FIRST-DAY ROAD LOG, FROM GALLUP TO GAMERCO, YAH-TA-HEY, WINDOW ROCK, FORT DEFIANCE, NAVAJO, TODILTO PARK, CRYSTAL, NARBONA PASS, SHEEP SPRINGS, TOHATCHI AND GALLUP

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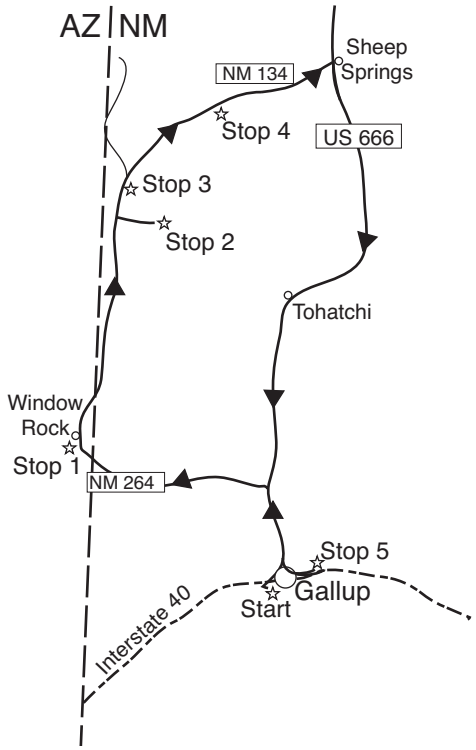
Assembly Point: Best Western Inn and Suites, 3009 West Highway 66, Gallup
Departure Time: 7:30 AM
Distance: 141.8 miles
Stops: 5



SUMMARY

The first day's trip takes us around the southern flank of the Defiance uplift, back over it into the southwestern San Juan Basin and ends at the Hogback monocline at Gallup. The trip emphasizes Mesozoic—especially Jurassic—stratigraphy and sedimentation in the Defiance uplift region. We also closely examine Cenozoic volcanism of the Navajo volcanic field.

Stop 1 at Window Rock discusses the Laramide Defiance uplift and introduces Jurassic eolianites near the preserved southern edge of the Middle-Upper Jurassic depositional basin. At Todilto Park, Stop 2, we examine the type area of the Jurassic Todilto Formation and discuss Todilto deposition and economic geology, a recurrent theme of this field conference.

From Todilto Park we move on to the Green Knobs diatreme adjacent to the highway for Stop 3, and then to Stop 4 at the Narbona Pass maar at the crest of the Chuska Mountains. The focus at Stops 3 and 4 is the Cenozoic igneous history of the Navajo volcanic field. The trip then returns to Gallup to end at Stop 5 on the Hogback east of town. Here, we discuss Cretaceous stratigraphy and coal geology.

NOTE: Most of this day's trip will be conducted within the boundaries of the Navajo (Diné) Nation under a permit from the Navajo Nation Minerals Department. Persons wishing to conduct geological investigations on the Navajo Nation, including 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, Arizona, 86515, 928-871-6587. Sample collection on Navajo land is forbidden.

Mileage	
0.0	Start in parking lot of Best Western Inn and Suites, 3009 West Highway 66 on west side of Gallup. **Turn left** and proceed west on West Highway 66. **Get in left lane**. **0.3**
0.3	Pass through traffic light at Rico Street. **0.3**

0.6 Tertiary Twin Cones minette intrusive on left, part of the Navajo volcanic field (for discussion of the Navajo volcanic field see Semken, this volume). **0.2**

0.8 **Turn left** onto onramp for Interstate Highway 40 East, before bridge (I-40 overpass). **0.2**

1.0 Merge left. **0.1**

1.1 Cross bridge on Interstate 40 eastbound looking down dip into the Upper Cretaceous Crevasse Canyon Formation (Bartlett Barren Member). **0.2**

1.3 Cross bridge over Burlington Northern Santa Fé (BNSF) main line. **1.2**

2.5 Cross bridge over Rio Puerco. An old foot bridge over the river, a little farther upstream, gave Gallup its Diné name, Na'nízhoozhí, Spanned Across (Diné terms and their definitions are from Van Valkenburgh, 1941; Austin and Lynch, 1983; and Young and Morgan, 1987; also see Blackhorse et al., this volume.) **0.2**

2.7 Good outcrops of the Crevasse Canyon Formation to the left next 0.2 miles. **0.7**

3.4 Coal-bearing and clinkered outcrops of the Upper Cretaceous Menefee Formation in roadcuts to left and right. **0.8**

4.2 Sign for Exit 20. Hogback forms skyline ahead. More Menefee Formation outcrops to left. **Prepare to take exit. 0.5**

4.7 Mile marker 20. **0.5**

5.2 **Take exit 20** to Muñoz Boulevard to right, **get into left lane on exit ramp. 0.3**

5.5 **Turn left at traffic light** to go north on US Highway 666. **0.1**

5.6 Pass through traffic light at Interstate 40 frontage road. **0.3**

5.9 Pass through traffic light at Metro Avenue. Menefee Formation outcrops to left. **0.2**

6.1 Pass through traffic light at West Jefferson Avenue. **0.5**

6.6 Gallup flea market on right. **0.3**

6.9 Sign on right "Leaving Gallup." View to 2:00 of Crevasse Canyon outcrops in Gibson Canyon. **0.2**

7.1 Good outcrops of crossbedded fluvial sandstones of Menefee Formation on left. **0.4**

7.5 Pass through traffic light at Chino (west) and Ninth (east) intersection. **0.6**

8.1 Old railroad bed on left. **0.4**

8.5 Old mine, headframe and power plant on left at Gamerco (Gallup American Coal Company). The community of Gamerco was platted as a company town in the early 1920s, as the Gallup American Coal Company began sinking shafts for coal mining nearby. The company moved abandoned houses from Heaton, an earlier coal camp, into Gamerco and built new houses as well (Julyan, 1996). By 1930, the town had more than 1000 residents, but it lost its post office in 1964, and now only about 400 people call Gamerco home.

Note the old Navajo No. 5-Gamerco mine's headframe and power plant stack on left at Gamerco. This is all that remains of one of the largest underground coal mines in the Gallup area that operated in the early part of the 20th century. In 1921, two shafts were sunk, and new facilities, including a power plant, were built. Production at the mine began in late 1922 and averaged about 300,000 tons per year (Fig. 1.1). Most of this coal was marketed for domestic use for the local area, while some was shipped to Arizona and California. At one point, over 400 miners worked in the mine. Operations ceased at the Navajo No. 5 in 1951 (Nickelson, 1988).

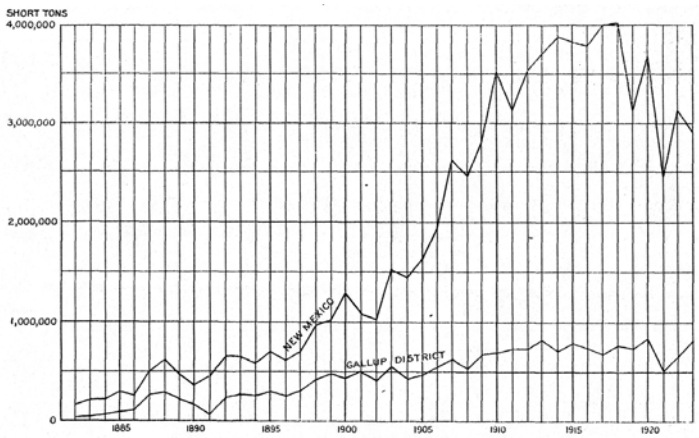


FIGURE 1.1. Annual coal production in the Gallup area and in New Mexico, 1882-1923 (from Sears, 1925).

Two coal seams were mined, the No. 3 and No. 5 beds, averaging 5-ft thick. These are the middle and lowermost coal seams in the Cleary and Gibson coal members of the Menefee and Crevasse Canyon formations, undivided. The Gallup coal field is south of the depositional pinchout of the Upper Cretaceous Point Lookout Sandstone, so the Gibson Coal Member and the Cleary Coal Member form one thick, continuous coal-bearing sequence. **0.9**

9.4 Crest of hill; note roadcuts in prominent red sandstone in Menefee Formation that caps ridge. **0.1**

9.5 Mile marker 4. Good view ahead of Cretaceous outcrops on southeastern flank of the Defiance uplift. All outcrops from here to Yah-ta-hey are Menefee Formation. **1.0**

10.5 Milemarker 5. Chuska (from the Diné Ch'óshgai, white spruce) Peak at 12:00; Deza (deez'á, "it extends out") Bluffs at 1:00; southeastern end of Chuska Mountains at skyline is capped by Paleogene Chuska Sandstone (Fig. 1.2). **2.0**

12.5 Approaching sign for Window Rock exit, **get into left lane. 0.3**

12.8 Edward O. Plummer Interchange. Edward O. Plummer, of the Coyote Canyon area near here, was the Eastern Agency Superintendent for the U.S. Bureau of Indian Affairs for many years, a member of the New Mexico State Roads Commission, and a noted advocate of road and highway improvement on the Navajo Nation. He was the father of former Navajo Vice President Marshall Plummer. **Go left on NM Highway 264 under bridge** to Window Rock. **0.2**

13.0 Enter Yah-ta-hey (population 580 by the 2000 census). The community is organized around the Yah-ta-hey trading post, established by J. B. Tanner (Julyan, 1996). The name is a common corruption of the Diné greeting Yá'át'ééh, meaning "It is good." From here to the Arizona state line we will be in a "checkerboard" region of the Navajo Nation and other jurisdictions. **0.5**

13.5 Leave Yah-ta-hey. **0.5**

14.0 Pass under powerlines. **1.5**

15.5 Green Meadows Road on right. **0.5**

16.0 Milemarker 13; crest hill, Menefee Formation outcrops in distance at 2:00. **0.4**

16.4 Smooth Rock Road to right. **1.6**

18.0 Crest hill; McKinley Mine surface coal mine ahead with spoil piles in distance. **0.5**

18.5 Winchester Road on right. **1.4**

19.9 Crest hill; road drops from Menefee Formation to Crevasse Canyon Formation. **0.5**

20.4 Cross Defiance Draw, McKinley Mine ahead. Pittsburg and Midway Coal Mining Company, a division of Chevron Texaco, operates the McKinley coal mine. It is the oldest operating surface mine in New Mexico and one of five coal mines presently operating in the San Juan Basin. Coal production began in 1962, and, at the end of 2001, total production from this mine was over 143 million tons. Production averages 6-7 million tons/year (McLemore et al., 2002). McKinley ships their coal by rail to generating stations in Arizona, including the Arizona Public Service Cholla plant in Joseph City and Arizona Electric Power Apache plant in Cochise. Coal extracted at McKinley is from the Cleary and Gibson coal members of the Menefee and Crevasse Canyon formations, undivided. **0.4**

20.8 McKinley Mine sign on right. Mine to left (Fig. 1.3), with reclaimed areas, and spoil piles on right. **0.3**

21.1 Mile marker 8. **1.1**

22.2 Reclaimed mined land: the scattered rock piles are intended to provide habitats for small mammals and birds. **0.3**

22.5 Sign on left proclaims the presence of reclaimed land. **0.6**

23.1 Orin Anderson's retirement business on right. **0.7**

23.8 Black Hat; note Menefee/Crevasse Canyon Formation coal beds on left. **0.5**

24.3 Cross tributary of Tsé Bonita Wash. The name means "pretty rock" and is an amalgamation of Navajo tsé ("rock") and Spanish bonita ("pretty"). **0.6**

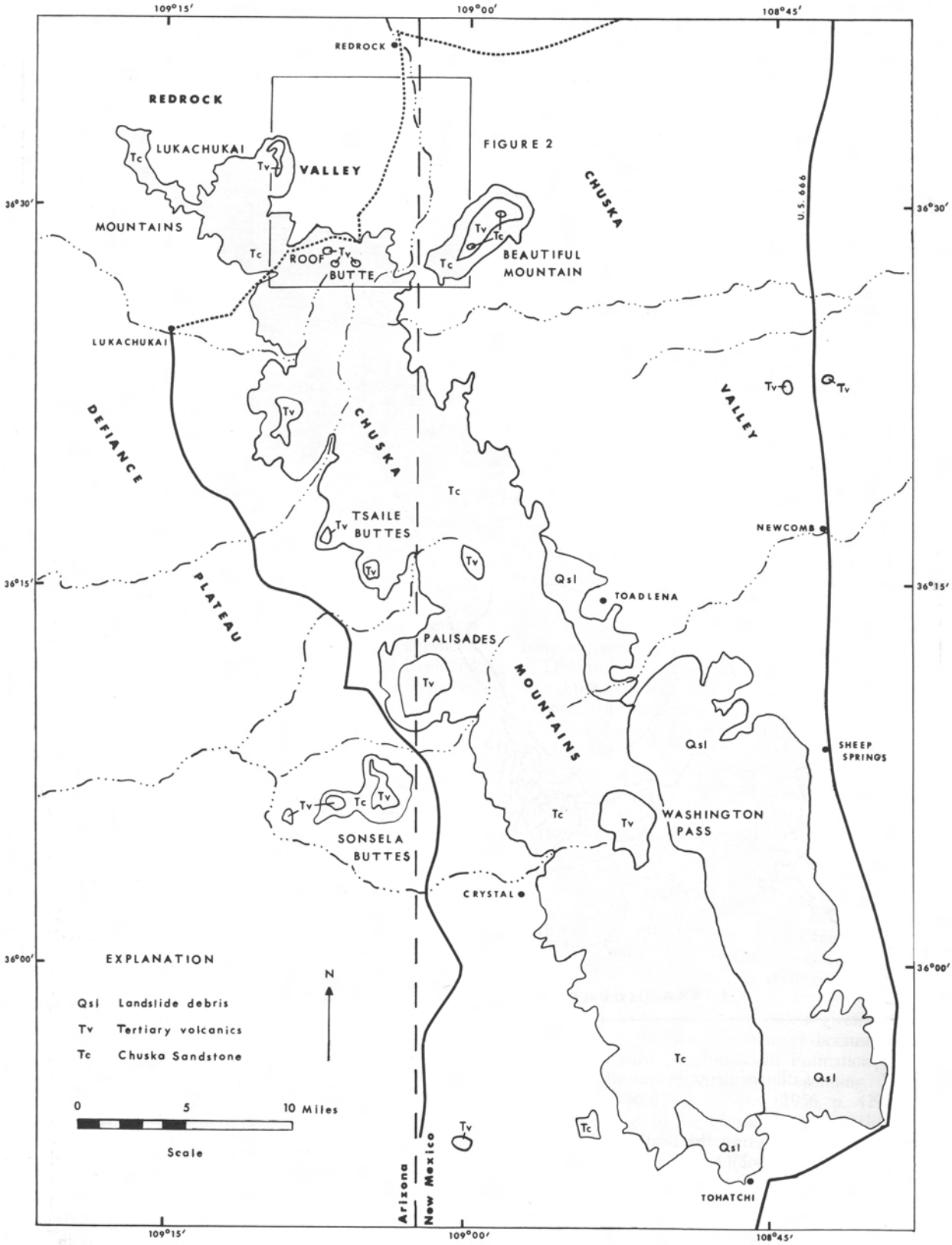


FIGURE 1.2. Generalized geologic map of the Chuska (Ch'óshgai) Mountains (from Blagbrough, 1967). Qsl = Quaternary landslide depositss, Tc = Chuska Sandstone and, Tv = Navajo volcanics.

FIGURE 1.3. Drag line at the McKinley Mine in Summer 2002, at mile 20.8.

24.9 Bridge over rail line, a BNSF mine spur. Road begins descent through Crevasse Canyon Formation. **0.2**

25.1 Mile marker 4. The highway now begins to descend through the stratigraphic section. **1.0**

26.1 Mile marker 3. **1.5**

27.6 Paved road to McKinley Mine headquarters to right; road is on Upper Cretaceous Mancos Shale. **0.4**

28.0 Pass through hogback on right and left capped by Gallup Sandstone (Fig. 1.4). The Gallup Sandstone is the regressive Late Cretaceous shoreline sandstone complex over which the coal-bearing lower part of the Crevasse Canyon Formation was deposited. **0.5**

28.5 Hilltop Drive on right and left. Roadcuts are Cretaceous Dakota Sandstone on Upper Jurassic Salt Wash Member of Morrison Formation. **0.1**

FIGURE 1.4. East-dipping cuesta of Gallup Sandstone at mile 28.0.

