 11 logs have been mapped (Hunt, 1984). The Fossil Forest is closed to collection of petrified wood under the 43 CFR 8224 regulations, which implement provisions of the SJB Act.

Stabilized dune sand and alluvium cover about 840 acres (30%) of the Research Natural Area. The dunes are commonly 5 to 10 ft thick and are divided into two layers by a Holocene soil horizon (Strobell et al., 1985).

Brick-red outcrops of "clinker" up to 30 ft thick occur over about 100 acres in the southern half of section 26. They were formed by natural burning of the highest major coal bed (the Blue) and the baking of overlying shale and sandstone beds.

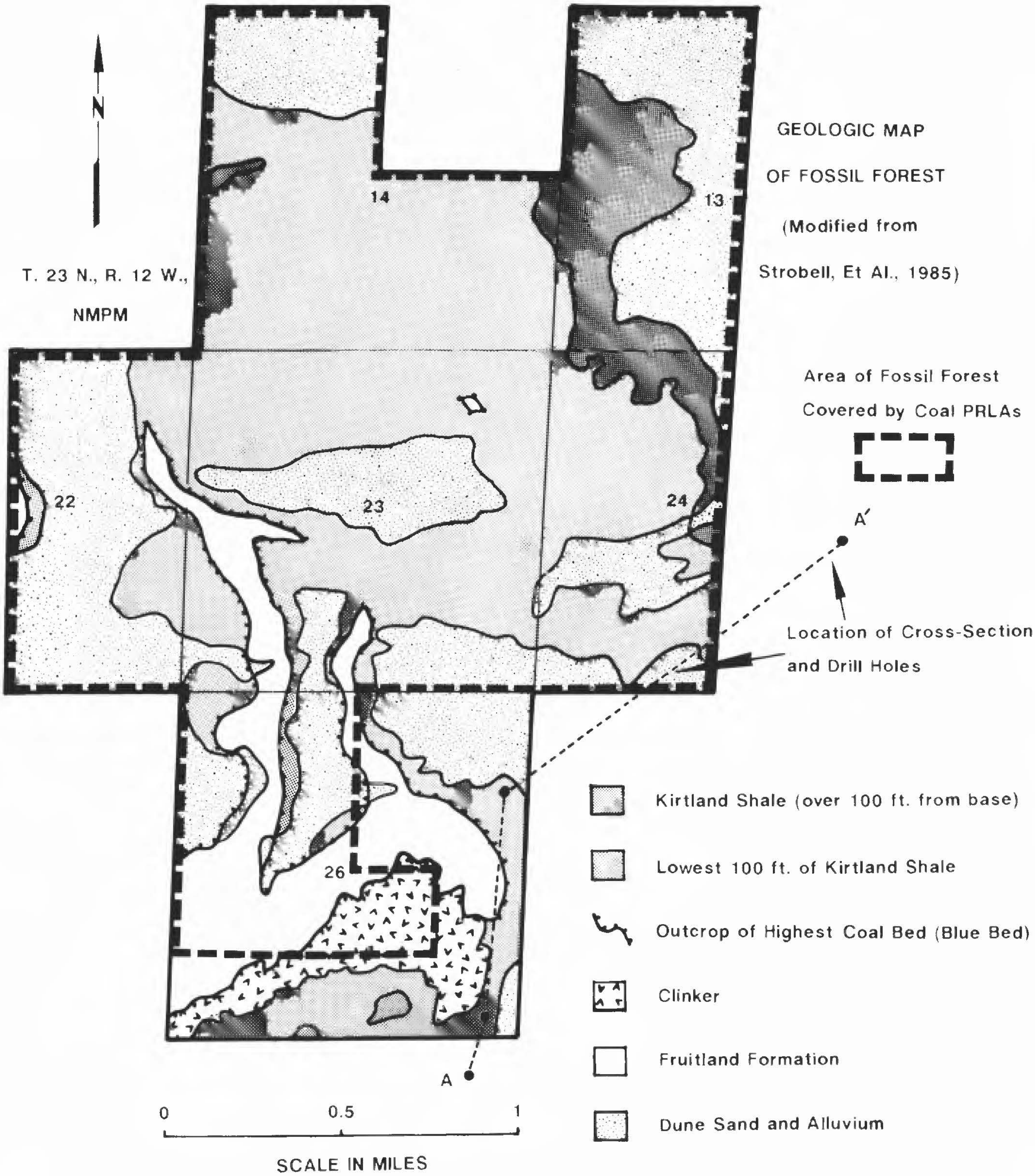

FIGURE 2.22. Generalized geologic map of the Fossil Forest.