28.6 Cross creek and enter town of Tsé Bonito (population 261 by 2000 census). **0.2**

28.8 Traffic light. **0.5**

29.3 Enter Navajo Nation and Arizona. The route now becomes Arizona Highway 264. Cuesta on right developed in Jurassic Zuni Sandstone. **0.2**

29.5 Window Rock, the capital of the Navajo Nation. The Diné name for the community is Tsé́ghá́hoodzání, "the rock with a hole in it." No settlement existed here prior to 1936, when the Bureau of Indian Affairs built an agency headquarters that evolved into the Navajo capital. Navajo Nation Museum on right. **Get into left lane. 0.1**

29.6 Navajo Nation Inn on right. **Turn left on Beacon Road (before the traffic light). 0.2**

29.8 **STOP 1.** Fork in road; paved road to right to Window Rock international airport, dirt road to left. The Defiance monocline, very visible here, is discussed in the accompanying minipapers by Cather and Lucas. Window Rock is visible to the north/right side of the main road.

Here, we have a chance to examine closely the Jurassic eolian sandstones exposed at the stop. Talking points include:

1. We are near the depositional edge of two Jurassic basins—the San Rafael and Morrison basins of Middle and Late Jurassic age.

2. The lower, prominent eolian sandstone here is the Entrada Sandstoine of Middle Jurassic age. A distinct notch separates it from an overlying eolian sandstone locally called the "Cow Springs Sandstone."

3. The "Cow Springs Sandstone" sits in the same position as the Bluff Sandstone farther north, so only one name (Bluff) need be used.

4. The Entrada plus Bluff ("Cow Springs") is essentially the same unit that Dutton (1885) originally named Zuni Sandstone. Therefore, at locations like this

one, Zuni Sandstone can be used to refer to the thick pile of eolian sandstone, where it cannot readily be mapped into its two components, Entrada and Bluff (Fig. 1.5).

5. The notch between the Entrada and Bluff ("Cow Springs") here is equivalent to the Todilto and Summerville formations, which have pinched out north of here (Fig. 1.5).

6. The Entrada regionally has crossbeds that dip southwest, whereas the Bluff ("Cow Springs") regionally has crossbeds that dip to the east. This records a marked change in wind direction related to the northward drift of the North American continent during the Jurassic. By Bluff time (Late Jurassic), this part of North America had drifted northward into the zone of prevailing westerlies (Anderson and Lucas, 1995; Lucas and Anderson, 1997).

After stop return to AZ-264. 0.1

THE LARAMIDE DEFIANCE UPLIFT

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The north–northwest-trending Defiance uplift is asymmetrical, with its steep eastern flank (the Defiance monocline) facing the Gallup sag and the San Juan Basin (Fig. 1.6). With the exception of a few small outcrops of Proterozoic quartzite, the majority of the exposures on the Defiance uplift are of Permian and Triassic sedimentary rocks. Structural relief between the highest part of the uplift and the Gallup sag is at least 7000 ft (2150 m) (Kelley, 1955). The Laramide Defiance uplift encompasses part of the broader Defiance–Zuni highland of late Paleozoic age (e.g., Ross and Ross, 1986, fig. 8). The structural controls on this earlier highland, however, are very poorly understood.

The timing of Laramide deformation in the Defiance uplift is not well constrained. A major deltaic depocenter existed during deposition of the Pictured Cliffs Sandstone in the southwestern San Juan Basin (Flores and Erpenbeck, 1981) in the late Campanian (*Baculites scotti* zone of Fassett, 2000; dated 75.89 ± 0.72 Ma by Obradovich, 1993). This deltaic depocenter was localized down depositional dip (northeast) of the Gallup sag, which suggests that the structural differentiation of the Defiance

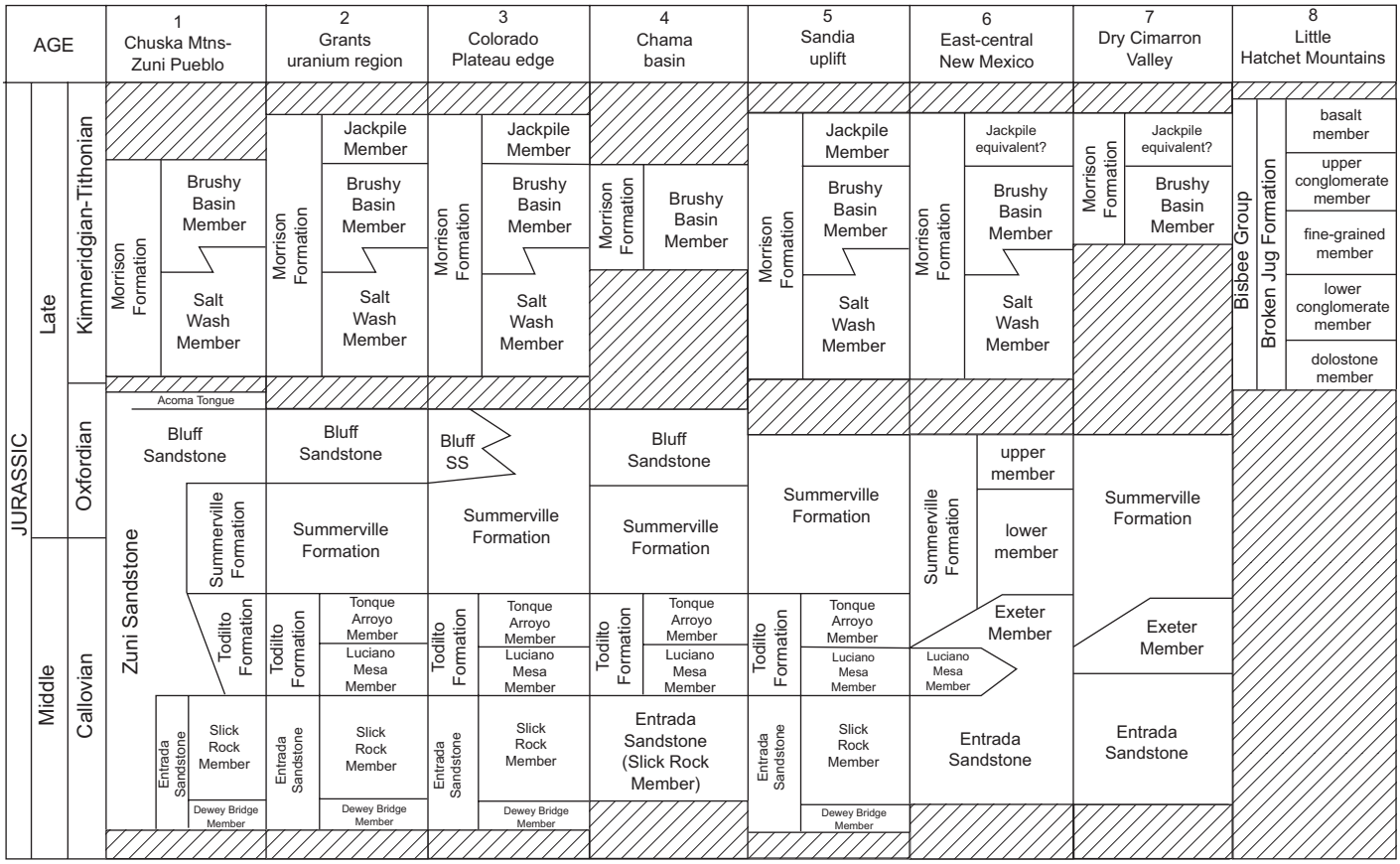

FIGURE 1.5. Correlation of Jurassic strata in New Mexico (from Lucas and Anderson, 1998).

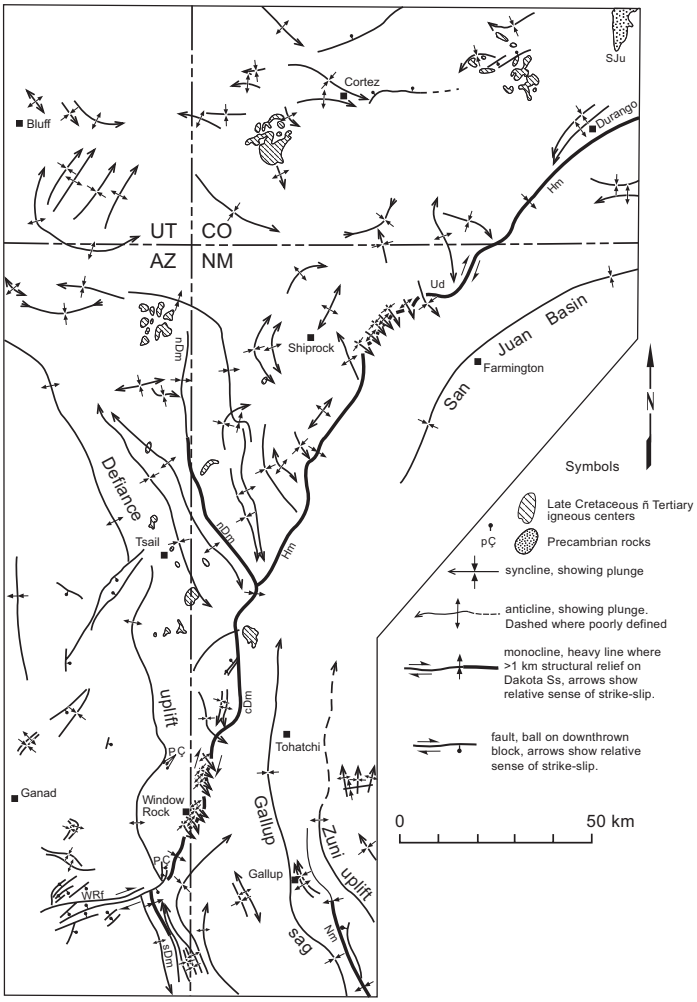

FIGURE 1.6. Map of structures in the Four Corners–Gallup region. Hm, Hogback monocline; SJu, San Juan Uplift; Ud, Ute dome; nDm, north Defiance monocline; cDm, central Defiance monocline; sDm, South Defiance monocline; WRf, Wide Ruins fault; Nm, Nutria monocline. Modified from Kelley (1967) and Woodward et al. (1997).

uplift–Gallup sag–Zuni uplift area may have begun to control fluvial patterns by this time.

The central Defiance monocline appears to be contiguous with the Hogback monocline to the northeast, although the southern part of the Hogback monocline is weakly developed. The central part of the Defiance monocline is highly sinuous due to the presence of a series of en echelon, southeast-plunging anticlines and synclines that modify the southeastern part of the uplift (Fig. 1.6; Kelley and Clinton, 1960). These en echelon folds are suggestive of right-slip along the central Defiance monocline, and Kelley (1967) proposed approximately 13 km of dextral deflection of Jurassic facies and pinchouts in this area. The Ute dome that adjoins the Hogback monocline northwest of Farmington (Fig. 1.6) also shows evidence of minor dextral deformation (Ralser and Hart, 1999). The timing of dextral wrenching along the Defiance–Hogback system is unclear; it probably postdates northwest shortening of the Hogback monocline (late Campanian–early Maastrichtian: Cather, this volume) and may be coeval with major Paleocene–Eocene northeast shortening in the San Juan Basin (e.g., Baltz, 1967).

The presence of a series of en echelon shortening structures to the northwest of the central Defiance monocline–Hogback monocline system, the most prominent of which is the northern Defiance monocline (Fig. 1.6), and the absence of such structures to the southeast of the monocline system, seemingly require significant lateral slip along the monocline system. Local differential shortening across the monocline system, however, is probably significantly less than the 13 km offset value estimated by Kelley (1967). If Kelley's estimate is correct, then dextral strike-slip on the basement faults that underlie the monocline system may accommodate deformation on a much larger scale (for example, perhaps transferring slip to the San Juan uplift to the northeast). If this is the case, then the fact that the central Defiance–Hogback monocline system does not appear to be broken by an exposed, throughgoing fault implies that significant components of strike-slip on the underlying basement fault would necessarily be accommodated by a broad zone of detachment, interstratal shear, and vertical-axis rotation in the overlying Phanerozoic sedimentary rocks (e.g., Jones, 2000; Cather, this guidebook). Such wrench deformation, if present, should be discernible with paleomagnetic analysis. The central Defiance monocline is dextrally separated from the southern Defiance monocline by the Wide Ruins fault (Fig. 1.6). This separation is about 8 km and suggests that the Wide Ruins fault may have dextral components of slip.

NO DEXTRAL OFFSET OF JURASSIC STRATA ACROSS THE DEFIANCE MONOCLINE

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Gregory (1917), followed by Kelley (1955, 1967), drew attention to the sinuosity of the Defiance monocline, a feature that distinguishes it from other Colorado Plateau monoclines. Furthermore, Kelley (1967, p. 31) explicitly suggested "the possibility of right shift at depth [there is no dextral strike-slip fault at the surface] as a cause of the irregularity." To support this suggestion, Kelley (1967, p. 31) stated that there is a right offset (of about 13 km) at the monocline of a facies line drawn between the "Zuni-Cow Springs sandstones" and the Morrison mudstones "so that there are essentially no mudstones south of the line in the Zuni-Cow Springs stratigraphic interval" (see tectonic map, fig. 3 in pocket of New Mexico Geological Society Guidebook 18 to accompany Kelley, 1967) (Fig. 1.7). Kelley (1967, p. 31) also stated that "a similar offset may be shown for the Todilto limestone wedge edge, but the intersection with the monocline is more acute and hence less definitive."

Kelley (1967) thus reconstructed a piercing line based on the well known southward pinchout of Jurassic mudstones (principally, if not wholly, the pinchout of the Brushy Basin Member of the Morrison Formation) in west-central New Mexico and adjacent Arizona (e.g., Anderson and Lucas, 1994, fig. 6). Nevertheless, Kelley (1967) made no explicit reference to the source of his

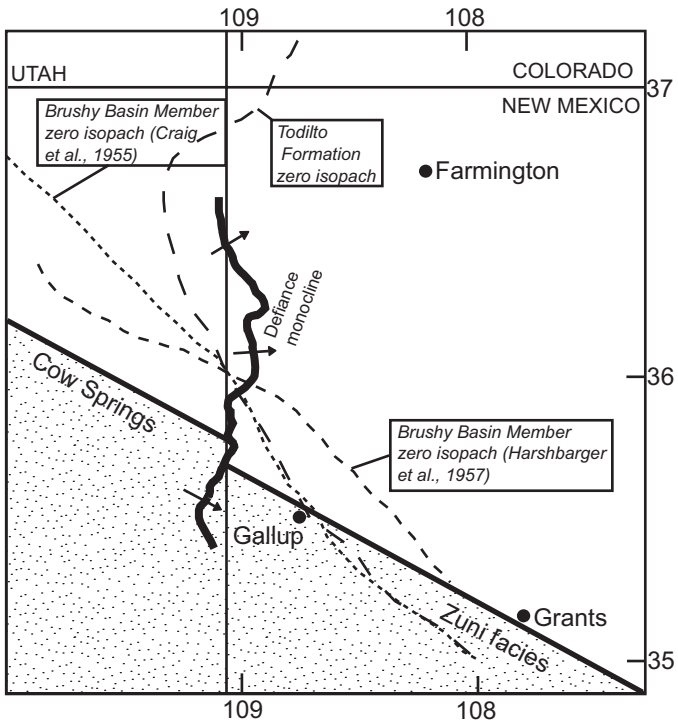

FIGURE 1.7. Map of part of northwestern New Mexico and northeastern Arizona showing dextral offset across the Defiance monocline (after Kelley, 1967) and zero isopach contours of the Todilto Formation (from Kirkland et al., 1995) and Brushy Basin Member of the Morrison Formation.

stratigraphic data, and it is impossible to find published data to support his claim. Indeed, isopach maps and lithofacies maps of the Jurassic strata in west-central New Mexico and adjacent Arizona provide no support for Kelley's (1967) envisioned dextral offset of Jurassic strata.

Thus, isopachs of the Brushy Basin Member of the Morrison Formation published by Craig et al. (1955, fig. 29) and Harshbarger et al. (1957, fig. 36) cross the Defiance monocline without deflection (also see Turner-Peterson and Fishman, 1986) (Fig. 1.7). Other isopach maps published by these workers of Jurassic units that pinch out in west-central New Mexico and adjacent Arizona also show no deflection across the Defiance monocline. Furthermore, the zero isopach of the Todilto Formation (Fig. 1.7) shows no dextral offset across the monocline, contrary to Kelley's (1967) claims.

Moreover, Kelley's (1967) map indicates that dextral offset took place on the Defiance monocline along a 13 km-long segment immediately east of Window Rock to Fort Defiance, Arizona (Fig. 1.7). Yet, the depositional pinchout of the Todilto Formation is north of Frog Rock, about 15 km or more north of Kelley's piercing line. And, the Brushy Basin Member is not present south of about Crystal, about 30 km north of the piercing line (see mapping by Allen and Balk, 1954, pl. 1 and Cooley et al., 1969, pl. 1, sheets 5-8). Thus, the lines Kelley drew that meet the Defiance monocline are not piercing lines based on the zero isopachs of the Todilto Formation or of the Brushy Basin Member of the Morrison Formation.