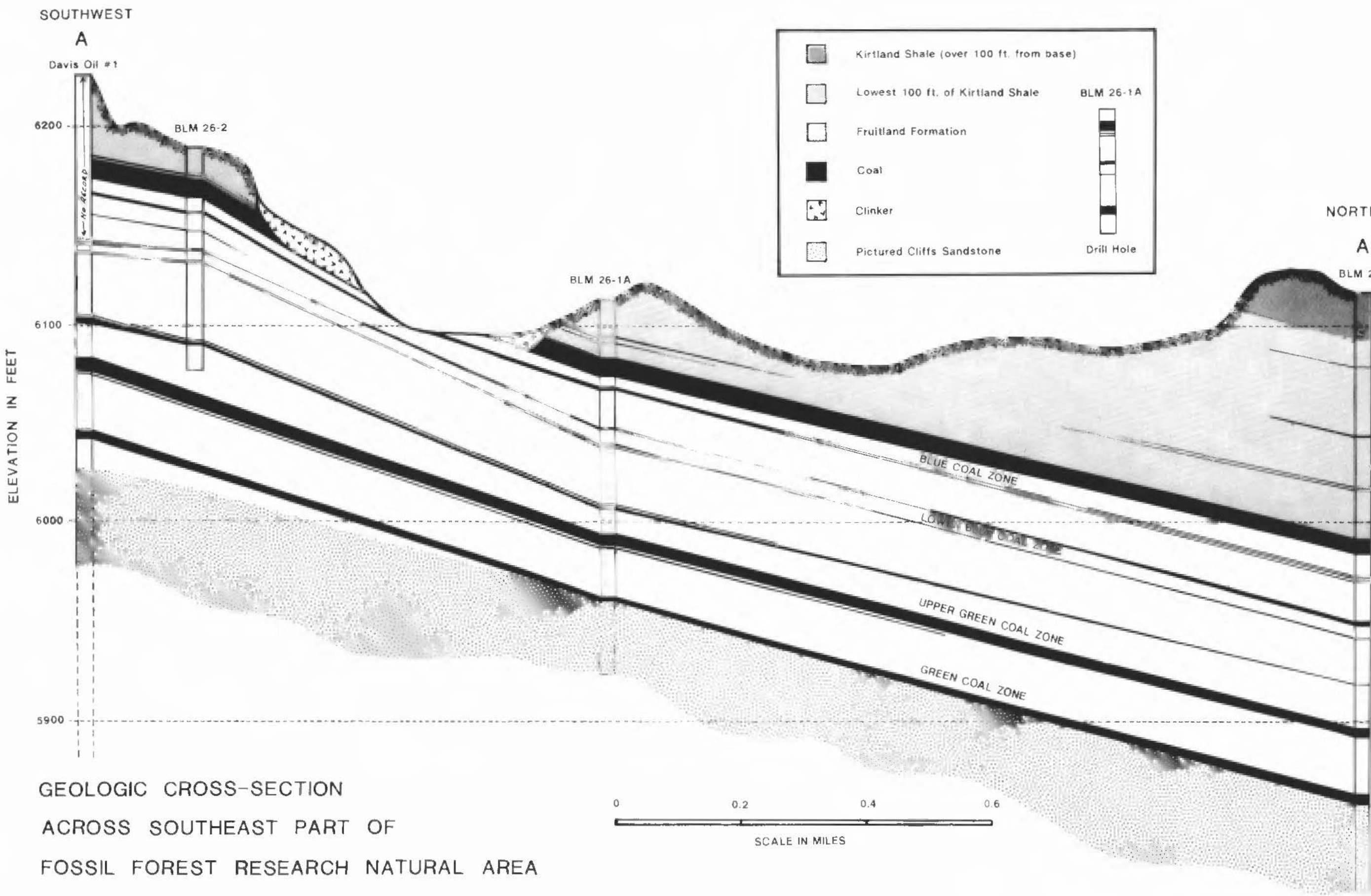

FIGURE 2.23. Geologic cross section through part of Fossil Forest.

105.0 Playa; **turn right.** **1.9**

106.9 Road forks; **go left.** **0.1**

107.0 **Go left** (east) on county dirt road. **1.5**

108.5 Junction with County Road 7870; continue straight. Roadcuts expose mid and late Holocene eolian units (Qe_2 and Qe_3) separated by a light brown buried soil developed on Qe_2. Road is nearly parallel to wind direction and parabolic dunes. Periodic road grading exposes Anasazi Indian fire pits from which C^{14} radiometric ages have been obtained for the eolian deposits and soils (Wells et al., 1983; McFadden et al., 1983). This road was renumbered in the mid-1980s; its previous designation was County Road 14 (C-14), which seemed more appropriate. **1.1**

109.6 Bluff at 10:00 on skyline is capped by Ojo Alamo Sandstone over Kirtland Formation. **1.3**

110.9 Cattle guard (bumpy one!). **0.9**

111.8 Roadcut on right in $Qe_{2,3}$ separated by a light brown buried soil. **1.6**

113.4 At 9:00, Ojo Alamo Sandstone is brown sandstone over somber Kirtland Formation badlands; no Naashoibito Member is present here. Farmington Member of the Kirtland Formation pinches out from left to right very near the road here (see geologic map of area in Smith, this volume). **0.7**

114.1 Kirtland Formation badlands on left. At 9:00, alluvial surfaces on far side of Coal Creek drainage slope to the southwest. **1.0**

115.1 Cattle guard; low outcrops at 10:00 across valley are Nacimiento Formation. **2.2**

117.3 **Turn left** on County Road 7635 before cattle guard. **0.6**

117.9 Road bed is Fruitland Formation red "clinker." Gray mudstone to right is Nacimiento Formation. **0.8**

118.7 Outcrops to right up valley are lower Nacimiento Formation. **0.9**

119.6 Low Nacimiento Formation outcrops to right. **0.7**

120.3 San Juan County Road 7515 to left; continue straight. **1.0**

121.3 Outcrops at 9:30–10:30 are Nacimiento Formation. **1.4**

122.7 Cattle guard; junction; **turn left.** Quartzite gravels of the Escavada Member of the Nacimiento Formation crop out along the crests of low ridges in this area. **0.5**

123.2 Crest of hill; El Huerfano in view ahead. **0.8**

124.0 Cross arroyo in the headwaters of Coal Creek; note low outcrops of Nacimiento Formation sandstones in arroyo. **0.3**

124.3 Pass under powerline. **1.6**

125.9 Navajo Brethren in Christ Mission complex on left. **1.1**

127.0 First pass under powerline (two more passes in next 0.4 mi). **1.6**

128.6 Blanco Trading Post; intersect NM-44; **turn right** and retrace route on NM-44 to Cuba. **59.1**

187.7 Cuba.

End of Second-Day Road Log.