It is possible that Kelley (1967) based his interpretation on McKee et al. (1956, pl. 7), who depicted lithofacies and isopachs of Jurassic strata they termed "interval D." This interval encompasses post-Summerville Jurassic strata, and includes parts or all of the units that have been termed Bluff, Cow Springs, Zuni and Morrison formations. This map shows a dextral deflection of one contour line, the 500 ft isopach of interval D, at the Defiance monocline. However, the other contour lines show no similar deflection, and the deflection occurs in an interval McKee et al. (1956) map as a single sandstone lithofacies, which makes it difficult to use the deflection to construct a piercing line. Indeed, as McKee et al. (1956, pl. 9, fig. 4) interpreted it, this deflection suggests a depositional embayment near the southern edge of the Jurassic basin (also see Peterson, 1972), not a dextral fault offset.

Thus, Jurassic strata provide no evidence of the dextral offset across the Defiance monocline posited by Kelley (1967). Little attention seems to have been paid to Kelley's suggestion by subsequent workers, other than Cather (1999), who uncritically cited Kelley's idea as evidence that the Defiance monocline is a Laramide dextral oblique structure. However, Kelley's (1967) suggestion that Jurassic strata demonstrate a dextral offset across the Defiance monocline does not stand up to critical scrutiny and should be rejected.

29.9 Stop sign. **Turn left on AZ-264. 0.1**

30.0 **Turn right at stop light onto Navajo Route 12. 0.6**

30.6 Traffic light; road to right to Navajo Nation government offices. **0.1**

30.7 Upper Triassic Owl Rock Formation (Chinle Group) outcrops on right in roadcut. Tree-covered dip slope from 8:00 to 12:00 on left is the Permian DeChelly Formation. Strike valley here is developed in the Upper Triassic Chinle Group from basal Shinarump Formation through Bluewater Creek, Petrified Forest, Owl Rock, and Rock Point formations. **1.3**

32.0 Good view to right of Middle Jurassic Zuni Sandstone (= Entrada and Bluff ["Cow Springs"] sandstones). **0.5**

32.5 Crest hill; Black Rock, a dike-like volcanic neck, part of the Navajo volcanic field, at 10:00. The neck is composed of minette and minette breccia. Roden et al. (1979) dated it at 26.5 ± 0.4 My by K-Ar on phlogopite phenocrysts. The Diné people refer to it as Tsézhįįh deezlį́, "into black rock it starts to flow." This was the site of a battle between the U.S. military and the

Navajo in 1864 (Van Valkenburgh, 1941). **0.1**

32.6 Roadcuts in Owl Rock Formation. **1.0**

33.6 Crest of hill; more Owl Rock Formation roadcuts. **0.7**

34.3 Navajo Veterans Cemetery on right. **0.2**

34.5 Mile marker 28. Slick Rock Wash is the large canyon to the right. Note Canyon Bonito, the water gap through the Permian DeChelly Formation to left, with Upper Triassic Shinarump Formation capping the cliffs. **0.4**

34.9 Enter Fort Defiance (population 4061 by the 2000 census), or Tséhootsooí, "Meadow Between the Rocks." Red sandstone on right is in the Painted Desert Member of the Petrified Forest Formation of the Chinle Group. With its numerous local springs and abundant vegetation, including medicinal herbs, this was an important Diné gathering place prior to the U.S. occupation (Van Valkenburgh, 1941).

Ft. Defiance was one of the earliest military bases established by the United States after the Mexican War. It was built in 1851 as part of New Mexico military commander Colonel Edwin V. Sumner's plan to subdue the Navajo and therefore to stop their frequent raids against the inhabitants of the upper and middle Rio Grande areas. It was the first U. S. settlement in what is now Arizona (which became detached from New Mexico as a separate territory in 1863). The next 10 years witnessed an almost continuous series of armed conflict, punitive expeditions by the military from Ft. Defiance, peace conferences, and broken promises (by both sides) (see Wagoner, 1975, and Thompson, 1976, for details). To the Navajo, Ft. Defiance was an unacceptable intrusion of American forces in the midst of their homeland. To the U. S. military authorities, force seemed to be the only way to convince the Navajo to cease their raids on New Mexican communities. The mutual antagonism boiled over in April, 1860, when about 1000 (some sources say 2000) Navajo attacked the Fort and its 150 defending soldiers and nearly overran it before being driven back. Another large punitive expedition was organized, and for a time some 1500 military and other personnel were stationed at or near Ft. Defiance, but this effort also produced no concrete results. Meanwhile, citizen militias formed, and without coordinating with the military authorities, raided and pillaged Navajo villages. The coming of the Civil War in April, 1861, led immediately to the recall of most frontier troops to the East, and Ft. Defiance was abandoned. The following year, Confederate forces invaded New Mexico. The withdrawal of many troops and the preoccupation of those that remained with repelling the Confederate invasion indicated to the Navajo that their resistance had been successful, and they mounted new attacks on New Mexican settlements. It was only in 1863, when Kit Carson, operating from a new fort, Ft. Wingate, decisively defeated the Navajo in this region (see Heckert et al. minipaper on Fort Wingate in the day 2 road log). Many surrendered at Ft. Defiance, and they were forced to resettle for a time in the Bosque Redondo reservation in central New Mexico. Other groups of Navajos escaped into the canyonlands of southern Utah.

In 1868, the surviving Navajo at Bosque Redondo were allowed to return to their homeland, and the southern limit of their reservation was defined by an east-west line passing through Ft. Defiance. Settlement around the Fort continued, and it became the location of a new Navajo Indian Agency. Missionaries established a school in 1870, and a post office for the town arrived in 1875. Today, Ft. Defiance is one of the largest towns on the Navajo Nation. **Prepare to turn right**. **0.2**

35.1 **Turn right** at traffic light, continuing on Navajo Route 12. **0.1**

35.2 **Junction** with Navajo Route 54 at traffic light; **go straight. 0.6**

35.8 Navajo Tribal Utility Authority complex on right. Tower on right is in the Painted Desert Member, probably the Perea Bed (see Heckert and Lucas minipaper on the Perea Bed in the Day 2 log). **0.5**

36.3 Window Rock High School on right. **0.5**

36.8 Reenter New Mexico while remaining in the Navajo Nation. Junction with Navajo Route 7. Continue straight through traffic light. Fort Defiance Hospital on left. **0.4**

37.2 Bridge over creek. Panoramic view is from Sonsela Member of Petrified Forest Formation (light-colored sandstone on far left) through Painted Desert Member (red cuestas in valley) through Owl Rock Formation (gray/purple cuestas on right side of the valley), to the lower orange cuesta in the Upper Triassic Wingate Sandstone and Dewey Bridge Member of the Entrada Formation beneath tall, rounded cliffs of the Slick Rock Member of the Entrada (Fig. 1.8). **0.6**

37.8 Owl Rock Formation roadcuts on right. **0.9**

38.7 Road to right up White Clay Spring Wash. **0.8**

39.5 Extensively crossbedded sands on right are Upper Triassic Wingate Sandstone. **0.3**

39.8 Crest hill. Sonsela Buttes, capped by Tertiary volcanics of the Navajo volcanic field, at 12:00. **0.4**

40.2 Road on right. Excellent view on right of steeply-dipping Jurassic Slick Rock Member of Entrada Sandstone; view ahead in distance of Ch'óshgai (Chuska) Mountains. **0.4**

FIGURE 1.8. Panoramic view of Mesozoic section from mile 37.2.

40.6 Roadcuts in Jurassic Entrada Sandstone. **0.6**

41.2 Cross wash; low ridge on right exposes Dewey Bridge of Entrada Sandstone on Wingate Sandstone. **0.5**

41.7 Owl Rock Formation roadcuts. **0.3**

42.0 Road on left; Owl Rock Formation to right with section up to Slick Rock Member of Entrada Sandstone. Light-colored rock visible at 10:00 is the Buell Park diatreme, another Cenozoic Navajo volcanic center, intruding the orange-red Permian DeChelly Sandstone. The diatreme, which may be the largest known anywhere (McGetchin et al., 1977), consists of an eroded 4.5-km-diameter crater filled with serpentinized ultramafic microbreccia (SUM: Roden, 1981), a well-mixed combination of mantle wall rock and crustal rocks. Goff et al. (2002) determined that the mantle component is chemically equivalent to serpentinized harzburgite. The SUM diatreme is intruded by a large plug and dikes of felsic minette in the northwest corner (Buell Mountain), and a ring dike of mafic minette on its southeast flank. Roden et al. (1979) dated the felsic minette at 26.1±0.4 Ma and the mafic minette at 24.9±0.4 Ma, both by K-Ar on phlogopite. The traditional Diné name for Buell Park is Ni'haldzis, "Earth hollow" or "basin." **0.4**

42.4 Owl Rock Formation outcrop on right. Slope above is Upper Triassic Rock Point Formation, cliff of Wingate, steep cliff of Dewey Bridge-Slick Rock, capped by Bluff Sandstone ("Cow Springs"), Salt Wash Member of Morrison Formation and Cretaceous Dakota Sandstone. **0.7**

43.1 Cross Twin Buttes Wash. **0.7**

43.8 Owl Rock Formation roadcuts on right, up to Dakota Formation cuesta on skyline to right (Fig. 1.9). Note thin Wingate and thick Entrada locally. **0.5**

44.3 Wingate roadcuts at crest of hill. **0.4**

44.7 Mile marker 38. **1.0**

45.7 Mile marker 39 on left. Buell Park diatreme visible again at 9:30. **0.9**

FIGURE 1.9. Panoramic view of Owl Rock to Dakota section at mile 43.8.

46.6 Crest hill; roadcuts in pediment gravels. **0.2**

46.8 Cattleguard. Enter Navajo, New Mexico (population 2097 by the 2000 census). The town grew up around a large sawmill constructed by the Navajo Nation, Navajo Forest Products Industries, which processed timber cut in the Chuska Mountains and surrounding areas. It was named by an official act of the Navajo Tribal Council in 1959 (Julyan, 1996). The sawmill is no longer in operation.

Note two Navajo volcanic field intrusives on right. (Frog Rock, also known as The Beast [Fig. 1.10A]), at 1:00, is a minette-cored, brecciated neck (Ar-Ar age 24.2 ± 0.5 Ma, G. Nowell, oral commun., 2002), and Zilditloi (Hairy or Fuzzy Mountain), at 3:00, is a minette diatreme capped by a columnar trachybasalt flow; Sonsela Buttes are in distance at 12:00 (Fig. 1.10B). Near these buttes, Akers et al. (1958) designated the type section of the Sonsela Sandstone Bed (Sonsela Member of our usage) for a sandstone- and conglomerate-dominated interval in the middle of the Petrified Forest Formation of the Upper Triassic Chinle Group. Lucas et al. (1997b) redescribed the type section, and Heckert and Lucas (this volume) also discuss the regionally persistent Sonsela Member.

Red Lake is in the left foreground beyond town. The community here is built on the Owl Rock Formation. **0.7**

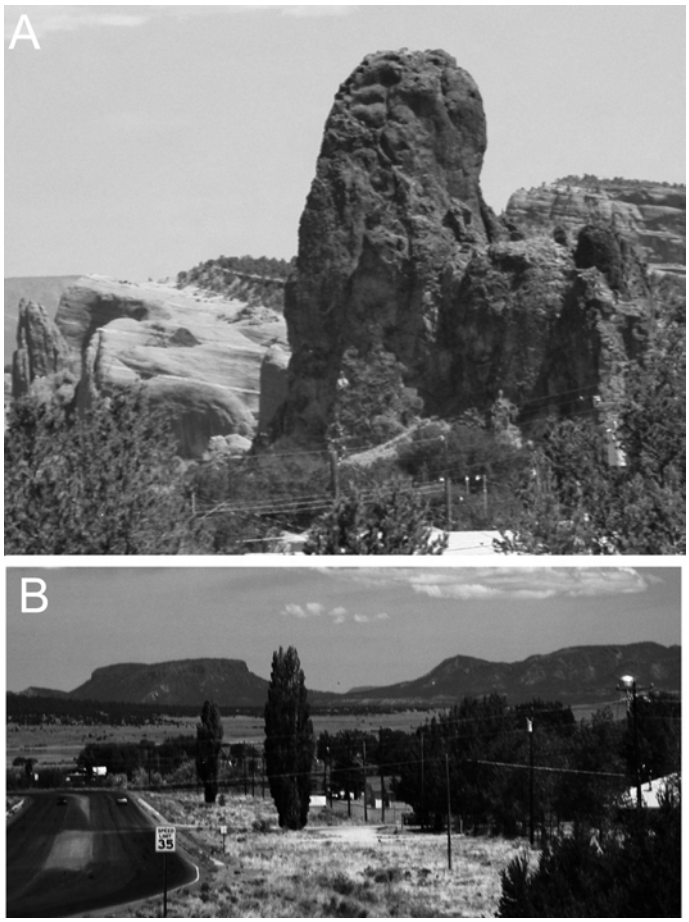

FIGURE 1.10. A, Frog Rock (The Beast). B. Sonsela Buttes seen from Navajo.

47.5 Cedar Avenue traffic light; continue straight. **0.2**

47.7 Walnut Avenue (traffic light), continue straight. Minette intrusive on left, just south of the Red Lake earthen dam, is Outlet Neck, similar in structure and composition to Frog Rock. Abandoned Navajo Forest Products Industries sawmill complex on right. Some parts of the facility have been leased to other businesses. **0.3**

48.0 Green Knobs, a SUM diatreme and a later stop, at 12:00. **0.4**

48.4 **Turn right** on unpaved road at Bowl Canyon Recreation Area sign. **Cattleguard.** Road follows the valley of Tó dildoní (Popping or Roaring Water) or Todilto Wash. The name refers to its occasional propensity to flood with runoff from the Chuska Mountains. Significant floods in the late 1880s motivated the Indian Irri-

gation Service to divert the wash into Red Lake (Van Valkenburgh, 1941). **0.1**

48.5 Owl Rock Formation on cuesta on left at irrigation dam in foreground (Fig. 1.11). **0.2**

48.7 Road curves left with contact of Dewey Bridge and Slick Rock members of Entrada Sandstone on right (white line). **0.2**

48.9 Road to right, continue straight. **0.2**

49.1 Slick Rock Member of Entrada Sandstone outcrop on left is overlain by Middle-Upper? Jurassic Summerville Formation. Cooley et al. (1969) map Todilto Formation here, but the interval they map does not include Todilto Formation lithotypes (limestone), so we refer it to the Summerville Formation. **0.4**

49.5 Cattleguard; note to north the section of Entrada overlain by thin Summerville in turn overlain by Bluff ("Cow Springs") (Fig. 1.12). **0.1**

49.6 Upper Jurassic Bluff Sandstone cliff on right over Summerville Formation. Contact is a white line. **0.5**

50.1 Note Entrada Sandstone top on right with a thin section of Summerville, with Bluff overlying. Certainly there are no Todilto Formation outcrops here. **0.4**

50.5 Curve; good view up the valley to north along anticline axis bounded by the Entrada Sandstone. Good Dewey Bridge-Slick Rock contact on left of road. **0.7**

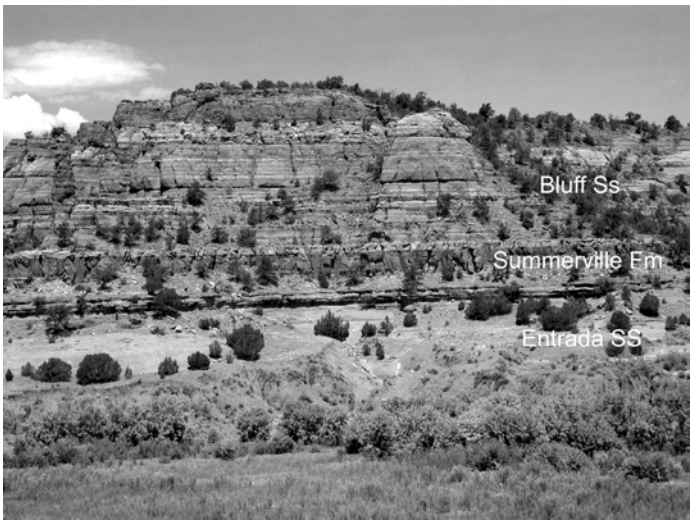

FIGURE 1.12. Entrada-Summerville-Bluff section north of the road at mile 49.5.

51.2 Crest hill. View of Venus Needle at 11:00. **0.6**

51.8 Venus Needle on left is Entrada Sandstone (Dewey Bridge Member capped by Slick Rock Member) (Fig. 1.13). Cross axis of Fuzzy Mountain syncline (Cooley et al., 1969). Enter Todilto Park here; Middle Jurassic Todilto outcrops begin on mesa to left.

Todilto Park is a broad, north-south oriented valley through the breached Todilto Park anticline (Fig. 1.14). The core of the

FIGURE 1.11. The Owl Rock Formation forms an east-dipping cuesta at an irrigation dam, mile 48.5.

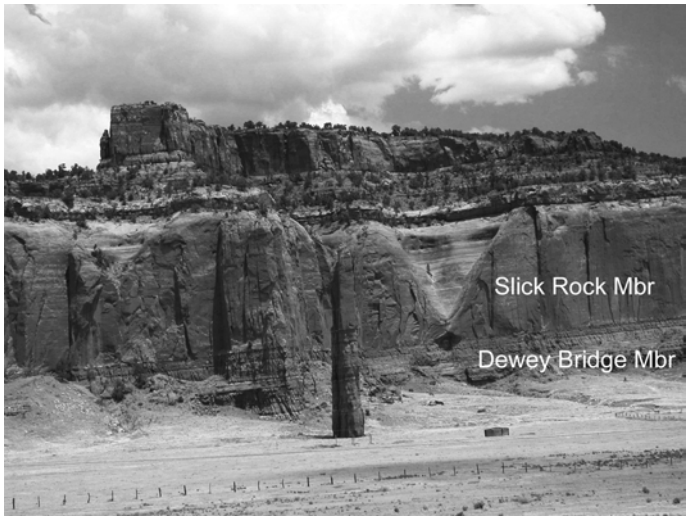

FIGURE 1.13. Venus Needle, an erosional outlier of the cliffs of Entrada Sandstone.

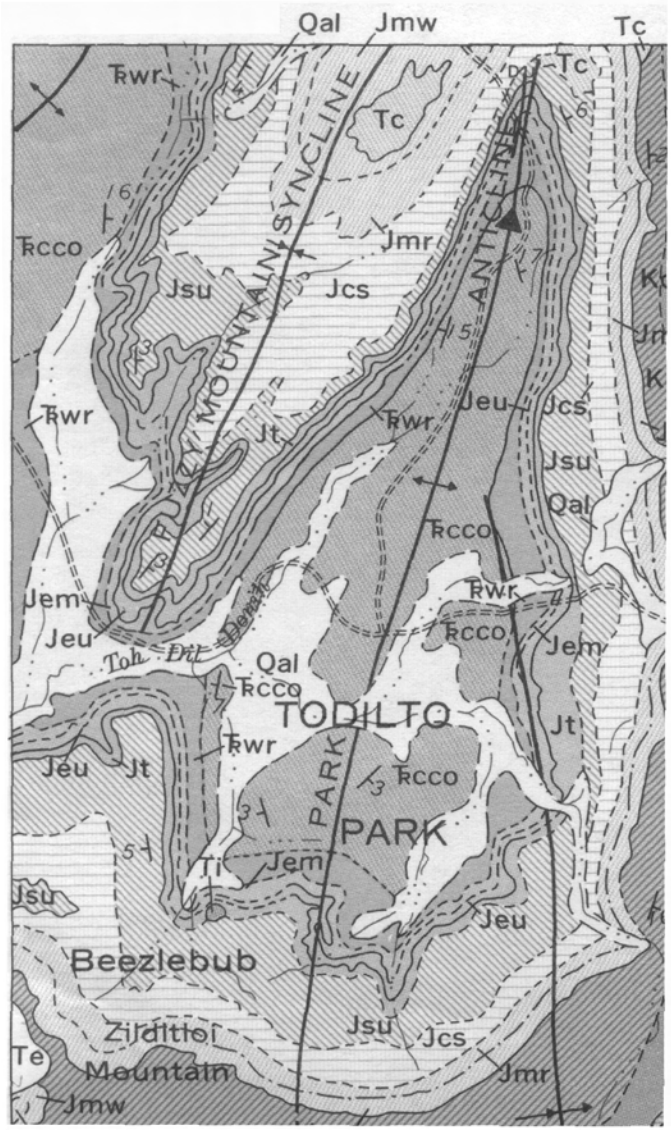

FIGURE 1.14. Geologic map of Todilto Park (from Cooley et al., 1969). Units are: Trcco = Owl Rock Formation, Trwr = Wingate Sandstone, Jem = Dewey Bridge Member of Entrada Sandstone, Jeu = Slick Rock Member of Entrada Sandstone, Jt = Todilto Formation, Jsu = Summerville Formation, Jcs = Bluff Sandstone (main body), Jmr = Recapture Member of Bluff Sandstone, Jmw = Salt Wash Member of Morrison Formation, Kd = Dakota Sandstone, Kml = Mancos Shale.

anticline is strata of the Upper Triassic Chinle Group, and its flanks are Jurassic strata capped by a thin veneer of Cretaceous rocks. **0.2**

52.0 Beelzebub, a Navajo minette neck and dike on the west flank of the Todilto Park anticline (Akers et al., 1971), is visible to the south. **0.2**

52.2 Owl Rock Formation cuesta to left. **1.2**

53.4 Houses on left, and dome crest. Humble Oil and Refining Company #1 Navajo well is approximately 1 mile north of here on crest of hill, right on the NNE-SSW axis of the Todilto Park anticline (Cooley et al., 1969; Thaden, 1990). Owl Rock strata form bluff to south. Dome is floored by Owl Rock Formation. **0.1**

53.5 Road forks. **Go left**; road to right goes to Twin Buttes. **0.3**

53.8 Roadbed is on Owl Rock Formation. Dome cores on Owl Rock Formation. **0.3**

54.1 Climb Owl Rock strata on east limb of dome; Squirrel Springs Wash to right. **0.7**

54.8 Crest hill; road on Wingate Sandstone. **0.4**

55.2 **Bear left at fork in road.** STOP 2. Oak Creek, where we can examine an excellent section of the Jurassic Todilto Formation in the creek (Fig. 1.15). The lectostratotype section of the Todilto Formation is also near here (see accompanying minipaper).

One of the most distinctive Jurassic lithostratigraphic units in the Southwest is the Todilto Formation of northern New Mexico and southwestern Colorado (Fig. 1.16). Its outcrop and subsurface distribution covers an area of about 100,000 km^2, and throughout its areal extent the Todilto rests on the Entrada Sandstone and is overlain by the Summerville Formation or eolianites of the Bluff Sandstone and its equivalents. Two members of the Todilto are recognized: (1) lower, Luciano Mesa Member, up to 13 m of mostly microlaminated, kerogenic limestone; and (2) upper, Tonque Arroyo Member, as much as 61 m of mostly massive and brecciated gypsum. Anderson and Kirkland (1960) suggested that the microlaminae of the Luciano Mesa Member formed as varved couplets, and they counted these couplets to estimate a duration of about 14,000 years for deposition of the Luciano Mesa Member. Luciano Mesa Member deposition took place in a vast, paralic salina that was followed by a smaller evaporitic basin that deposited the Tonque Arroyo Member (Lucas et al., 1985; Kirkland et al., 1995).

The Todilto Formation has remarkably diverse economic importance in New

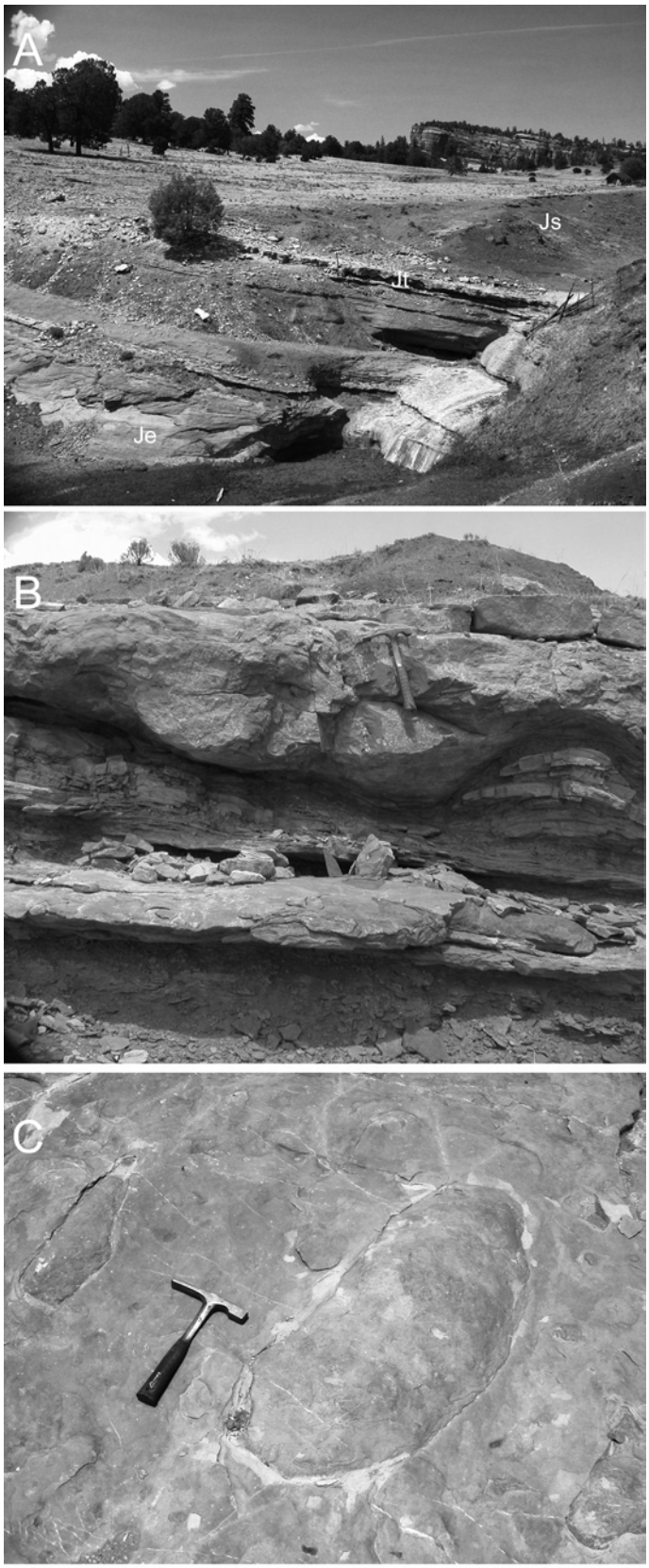

FIGURE 1.15. Outcrop of the Todilto Formation at Stop 2. A, Overview Je = Entrada, Jt = Todilto, Js = Summerville). B-C, Cross section (B) and outcrop (C) views of so-called Todilto stromatolites.

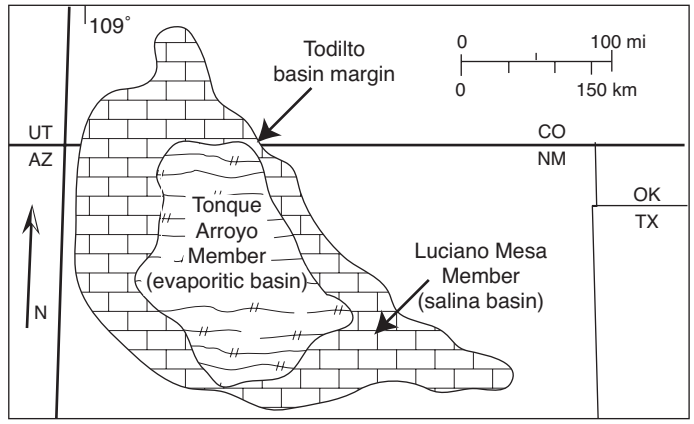

FIGURE 1.16. Distribution of the two members of the Todilto Formation in northern New Mexico and southwestern Colorado (after Lucas and Anderson, 1997).

Mexico. One product is limestone, produced from the Luciano Mesa Member. Limited quarrying has been carried out here at Todilto Park, where the limestone is of moderate quality (Barker, 1986). There are several limestone quarries in the Todilto outcrop belt between Gallup and Grants, with intermittent production; one will be visited during the second day of the Field Conference.

Gypsum has been produced from the Tonque Arroyo Member of the Todilto, which is more restricted in its occurrence than the limestone member. It has been quarried at several locations, with current production at White Mesa, near San Ysidro, north of Albuquerque. Todilto gypsum has one unusual use; at Cedar Crest, east of Albuquerque, the gypsum is sufficiently massive to be used as a raw material for sculpture, and is known to sculptors as Cedar Crest alabaster (Maynard et al., 1991).

Limestone of the Luciano Mesa Member is the host for important uranium deposits in the Todilto mostly north and west of Grants; these deposits will be discussed during the third day of the Field Conference. There was also limited uranium production from the Todilto near Laguna, with extremely minor production from locations elsewhere in the San Juan Basin. Finally,

the Todilto is believed to be the source rock for petroleum produced from the Entrada Sandstone in the San Juan Basin (Vincelette and Chittum, 1981).

At this stop, only the Luciano Mesa Member of the Todilto Formation is present. Here, it is about 3 m thick and mostly light gray limestone with a prominent, medial interval of pale red silty sandstone. The Todilto rests directly on pale reddish brown and reddish orange, very fine grained sandstone of the Entrada Sandstone. These sandstones appear to be water reworked, but examination of this outcrop fails to convince us that the onset of Todilto deposition was by a catastrophic flood, as some have suggested. Also note the hummocky limestone bed in the upper part of the Todilto (Fig. 1.15B-C)—this is the basis (an incorrect one) for the identification of Todilto stromatolites at Todilto Park, widely cited in the literature.

Also note Bluff, Recapture, Salt Wash, and Dakota section up road to northwest. The grayish color of the valley fill in this area derives from mud and coaly fragments eroded from Cretaceous rocks higher in the Chuska Mountains (Cooley et al., 1969). The ready availability of water made Tó dildo'ó (Popping or Roaring Water) a popular gathering place for Diné people in pre-US time (Van Valkenburgh, 1941) **After stop, turn around and return to highway. 1.7**

LECTOSTRATOTYPE SECTION OF THE JURASSIC TODILTO FORMATION, WESTERN NEW MEXICO

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Gregory (1917, p. 55) introduced the name Todilto Formation as follows:

> ….I propose the name Todilto Formation, from Todilto Park, where I first studied it. At this locality it caps an eastward-sloping mesa of Wingate Sandstone, and consists of 10 feet of resistant compact blue-gray limestone separated into two parts by a few inches of red sandy lumpy shale containing flattened calcareous mud pebbles. Near the top are well-worn fragments of black, white, and gray chert in quantities sufficient to form irregular bands embedded in the limestone.

Other than this, Gregory (1917) offered no description of a specific type section. Indeed, no such description exists, even though the Todilto Formation is an extensively studied unit of economic, sedimentologic and paleontologic interest (see reviews by Lucas et al., 1985; Armstrong, 1995; Kirkland et al., 1995). Here, we rectify this omission by describing a lectostratotype section of the Todilto Formation (Fig. 1.17).

This lectostratotype section is in Todilto Park, on the east-dipping flank of the Todilto Park anticline and is essentially identical in location, thickness and lithology to Gregory's (1917) original description. The section is just north of the confluence of Oak Creek and Little Water Creek; its base is at UTM zone 12, 686137E, 3981080N, NAD 27, and the top is at 686476E, 3980828N. Thaden (1990) mapped the Todilto Formation here between the Entrada Sandstone (Gregory's "Wingate") and the Summerville Formation (Thaden's "Beclabito Member of Wanakah Formation").

Strata at the lectostratotype section dip 10° to N80°E, and the Todilto Formation is about 3 m thick (Fig. 1.17). Most of the Todilto is pale yellowish brown to light brownish gray, thinly laminated sandy limestone. About 2 m above the formation base, there is a notch formed by grayish orange pink to moderate orange, silty, very fine grained calcareous sandstone. The uppermost bed of the Todilto is limestone with small (up to 4 mm diameter), angular pebbles of black, gray, brown, red and white chert. The basal contact of the Todilto on the Entrada Sandstone is a sharp surface, and the underlying 3 m of sandstone of the Entrada are ripple laminated, strata we interpret to be water reworked eolianites. The Summerville Formation rests with distinct disconformity on the Todilto. The contact is marked by a thin (0.3 m), lenticular conglomerate of Todilto limestone rip-up clasts. Above that, the Summerville section is 2-3 m of pale reddish brown and very pale orange silty sandstone that is ripple laminated, laminated or massive. Trough-crossbedded eolian sandstone of the Bluff Formation overlies the Summerville.

The lectostratotype section of the Todilto Formation is near the western and southwestern pinchout of the Todilto depositional basin, which covered an area of about 100,000 km^2 in northern New Mexico and southwestern Colorado. Todilto deposition took place during a short interval of Middle Jurassic time in a paralic salina culminated by a gypsiferous evaporitic lake (Lucas et al., 1985; Kirkland et al., 1995; Lucas and Anderson, 1996). The salina deposits are the lower, limestone member (Luciano Mesa Member of Lucas et al., 1995), and the evaporitic lake deposits are the upper, gypsum member (Tonque Arroyo Member of Lucas et al., 1995). The lectostratotype section of the Todilto is composed only of the lower, Luciano Mesa Member, which has a maximum thickness of 13.3 m, but it is only ~ 3-5 m thick here, in the type area.

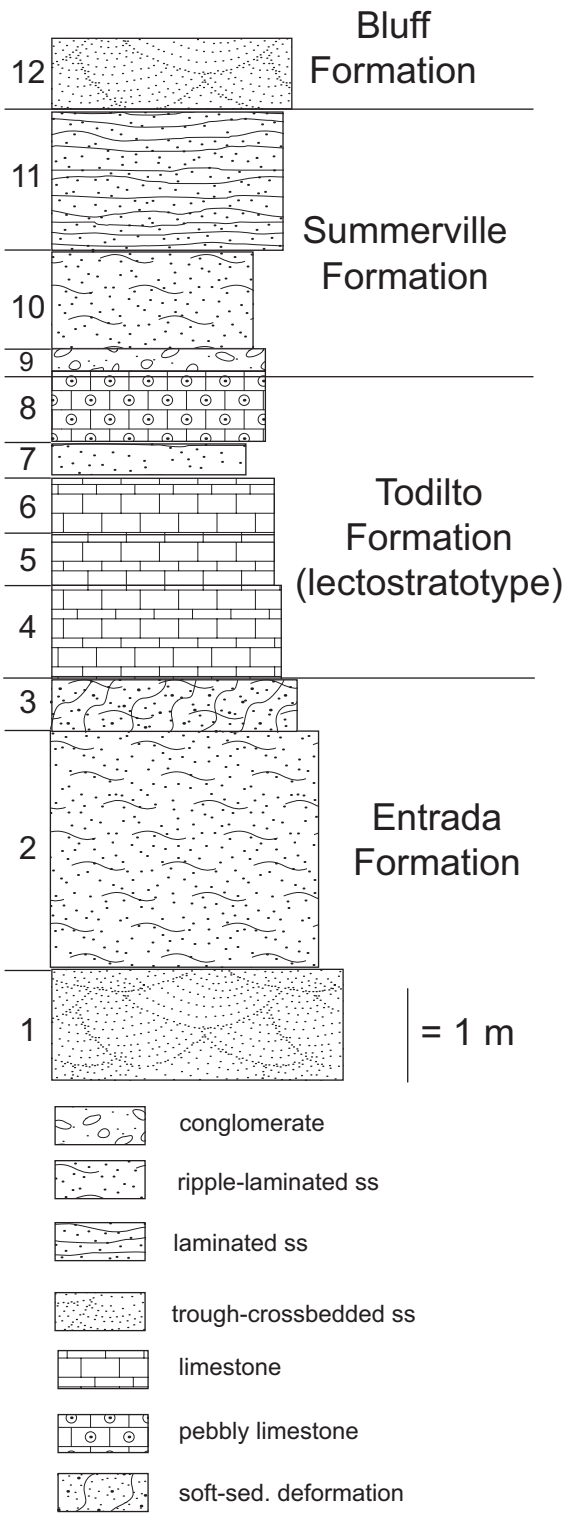

FIGURE 1.17. Lectostratotype section of the Jurassic Todilto Formation.

56.9 Road to left, continue straight. **1.5**

58.4 Road curves left; Venus Needle on right. **3.4**

61.8 View of Zilditloi and Frog Rock at 9:00; abandoned sawmill on left. **0.3**

62.1 Intersection with NR 12; **go right**. Cross Tó dildoní (Todilto) Wash. **0.2**

62.3 Owl Rock Formation outcrops on right. **0.3**

62.6 Red Lake on left, good view of Sonsela Buttes at 11:00. **0.6**

63.2 Crest hill, Green Knobs diatreme on right ahead (Fig. 1.18). **1.5**

64.7 **Stop 3. Pull off on right** to Green Knobs, discussed in the accompanying minipaper by Goff. For your own safety, **please stay off the highway**. Also, this is a culturally sensitive area, so **please do not cross the fence!** After stop, continue north on the paved highway. **0.3**

GREEN KNOBS ULTRAMAFIC DIATREME AND CARBON DIOXIDE SEQUESTRATION INVESTIGATIONS

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Steady increases in world CO_2 emissions have raised legitimate concerns about global warming and the terrestrial carbon cycle (Ramanathan, 1988; Sabine et al., 1997; Weart, 1997). These concerns have resulted in research on new technologies to capture and immobilize waste CO_2 to prevent environmental impacts to the atmosphere and climate (Lackner et al., 1998). Conversion of CO_2 into thermodynamically stable magnesite is one of many technologies under current examination because the sequestered CO_2 is comparatively immobile in geologic environments (Lackner et al., 1995). Considerable resources of ultramafic rocks (Mg-rich peridotite, serpentinite, and volcanic rocks) exist within the United States and Puerto Rico (Goff and Lackner, 1998; Goff et al., 2002). Engineering and technology advances in the chemical conversion of these minerals into mag-

FIGURE 1.18. Green Knobs diatreme.

FIGURE 1.19. Digital elevation model of Green Knobs (GK) diatreme and Buell Park (BP).

nesite could lead to the construction of coal- or gas-fired power plants in which waste CO_2 is fed to a sequestering plant adjacent to an open-pit ultramafic mine. A synopsis of CO_2 sequestering in solid form, including probable mining costs, has been outlined previously (Lackner et al., 1995).

Green Knobs diatreme (Fig. 1.19) consists of a semicircular cluster of small, rounded hills composed of sage-green tuffs (Williams, 1936; Smith and Levy, 1976; McGetchin et al., 1977). The diatreme is about 0.8 km in diameter and is enclosed on the east by east-dipping sedimentary strata of Triassic to Jurassic age. The Triassic rocks (Chinle Group) are relatively soft and have been eroded away on the west side of the diatreme. Where exposed on the east, the contact between diatreme and sandstone is vertical to near vertical, and the sandstone is locally bleached white. The diatreme is nowhere intruded or overlain by minette dikes or lavas.

The tuff at Green Knobs is massive-to-weakly bedded. Maximum xenolith size is up to 1 m in diameter, and the xenoliths contain a high percentage of granitic and metamorphic fragments. Only 11% of the xenoliths are of sedimentary origin, and about 1% are mantle peridotite (Smith and Levy, 1976). Peridotite fragments are sheared and partially serpentinized. No eclogite xenoliths were found by Smith and Levy (1976) or by us (October 1999), although O'Hara and Mercy (1966) apparently found one eclogite fragment. Thin section examination reveals that the tuff contains mostly serpentinized olivine (Fo92) and pyroxene with lesser amounts of quartz, feldspar, garnet, spinel, and rare Cr-diopside. As at Buell Park, we found no primary igneous phlogopite.

The tuff appears less serpentinized than the Buell Park tuff, a few km to the southwest. Williams (1936) incorrectly identified the tuff as "a paste of minette so soft and rotten as almost to resemble a micaceous mudstone." X-ray diffraction analyses of the matrix by Smith and Levy (1976) shows that the matrix is composed of serpentine, clay, chlorite, and talc. Our quantitative X-ray diffraction analyses on two matrix samples indicate that they contain about 45 wt % saponite, 25% lizardite, 8% talc, and 1.5% chlorite. The two samples vary considerably in their percentages. One sample also contains 11% unaltered olivine and pyroxene fragments (verified in thin section). The other sample contains 3% magnesite. The remainder of the phases is debris from granitic and metamorphic rocks.

Chemically, the Green Knobs SMD averages about 25 wt % MgO, somewhat less than its cousin at Buell Park (29 wt % MgO). Green Knobs SMD has an average MgO/SiO_2 ratio of about 0.45 (n=3) and contains systematically higher SiO_2, Al_2O_3, Na_2O, and K_2O than Buell Park material. Presumably, this results from a higher fraction of comminuted granitic and metamorphic debris. Typical peridotite fragments from Green Knobs consist of lherzolite with Ni + Cr contents similar to mantle peridotite. On MgO versus SiO_2 and $Na_2O + K_2O$ versus SiO_2 plots, the Green Knobs SMD appears to be a mixture of serpentinized mantle harzburgite and upper crustal crystalline debris (Goff et al., 2002).

The thickness of the Green Knobs diatreme is unknown. Assuming that the SMD extends to an exploitable depth of 200 m, we estimate that the deposit contains about 0.1 km^3 of relatively soft, friable rock averaging about 15 wt % Mg. This would amount to about 3 x 10^7 metric tons of Mg. The deposit contains about 1/25 the estimated Mg mass of Buell Park. It is also well known that Green Knobs has religious and spiritual significance to the Navajo Nation and would probably never be mined under any circumstances.

65.0 Wingate roadcuts. **0.3**

65.3 Mile marker 45. Note Entrada-Summerville-Bluff (no Todilto Formation) section on right. **0.2**

65.5 Road to left. The Sonsela (Sǫ'silá, "stars lying down") Buttes are now clearly visible ahead and are part of the Navajo volcanic field (Fig. 1.20). These and several other Navajo volcanoes to the east and north erupted within the Chuska Mountains, and are less deeply exhumed than outlying necks such as Ship Rock (see Semken, this volume). West Sonsela Butte is a crater formed of bedded minette tuff topped by a trachybasalt dome; the larger and higher

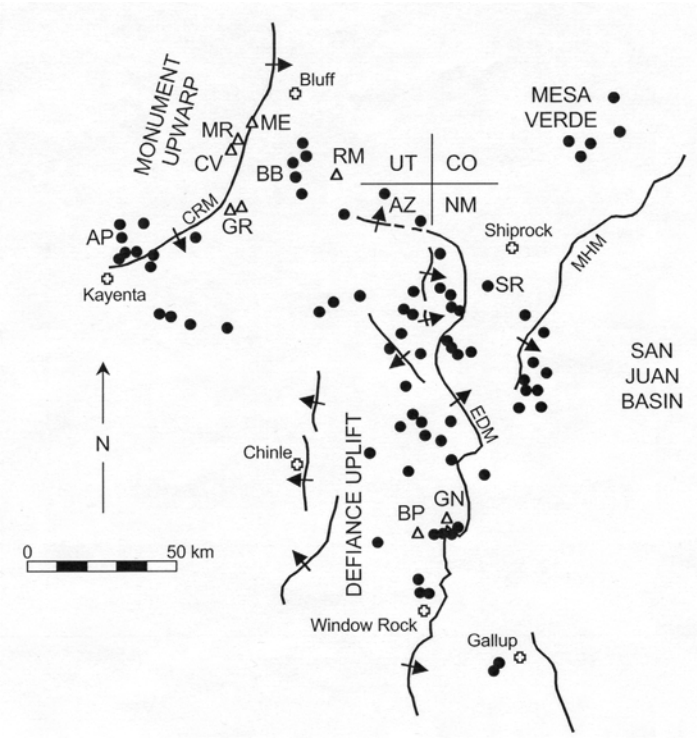

FIGURE 1.20. Map of the central Navajo volcanic field, after Smith and Levy (1976) and McGetchin et al. (1977). Dark circles indicate minettes; open triangles represent SMUs. Monoclines are indicated by heavy lines. Abbreviations: AP = Agathla Peak, AZ = Arizona, BB = Boundary Butte, BP = Buell Park, CO = Colorado, CRM = Comb Ridge monocline, CV = Cane Valley, EDM = East Defiance monocline, GN = Green Knobs, GR = Garnet Ridge, ME = Mule Ear, MHM = Mesaverde Hogback monocline, MR = Moses Rock, NM = New Mexico, RM = Red Mesa, SR = Ship Rock, UT = Utah.

East Sonsela Butte is capped by three trachybasalt flows, some of which may have issued from West Sonsela and some from a small neck in the pass between the Buttes (Appledorn and Wright, 1957).

The lavas erupted onto the Eocene-Oligocene Chuska Sandstone (white unit), now an outlier of the extensive Chuska bed that caps the entire mountain range. Immediately to the west of West Sonsela Butte, not visible from this location, a trachybasalt flow sits directly on the Upper Triassic Chinle Group, indicating that the western edge of the Chuska Mountain front was here in the mid-Cenozoic (Appledorn and Wright, 1957). A minette dike extending southwestward from West Sonsela Butte, intruding the Chuska Sandstone at one end and the Chinle Group at the other, has been K-Ar dated at 27.7±0.6 Ma using phlogopite (Laughlin et al., 1986). We will explore an even better-preserved and more complex Navajo volcanic center at the next stop in Narbona Pass. **0.6**

66.1 Owl Rock Formation roadcuts and outcrops off to left for next mile or so. **1.3**

67.4 Crest hill with good view of Sonsela Buttes and Little White Cone, a small outlier of Chuska Sandstone. We enter San Juan County, NM hereabouts, but the county line is not marked. **Prepare to turn right. 0.6**

68.0 **Turn right on paved road, NM Highway 134,** at the housing development. Entering Navajo Nation Forest. **1.2**

69.2 Crest hill; Chuska Mountains ahead are light colored Chuska Sandstone (tree-covered slopes) over low, red, Middle and Upper Jurassic sandstone cliffs. **0.2**

69.4 Mile marker 21; View of the spectacular, columnar-jointed Palisades at 10:00. This Navajo volcanic landform is an erosional remnant of a deep paleovalley fill of coalesced trachybasalt lava domes and agglomerate, overlying fluvially-reworked tuff beds on top of Chuska Sandstone (Appledorn and Wright, 1957). The lavas issued from several vents now marked by domes. The Palisades rise to an elevation of 2800 m (9200 ft), about 550 m (1800 ft) above the local valley floor. (For purposes of comparison, that is about the same height as Ship Rock.) The south wall of the Palisades, visible from here, is referred to as Falling Iron Cliffs and is a 120-m (400-ft) high, mile-long rampart of myriad columns, each approximately 2-3 m in diameter. **1.5**

70.9 "Tsa'h-be-toh" housing development on left. **0.7**

71.6 Road cuts through cuesta formed by Zuni Sandstone. **0.3**

71.9 Crystal community on left. Crystal (Tó niłts'ílí, "crystal-clear water") began in 1884 around a trading post, had a post office from 1903 to 1941 (Julyan, 1996) and maintains a community school. **0.3**

72.2 Bowl Canyon turnoff on right leads back to Todilto Park. Road cuts developed in the Zuni Sandstone (Bluff Sandstone). **0.6**

72.8 Second road to Crystal on left. **0.1**

72.9 Bluff sandstones in roadcut. **0.2**

73.1 Lazy C Rodeo Arena on right. **0.1**

73.2 Upper Jurassic Recapture Member of the Bluff on left. **0.7**

73.9 Upper Jurassic Salt Wash Member of the Morrison Formation sandstones in roadcuts. **0.7**

74.6 Approximate base of the Chuska Sandstone on right. The Chuska here overlies a poorly exposed Cretaceous section of Dakota and Mancos strata (Cooley et al., 1969). The base of the Chuska Sandstone is an angular unconformity where the flat-lying Chuska overlies eastward-dipping Mesozoic strata (Fig. 1.21). Road follows Crystal Creek. **0.9**

75.5 Good exposures of Chuska Sandstone at 2:00. **1.2**

THE AGE OF THE CHUSKA SANDSTONE

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New Mexico Museum of Natural History,
1801 Mountain Road NW, Albuquerque, NM 87104

The Chuska Sandstone (of Gregory, 1916, 1917) forms the caprock of the Chuska Mountains of the Arizona-New Mexico borderland, from north of Tohatchi, New Mexico to just north of Lukachukai, Arizona. In this region, it is as much as 580 m thick and consists of a relatively thin, basal fluvial unit (the Deza Formation of Wright, 1956) overlain by gray to white, fine- to medium-grained, trough-crossbedded arkosic sandstone of eolian origin (Fig. 1.21). The Cenozoic age of the Chuska Sandstone has never been doubted, but more precise age estimates have varied considerably. This is largely because the Chuska Sandstone has never yielded any fossils or other data by which its age can be estimated directly.

The first estimates of the age of the Chuska Sandstone assigned it to the early Eocene. Dutton (1885, p. 140) first discussed the unit, and, based on gross lithology and stratigraphic position, he correlated it to the lower Eocene "Wasatch beds" (now San Jose Formation) in the east-central San Juan Basin. Dutton (1885, pl. 16) even used the term "Wasatch sandstones" for the unit later named the Chuska Sandstone. When Gregory (1917, p. 81) named the Chuska Sandstone he advocated the same correlation, noting that "its position and lithology suggest correlation with the Wasatch Formation of north-central New Mexico."

By the 1940s and 1950s, however, several workers assigned the Chuska Sandstone a Neogene age. Pliocene age assignments

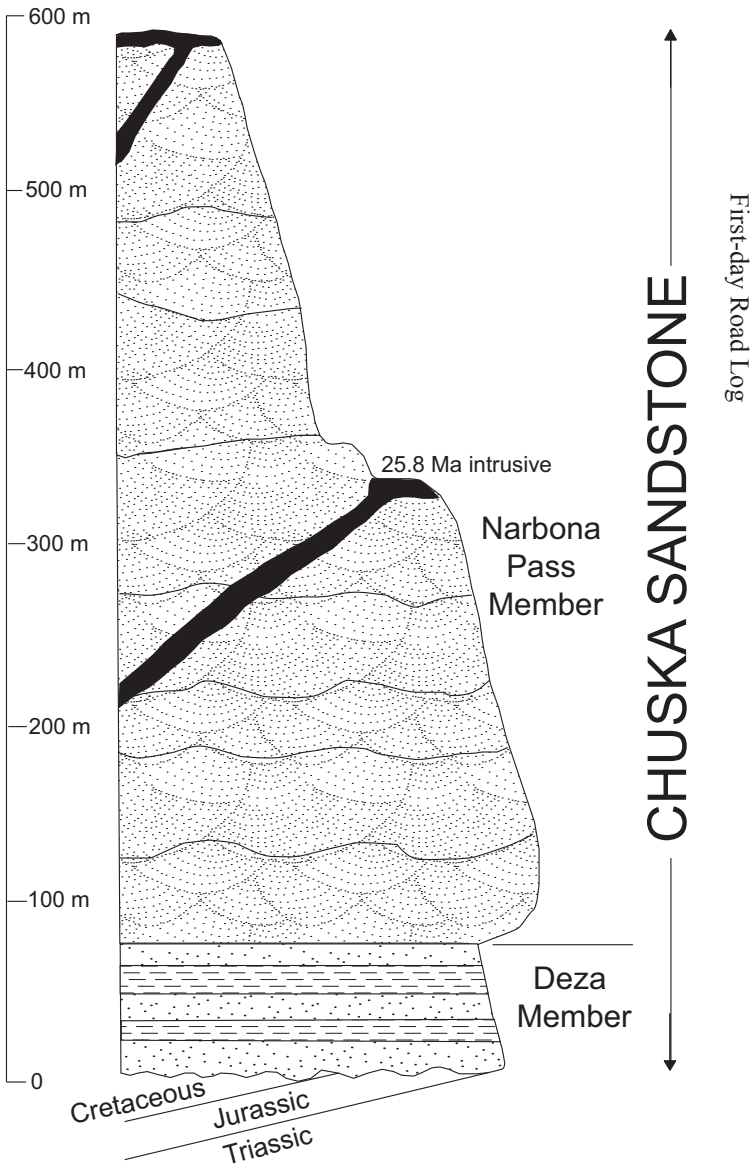

FIGURE 1.21. Generalized stratigraphy of the Chuska Sandstone (modified from Trevena, 1979).

were based primarily on correlating the Chuska to the Bidahochi Formation of northeastern Arizona (e.g., Reiche, 1941; Hack, 1942; Allen and Balk, 1954; Repenning and Irwin, 1954). Supposed lithologic similarity and correlation of the erosion surface beneath the Chuska, Bidahochi and other Neogene units in the region formed the basis for this correlation.

Wright (1956, p. 428-431) presented a detailed critique of previous correlations of the Chuska Sandstone and well explained their shortcomings. Instead, he advocated a Miocene? age for the Chuska Sandstone, based primarily on then accepted ideas about the geomorphological history of the Colorado Plateau (Gregory, 1947).

More recent data, however, also indicate that Wright's age estimate was incorrect. Several intrusives of the Navajo volcanic field cut the Chuska Sandstone (Fig. 1.21), and thereby provide a way to estimate its minimum age. The oldest age of the intru-

sives in the field is about 28 Ma (Naeser, 1971; Trevena, 1979; Laughlin et al., 1986; Semken, 2001), thus indicating that the Chuska Sandstone cannot be younger than early Oligocene (the early-late Oligocene boundary is very close to 28 Ma: Berggren et al., 1995). Indeed, Laughlin et al. (1986) report a K/Ar age of 27.7±0.6 Ma for a dike they termed "Sonsela Butte" that cuts the Chuska Sandstone. So, earlier assignments of a Neogene age to the Chuska Sandstone must be abandoned.

An older age limit for the Chuska Sandstone is less certain, but almost certainly is late Eocene. The mostly eolian Chuska Sandstone bears no resemblance to the fluvial lower Eocene San Jose Formation to the east. Trevena's (1979; Trevena and Nash, 1978) petrographic study of the Chuska Sandstone indicates that it contains abundant detrital alkali feldspar that is highly potassic. About 20% of the plagioclase Trevena analyzed is of volcanic origin, another 19% is of volcanic or plutonic origin, and the remainder appears to have been derived largely from low-grade metamorphic rocks. Crossbed dip directions of eolian sandstone beds in the Chuska Sandstone indicate a source area to the south (Wright, 1956; Trevena, 1979). The large Mogollon-Datil volcanic field to the south, which is of late Eocene-Oligocene age, is the obvious source area for the Chuska Sandstone (Smith et al., 1985). A late Eocene or early Oligocene age for the Chuska Sandstone thus seems certain.

76.7 Cross Crystal Creek. **0.4**

77.1 Good view of Narbona Pass bedded pyroclastic deposits in cliff ahead (Fig. 1.22). **0.4**

77.5 Light colored rocks on left are cross-bedded eolian Chuska Sandstone. **Slow to prepare for Stop 4. 0.9**

78.4 **Turn right into Narbona Pass day-use area. STOP 4. Lunch stop.**

This historically-significant pass through the Chuska Mountains was originally named Béésh líchíi'ii bigiizh, which literally translates as Copper Pass, but actually refers to the locally-abundant copper-colored jasper that Navajos worked into tools.

The first Americans to inspect Narbona Pass were members of a military expedition against the Navajo, led by Colonel John M. Washington and including Lieutenant James Hervey Simpson, of the Army Corps of Topographical Engineers (Fig. 1.23). The expedition ascended the pass on September 2, 1849, en route from Santa Fe to northeastern Arizona. Simpson (1850) published a journal of his geological and other observations on this expedition, including Chaco Canyon, El Morro, and Canyon de Chelly, and his route was traced again by Kues (1992). Of the pass, Simpson wrote: "On the north side is a wall of trap, capped with sandstone, running perpendicularly up from the bottom of the defile to a height of about 600 feet; and, in addition to this, there are two others, but further removed. On the left side is another height, running up from the defile, with an accessible slope, to a height of probably 300 feet. The width of the pass at this point is probably not more than 50 feet, and barely furnishes a passageway…for the artillery" (Fig. 1.23).

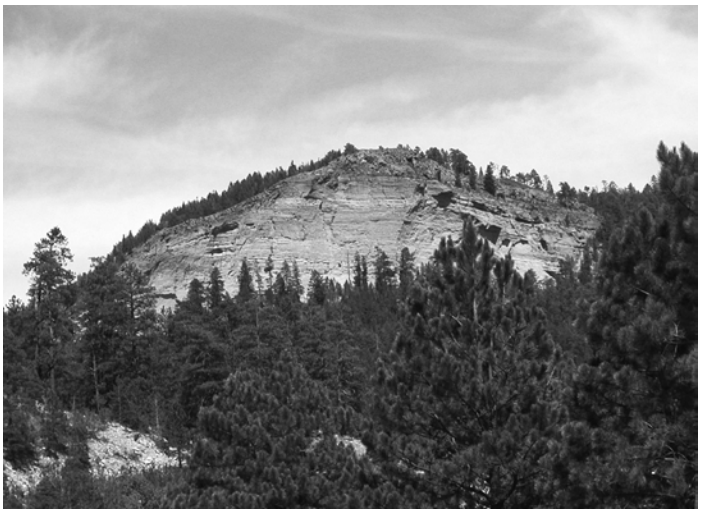

FIGURE 1.22. Bedded pyroclastic deposits at Narbona Pass, mile 77.1.

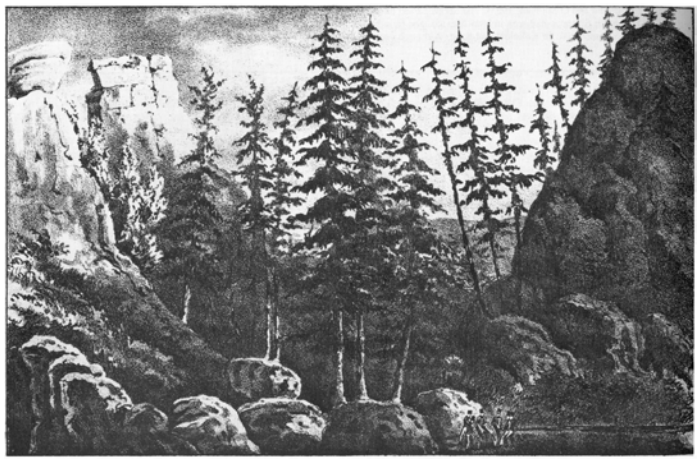

FIGURE 1.23. Simpson's (1850) drawing of Narbona (Washington) Pass.

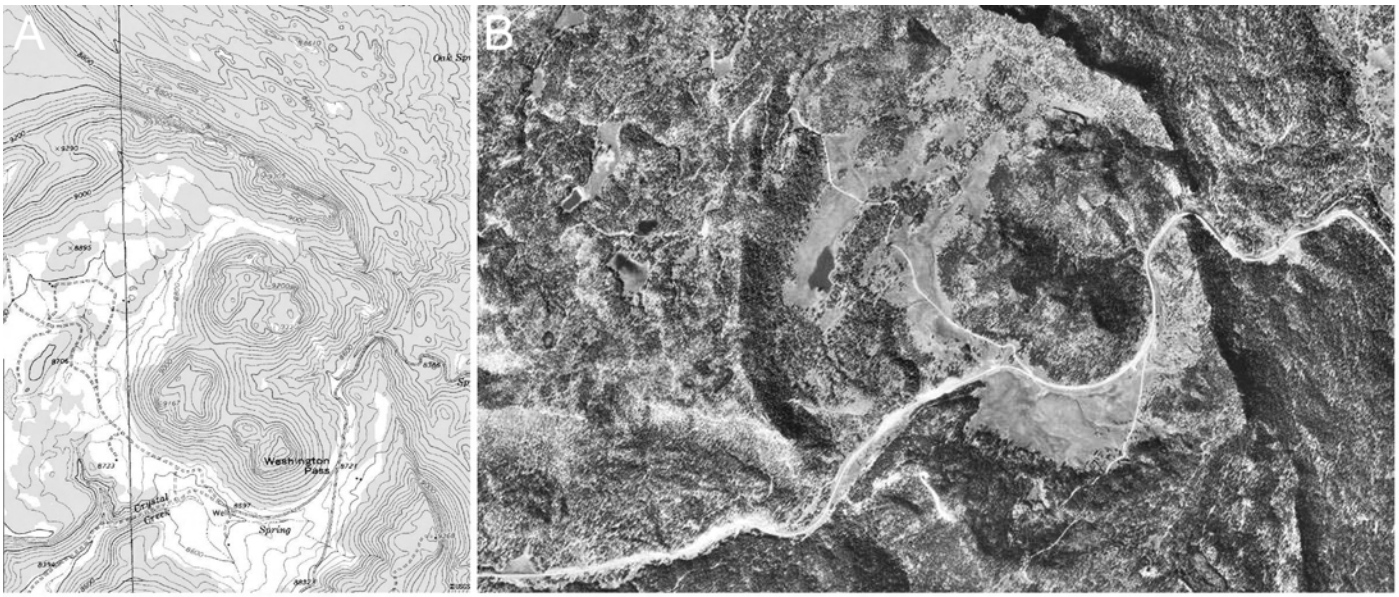

FIGURE 1.24. Topographic map (A) and aerial photograph (B) of Narbona Pass maar.

Several days earlier, Washington's party had met with a large group of Navajos about 20 km (12 mi) northeast of here, near the present-day site of the Two Grey Hills Trading Post (Acrey, 1994). The Diné were led by three respected headmen, Narbona, José Largo, and Archuleta, and were mostly seeking explanations for depredations (including destroyed crops) committed by Washington's soldiers along their route. Washington was focused on pacifying the Navajos by either diplomacy or military force (Acrey, 1994). Although the conference itself concluded well, with a promise by the Diné to hold a treaty council with Washington at Canyon de Chelly, the encounter ended in violence, as recounted by Acrey (1994). A New Mexican claimed to have spotted a stolen horse among the mounted Navajos, and as the soldiers attempted to seize it, the Diné fled. A firefight followed, in which six Navajos, including the 80-year old Narbona, were killed. The honored, elderly headman was summarily scalped by a trophy hunter. This incident ended any real possibility of peace between the Navajos and the Americans until the Treaty of 1868 after Bosque Redondo (Acrey, 1994).

Simpson named this pass Washington Pass for his commanding officer, and that name remains on all but the most recently-published maps. Following community action initiated by Navajo History students at Diné College in the early 1990s, the pass has been officially renamed to honor Narbona.

The Narbona Pass volcanic center (Appledorn and Wright, 1957; Ehrenberg, 1978; Figs. 1.24-1.25) is a partially-eroded maar crater approximately 3.2 km (2 mi) in diameter and 215 m (700 ft) deep. Minette magmas erupted through the Chuska Sandstone from 27.5 to 24.3 Ma (Ar-Ar ages; G. Nowell, pers. comm., 2002). The crater is floored by bedded pyroclastic rocks (some fluvially reworked around the rim) overlain by two mafic trachybasalt flows and a felsic trachybasalt flow, and intruded by two minette plugs and a cluster of minette dikes near the east rim. The lava flows extend beyond the crater rim on the south and west. Rocks in the rim dip steeply inward and are locally sheared and faulted, indicating crater subsidence estimated at 90 m (300 ft) (Appledorn and Wright, 1957).

Like other Navajo volcanic centers (Semken, this volume), Narbona Pass

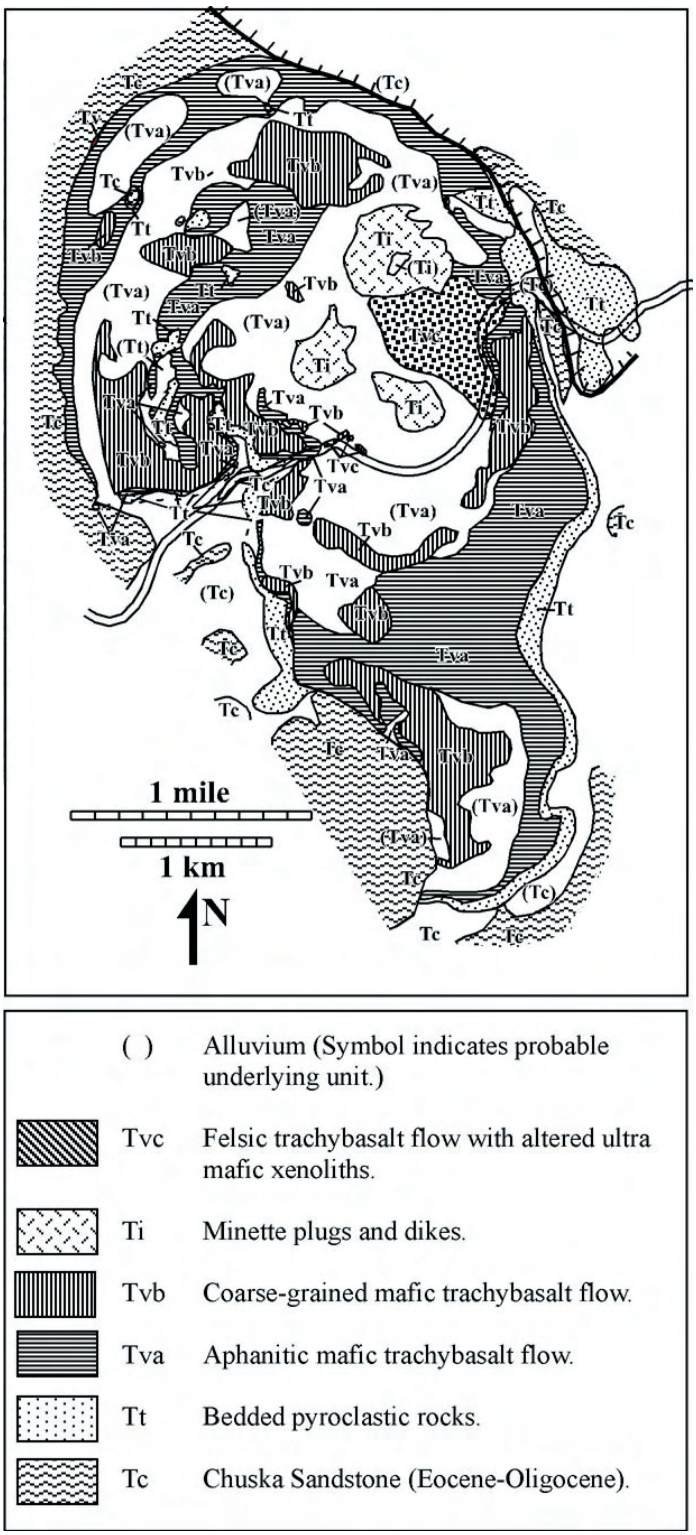

FIGURE 1.25. Geologic map of Narbona Pass maar (after Ehrenberg, 1978).

presents abundant evidence of hydrovolcanic (or phreatomagmatic) eruption. Surge deposits in the rim, silicification of the Chuska Sandstone in a zone immediately beneath the pyroclastic deposits, and abundant reddish-brown (béésh líchíi'ii) to milky-white jasper, chert, and chalcedony bear witness to the presence of hydrothermal water.

After stop, **leave the day-use area and turn right**; elevation 2536 m (8320 ft). **0.1**

78.5 Cross Crystal Creek, which cuts through the crater rim ahead. Ridge of Chuska Sandstone high on left. The highway is on Quaternary alluvium, colored dark by volcanic fragments. **0.05**

78.55 Columnar-jointed trachybasalt flow (Fig. 1.26), the middle in a sequence of three flows (flow **b** of Appledorn and Wright, 1957) sits on greenish-tan, bedded pyroclastic deposits above road level at 11:30. **0.05**

78.6 Milepost 12. Note the smoothing and rounding of the trachybasalt columns, 10-15 m high, above on the left. **0.3**

78.9 Pieces of trachybasalt **b** lava from the columnar-jointed flow can be studied in the float here. The rock is coarse-grained, with 1-3 mm phenocrysts of phlogopite, olivine, and clinopyroxene in a matrix of poikilitic sanidine crystals 0.5 to 1.0 mm in diameter (Ehrenberg, 1978). The coarse phenocrysts readily weather out of the

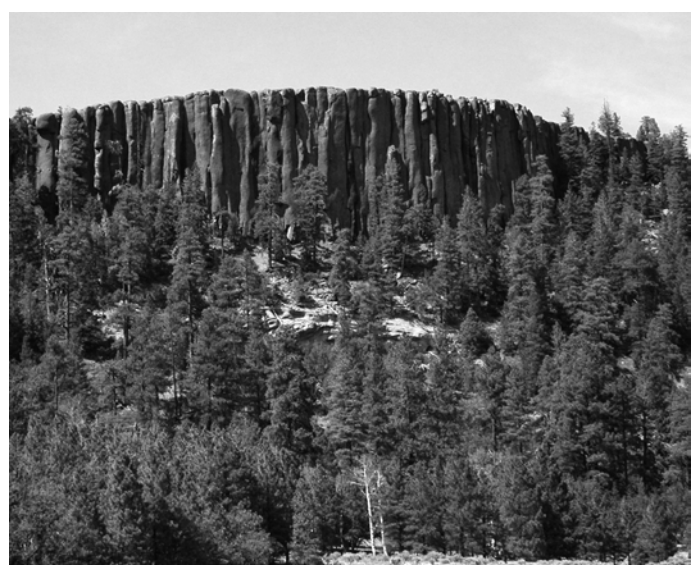

FIGURE 1.26. Columnar-jointed trachybasalt **b** flow at Narbona Pass.

rock, creating spheroidal shapes and the rounded columns of the flow above. **0.1**

79.0 "Watch for Rocks" sign; cross a branch of Crystal Creek and proceed into the western entrance of Narbona Pass maar (Fig. 1.24). **0.1**

79.1 Outcrop of Narbona Pass Member of Chuska Sandstone held up by volcanic rocks in the west rim of Narbona Pass crater. The sandstone at the base of the exposure is light tan, cross-bedded, friable, and highly permeable. This is the type section of the Narbona Pass Member of the Chuska Sandstone of Lucas and Cather (this guidebook). Upsection, it has been sheared and faulted by crater subsidence, and silicified by hydrothermal fluids associated with the phreatomagmatic eruption of the volcano. Note the prominent vertical spine about one-third of the way along the outcrop, probably a silicified fracture. **0.05**

79.15 The uppermost Chuska Sandstone here has been strongly silicified in a band approximately 5-8 m thick and roughly parallel to the overlying pyroclastic beds. The contact between the sandstone and the pyroclastics (Fig. 1.27) marks the edge of the maar crater rim.

The bedded pyroclastics are more than 100 m thick in this part of the west rim and at the east portal of the pass, but thin to less than 1 m in other parts of the crater rim, indicating that the pyroclastics were probably erupted into valleys or canyons in the Oligocene Chuska Mountains, similar to the one we are currently following (Appledorn and Wright, 1957). The pyroclastics consist of interbedded sandy tuffs and coarser tuff-breccias. Low-angle cross-beds, dunes, and scours are present in the tuff beds. Some beds bear evidence of fluvial transport back toward the center of the crater, and a thin layer of chert and limestone within the tuffs may reflect a brief fluvial or lacustrine interval between pyroclastic blasts (Ehrenberg, 1978).

The sand-sized to gravel-sized clasts in the tuff-breccia beds are an approximately equal mixture of minette or trachybasalt and igneous and metamorphic basement rocks. These pyroclastics were probably deposited by ballistic fall-back during a periodic sequence of hundreds of explosions, alternating with quiet periods of fluvial reworking (Ehrenberg, 1978). **0.05**

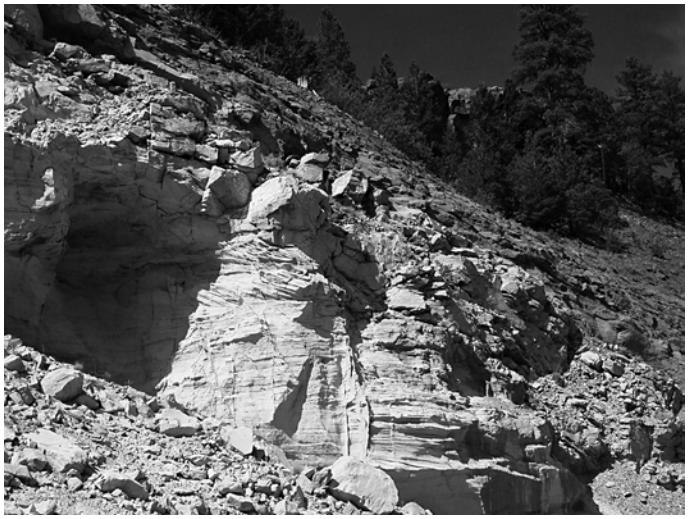

FIGURE 1.27. Narbona Pass Member of Chuska Sandstone and overlying pyroclastic beds at mile 79.15.

79.2 Note the steep inward dip of the pyroclastic deposits and the overlying trachybasalt flow (visible on high), reflecting crater subsidence. **0.05**

79.25 Weathered top of the bedded pyroclastic deposits and scoriaceous base of the oldest lava flow (flow **a** of Appledorn and Wright, 1957). This is a greenish-gray to black aphanitic trachybasalt with 0.5-1.0 mm phenocrysts of phlogopite and olivine. Flows **a** and **b** have been mapped separately (Fig. 1.25) on the basis of their differing textures, but Appledorn and Wright (1957) observed that the contact between the two flows is sharp and unweathered, and suggested that **a** and **b** may simply be different facies of a single trachybasalt flow. **0.1**

79.35 Jasper, chert, chalcedony, and botryoidal silica clasts mingled with lava in the float. Thick, cliff-forming trachybasalt **a** above the highway may mark a small lava lake. **0.03**

79.38 At the "curve right" sign, note two hills formed by minette intrusions ahead. The western hill, at 10:00, is a dome-like pile of trachybasalt blocks intruded by minette dikes. The southern hill, at 12:00, is a columnar-jointed minette plug. The minette in both intrusions is lithologically similar to flow **a** (Ehrenberg, 1978). A third intrusion is hidden behind these two, but will become visible farther along the highway. Just ahead, the trachybasalt **a** flow dips beneath the alluvium. **0.02**

79.4 NM-134 curves right and enters the eroded, alluvium-filled bowl of the Narbona Pass maar crater. The **a** and **b** flows hold up the south crater rim visible across the bowl. **0.1**

79.5 Trachybasalt and minette talus cover the slope on the left. **0.1**

79.6 Pass graded road on the left, Navajo Route 30 to Todacheene Lake (within the crater) and across the north rim to Berland Lake. **0.05**

79.65 NM-134 curves left. The highway is still on alluvium atop the **a** flow (Appledorn and Wright, 1957). Note the deep incision of the alluvium by arroyos feeding Crystal Creek on the right. **0.05**

79.7 Milepost 11. Alluvium well-exposed along the left side of the highway. **0.3**

80.0 The garage on the right houses snow equipment needed for winter access to a Federal Aviation Administration (FAA) radar station and lookout tower on the south rim (not visible from here). **0.1**

80.1 Summit of Narbona Pass, elevation 2658 m (8721 ft). Navajo Route 30 on the right leads to the FAA station and continues south along the ridge, atop trachybasalt flows that extend for more than 2 km south of the crater. **0.1**

80.2 Youngest lava flow (flow **c** of Appledorn and Wright, 1957) exposed in the roadcut on the right. This rock is a felsic trachybasalt: a light greenish-gray aphanitic flow with small phenocrysts of phlogopite and clinopyroxene, and larger weathered inclusions of spinel peridotite, websterite, and crystalline basement rocks. The larger inclusions compose about five volume percent of the rock (Ehrenberg, 1978). Most of the peridotite inclusions have weathered out, so that the flow is vuggy and seemingly vesicular from a distance, but the websterite and basement inclusions are fresher. Trace-element and Sr isotopic studies by Roden (1981) indicate that felsic minette magmas such as this originated by fractionation of mafic minette in the upper-mantle source region. The rock also includes lenses and marbling of minette similar to that of the adjacent plugs, perhaps reflecting assimilation (Ehrenberg, 1978) or incomplete magma mixing. This flow overlies the mafic trachybasalts and issued from the northeast, apparently from a vent alongside the northernmost minette plug (Ehrenberg, 1978). **0.1**

80.3 NM-134 descends toward the east portal of Narbona Pass. Felsic trachybasalt **c** is exposed in the roadcut on the left. The northernmost minette plug, 235 m (770 ft) tall and called "Sun Resting" by some Diné (Van Valkenburgh, 1941), is at 11:00. The east rim of the crater is visible at 12:00. **0.1**

80.4 Narbona Pass looms straight ahead (Fig. 1.28). We will now go back down through

FIGURE 1.28. East portal of Narbona Pass.

the Narbona Pass eruptive sequence as we leave the crater. **0.1**

80.5 NM-134 curves right and begins a steep descent. Coarse-grained trachybasalt **b** sits on weathered aphanitic trachybasalt **a** across the arroyo on the right. **0.2**

80.7 Milepost 10. Trachybasalt **a** in roadcuts on both sides. **0.1**

80.8 Sharp right curve across the arroyo and through the east portal. Pyroclastic beds in the roadcut on the right are about 35 m thick and capped by scoriaceous trachybasalt **a**. The prominent prow of pyroclastics to the left of the highway is more than 120 m thick and features interbedding of steeply cross-bedded tuffs and horizontally-bedded tuff-breccias. Ehrenberg (1978) interpreted the cohesive, well-sorted, more-resistant bedded pyroclastics here in the east rim of Narbona Pass as base-surge flow deposits. **0.1**

80.9 Lower pyroclastic beds here are covered by alluvium and talus. **0.2**

81.1 Highway cuts through reworked pyroclastic beds. **0.2**

81.3 Trachybasalt rubble on the right and in the roadcut ahead, on top of deeply-weathered and possibly reworked pyroclastics. NM-134 snakes down onto the scarp of a vast Quaternary landslide (Fig. 1.2). **0.1**

81.4 Several good and well-used springs are found in the Chuska Sandstone immediately north of here. View ahead into San Juan Basin. The Chaco River drainage extends toward us from Chaco Canyon in the southeast, before curving northward toward the San Juan River at Shiprock. **0.6**

82.0 Sharp curve left; begin descent down enormous Quaternary landslide deposit composed mostly of Chuska Sandstone. Landslide deposits extend along the Chuska Mountain front more than 40 km north and 24 km south of here, and in this vicinity, more than 12 km out into the basin (Fig. 1.2). **1.5**

83.5 View of two well-exhumed Navajo volcanic field minette diatremes at 9:00. Bennett Peak (Tsé naajiin, "it is black rock downward") is on the left, and the smaller Ford Butte is on the right; both are composed of tuff-breccia and intruded by small minette dikes. They are about 20 mi from here. G. Nowell (pers. comm., 2002) obtained an Ar-Ar age of 24.5 Ma for Bennett Peak. **1.5**

85.0 Leaving Navajo Nation Forest. **0.3**

85.3 View to north of Ship Rock (Tsé bit'a'í, "rock with wings"), 40 mi distant, largest and best-known exhumed diatreme in the Navajo volcanic field (see Semken, this guidebook). Bennett Peak and Ford Butte are again visible in the middle distance. The diatremes on the west flank of the San Juan Basin are aligned along Laramide monoclines, roughly parallel to the mountain front. **0.1**

85.4 Roadcuts to north are of landslide debris, primarily Chuska Sandstone. **0.5**

85.9 Upper Cretaceous Tohatchi Formation outcrops on both sides of road. (Tó hách'í, "where water is customarily scratched out," referring to the high water table at Tohatchi Wash to the south, where shallow, hand-dug holes fill with water; Young and Morgan, 1987). **1.0**

86.9 Tohatchi Formation outcrops on both sides of road again. The Upper Cretaceous Tohatchi Formation is at least 160 m of nonmarine siliciclastic strata exposed in western New Mexico along the SE and E flank of the Chuska Mountains. The Tohatchi Formation conformably overlies the Menefee Formation, is unconformably overlain by the Paleogene Deza Member of the Chuska Sandstone and consists of a lower, sandstone-dominated member and an upper, mudstone-dominated member.

Dinosaur fossils found throughout the Tohatchi Formation indicate a Late Cretaceous age, and extensive palynomorph assemblages refine this age assignment to early Campanian (see Lucas et al., this guidebook). The presence in the Tohatchi Formation of

such pollen species as *Accuratipollis lactiflumis*, *Brevimonosulcites corrugatus*, *Callialasporites dampieri*, *Microfoveolatosporis pseudoreticulatus*, *Periretisynolporites chinookensis*, and *Rugubivesiculites reductus* suggest links to upper Santonian assemblages of the Milk River and lower Eagle formations of Alberta-Montana. However, other Tohatchi species such as *Aquilapollenites attenuatus*, *A. trialatus*, *A. turbidus*, *Pulcheripollenites krempii* and *Tricolpites reticulatus* are more closely related to assemblages from the Pakowki Formation and Judith River Group of Alberta and the Claggett and Judith River formations of Montana. The palynomorph assemblages in the Tohatchi Formation thus fall within the *Aquilapollenites senonicus* Interval Zone of early Campanian age. Therefore, the Tohatchi Formation is not, as has been thought for 50 years, a correlative of part of the upper Campanian Pictured Cliffs-Fruitland-Kirtland formations succession to the east. Instead, the Tohatchi Formation is the uppermost part of the Mesaverde Group in western New Mexico, younger than the underlying Allison Member of the Menfee Formation locally, and older than the late Campanian turnaround of the Cliff House-Pictured Cliffs shoreline to the east (Fig. 1.29). **2.3**

89.2 Leave landslide deposits and emerge on coal-bearing Menefee Formation outcrops on left and right. **1.0**

90.2 Enter greater Sheep Springs (Tooh haltsooí, "spring in the meadow") (population 237 by the 2000 census). In 1892, a Lieutenant W. C. Brown visited the springs and reported them a well-known camping place. Charles Newcomb established a trading post in 1912 about 1.5 mi east of the springs that became the nucleus for the present community (Julyan, 1996). **0.5**

90.7 Slow down for Intersection with US-666; **turn right.** Highway is developed on Menefee Formation. View of minette diatremes; Bennett Peak at 9:00, Ford Butte at 9:30. **2.1**

92.8 Crest hill in Menefee Formation outcrops. **2.2**

95.0 Mile marker 43. Note continuation of enormous Quaternary landslide to right below the crest of the Chuska Mountains. **1.1**

96.1 Enter Naschitti (Nahashch'idí, badger; literally "the one who digs about") (population 360 by the 2000 census). This settlement began in 1886, when Tom Bryan established a trading post, one of the first on the eastern side of the Chuska Mountains (Julyan, 1996). **0.5**

96.6 Naschitti Wash. **1.1**

97.7 Cross tributary wash. **1.0**

98.7 Crest hill; hills on right are developed in the Menefee Formation. **1.3**

100.0 Mile marker 38. White Rock road to left. **1.1**

101.1 McKinley County line. Landslide remains visible. **0.4**

101.5 Cross Salt Springs Wash. **1.4**

102.9 Menefee Formation outcrops along road. View of physiographic continental divide at 10:00. **2.4**

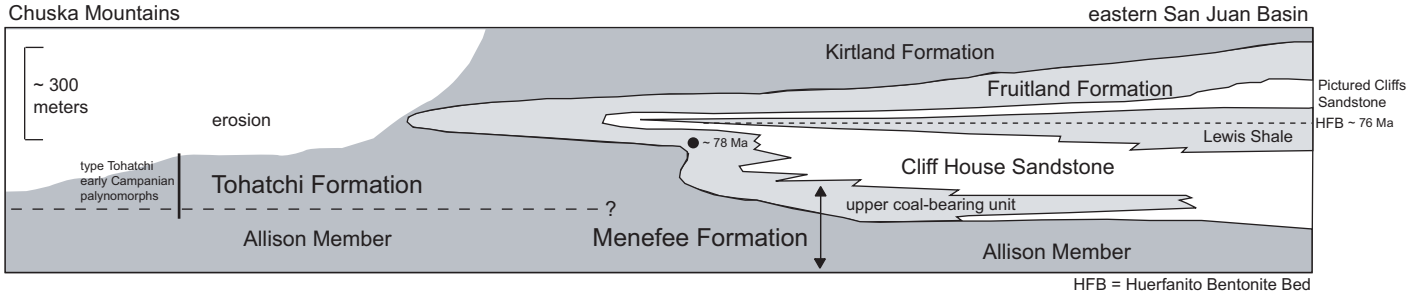

FIGURE 1.29. Restored cross section (based in part on O'Sullivan et al., 1972, fig. 8) showing correlation of Tohatchi Formation in Chuska Mountains to units in the eastern San Juan Basin. Ar/Ar age of upper Menefee Formation from Amarante et al. (2002) and of Huerfanito Bentonite Bed from Fassett et

105.3 Crest hill; roadcuts in Menefee sandstones. **0.4**

105.7 Buffalo Springs highway department yard on right. **0.6**

106.3 Landslide deposits on right particularly close to the highway. **1.9**

108.2 Road curves hard right around toe of landslide deposits. El Paso Natural Gas, Gallup Turbine station on left. **1.8**

110.0 Crest hill with excellent view of outcrops of Menefee and Tohatchi formations. **1.4**

111.4 Towers to right at Tohatchi Lookout on Deza Bluffs are on the Chuska Sandstone (tree covered slopes), which, in turn, overlies the Tohatchi Formation (barren slopes). **1.9**

113.3 Crest hill. Town of Tohatchi, near where water was customarily scratched out, ahead; Chuska Peak at 2:00. Good Menefee outcrops on left. Tohatchi (population 1037 by the 2000 census) formed when George Washington Sampson opened a trading post here in 1890. A Navajo day school was established in 1895, followed by a U. S. Indian Services hospital, and a post office arrived in 1898. Christian missionaries were active in the area, and succeeded in putting together a partial Navajo-English dictionary (WPA, 1940; Julyan, 1996). **0.5**

113.8 Ch'ooshgai Community School at 10:00, on the shores of the manmade Chuska Lake. **0.6**

114.4 Tohatchi High School on right. **0.3**

114.7 Historical marker for Navajo Indian Reservation on right. **0.4**

115.1 Cross Red Willow Wash. **0.5**

115.6 Cross branch of Red Willow Wash. **0.4**

116.0 Note old terraces on left: Tohatchi Flats terraces related to Chaco drainage. **2.3**

118.3 Crest hill; cross through Menefee roadcuts; note dune sands ahead on right. **0.9**

119.2 Mile marker 19; note backside of hogback at 9:00-10:30. **1.1**

120.3 Road to Nakaibito (Mexican Springs). **0.7**

121.0 Cross Catron Wash. **1.6**

122.6 Begin divided highway. **0.4**

123.0 Pass Navajo Route 9 to Crownpoint on left. **1.8**

124.8 Enter Twin Lakes (Bahast'ah, "inside corner"); Navajo Route 19 on left. Julyan (1996) commented that the origin of the name Twin Lakes for this small community is unknown, but Van Valkenburgh (1941) stated that the name referred to two small, ephemeral lakes once present nearby. **0.2**

125.0 Twin Lakes Chapter House on left. **2.7**

127.7 Enter area of extensive Menefee Formation outcrops. **0.5**

128.2 Mile marker 10. We leave the Navajo Nation as we pass by the ridge of Menefee Formation. **0.4**

128.6 Village of Tohlakai. This small settlement developed around the Tohlakai trading post. The Navajo name, Tó łigaaí háálíní, means "where white water flows up," a reference to whitish kaolin-laden water seeping from springs near the trading post (Julyan, 1996). **1.1**

129.7 Crest hill in Menefee outcrops. **0.1**

129.8 Cross under powerlines. **0.8**

130.6 Get into left lane. **0.1**

130.7 Junction with NM-264; **go straight on US-666. 0.3**

131.0 Hogback at 10:00. **0.3**

131.3 Merge left. **0.9**

132.2 Cross Many Arrow Wash, a tributary of Burned Death Wash. **1.2**

133.4 Crest hill; Menefee outcrops along roads. **1.2**

134.6 Good view of hogback at 9:00-10:00. **0.7**

135.3 Gamerco on right. **1.0**

136.3 **Traffic light. Turn left on Ninth Street and continue to south**. Gibson Canyon, site of one of the earliest coal mines in the area, the Gallup-Gibson mine (Fig. 1.30), on left. The mine began operating in 1882 and continued until 1904 (Nickelson, 1988), first operated by Crescent Coal Company and later by American Fuel Company. The town of Gibson developed around the mine and was named after the mine superintendent, John Gibson. The town had a company store, hospital, church,

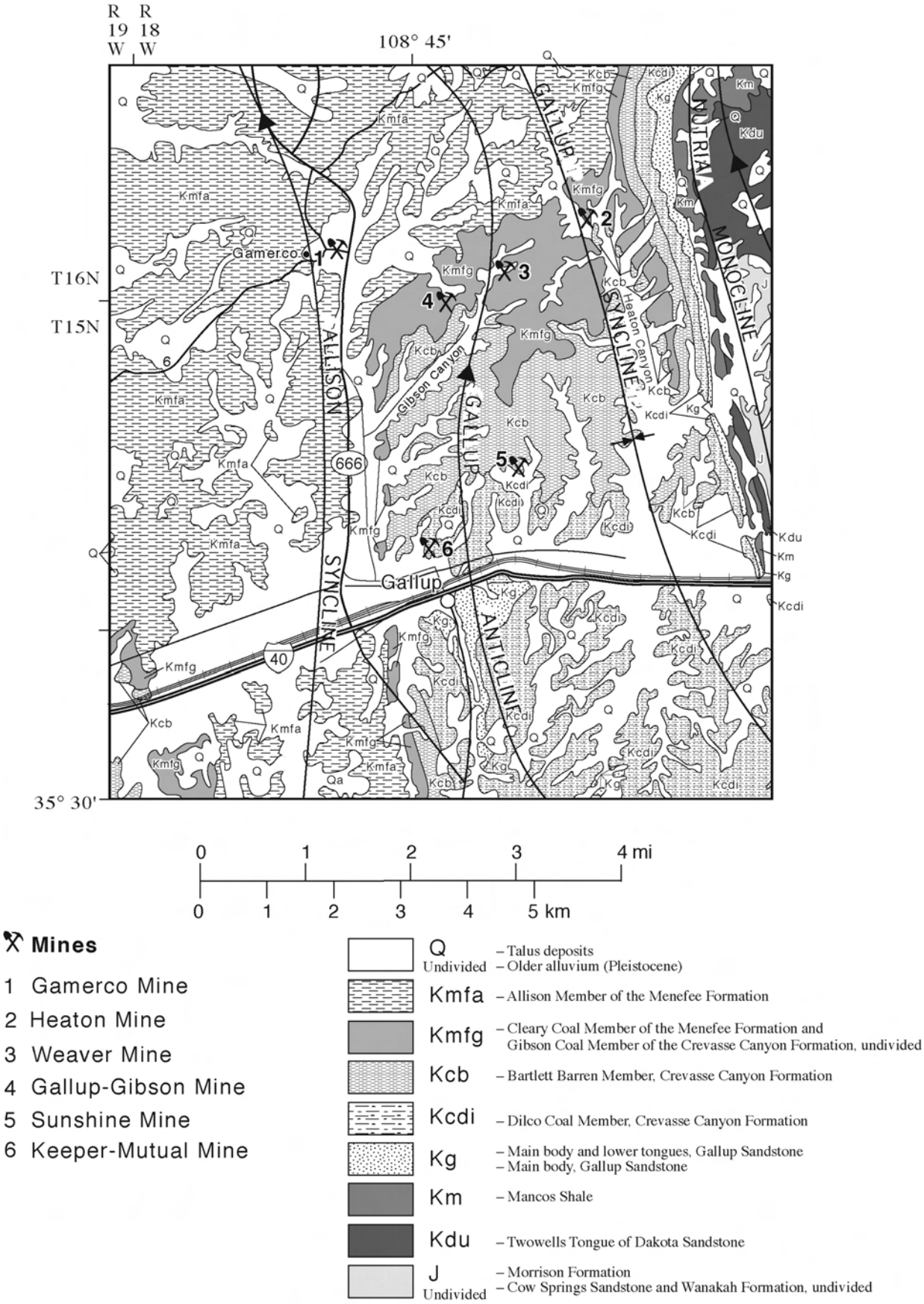

FIGURE 1.30. Geologic map and location of principal coal mines in Gallup area.

school and post office. Eventually the mine also became the Gibson mine. Production in 1885 was 52,269 tons; from 1893 until 1900 annual production ranged from 104,310 to 180,000 tons (Nickelson, 1988). Coal from the Gibson mine was shipped by rail throughout the southwest. The Nos. 3, 31/2, and 5 seams in the Cleary-Gibson coal member were mined, each averaging 5-6 ft thick. In 1902, fire was discovered in old workings in the No. 4 bed. Attempts were made to control the fire but by 1904, the mine had to be closed permanently. Stone barriers were built to protect the remaining coal, and the mine entries were sealed. The town of Gibson continued to be occupied until the late 1940s (Nickelson, 1988). **0.7**

137.0 Gallup flea market on left. **0.4**

137.4 Gallup city limit. **Get in left lane. 0.9**

138.3 Intersection with Maloney Avenue. **Turn left and get into left lane** on eastbound Maloney. Just north of Maloney Avenue are outcrops of the Dilco Coal Member of the Crevasse Canyon Formation (Figs. 1.30-1.31). Several coal beds are exposed in this area, where over 26 mines extracted coal from the Dilco in the late 1880s to early 1900s. The Dilco Coal Member is at the base of the Crevasse Canyon Formation and represents a regressive sequence of shales, siltstones, sandstones, and coal overlying the predominantly marine Gallup Sandstone (Fig. 1.31). The Dilco contains at least five economic coal beds within a 200-ft thick sequence. Several of these coals were named for the operations where they were mined northeast of Gallup. The lowest of these coals is the

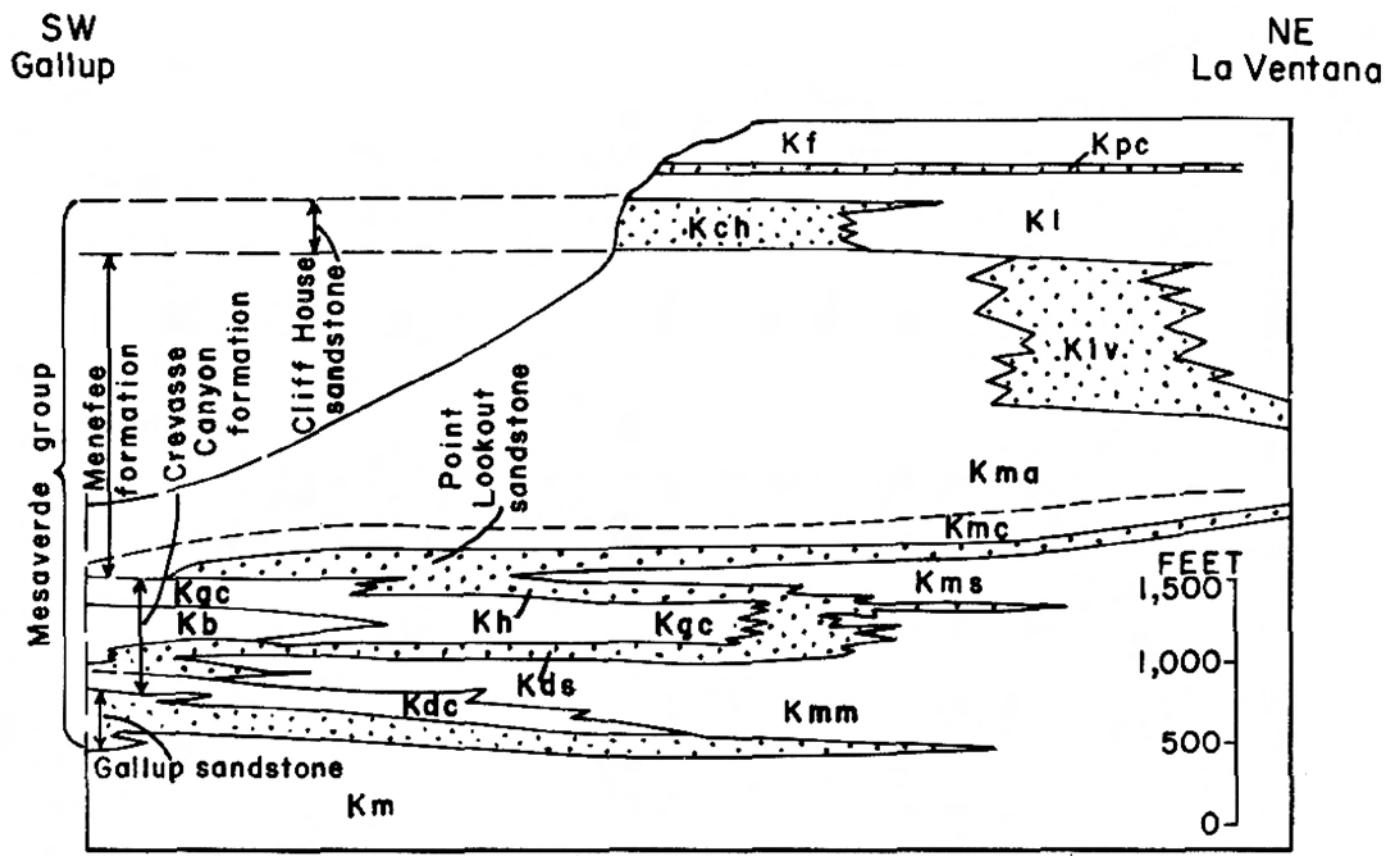

FIGURE 1.31. Cross section of intertongued marine, shoreline and coal-bearing Cretaceous strata in the Gallup area and across the San Juan Basin (from Baltz et al., 1967). Stratigraphic units are: Kf = Frutiland Formation and younger strata, Kpc = Pictured Cliffs Sandstone, Kl = Lewis Shale, Kch = Cliff House Sandstone with La Ventana Tongue (Klv), Kma and Kmc = Allison Member and Cleary Coal Member of Menefee Formation, Kh = Hosta Tongue of Point Lookout Sandstone, Kg, Kb, Kds and Kdc = Gibson Coal Member, Bartlett Barren Member, Dalton Sandstone Member and Dilco Coal Member of the Crevasse Canyon Formation, Km = Mancos Shale with Satan (Kms) and Mulatto (Kmm) tongues.

Otero that averages 4 ft thick; above the Otero is the Black Diamond, averaging 3-5 ft thick, and the Thatcher bed averages 4 ft (Sears, 1925). Many of the Dilco coals thin or split, but the Black Diamond coal is distinctive because of its lateral continuity and persistent white tonstein band in the upper part of the bed. Most of the older mines that extracted coal from the Dilco Coal Member were small operations, but the Sunshine (1889-1899), which extracted coal from the Thatcher and Black Diamond beds, produced over 350,000 tons. The Keeper-Mutual (1918-1938) mines produced over 670,000 tons from the Black Diamond bed (Nickelson, 1988) and supplied coal to the Mutual Coal, Light and Power Company. **0.1**

138.4 Railroad crossing. **0.4**

138.8 Light at Third Street; **go straight**. Maloney Avenue becomes Montoya Boulevard. **0.1**

138.9 Light at Second Street; **go straight**. **0.8**

139.7 Road to left into Miyamura State Park complex. **0.1**

139.8 **Turn left (carefully!)** on Hasler Valley Road before hard curve to right and guard rails. **Be alert when making this turn.** The broken arrow on the left is a good landmark. **0.4**

140.2 Outcrops on left of Bartlett Barren Member of Crevasse Canyon Formation. **0.2**

140.4 National Guard Armory on right. **0.1**

140.5 Gallup Sand and Gravel company pit on left, mining from Pleistocene fill of the Rio Puerco valley. **0.2**

140.7 Old coal mine on left. **0.3**

141.0 "Northwest New Mexico Regional Juvenile Services Center" (a jail) on left. **0.8**

141.8 **Turn left** on unpaved road to left. **STOP 5** to look at hogback ahead. Note bend in monocline to north developed in Cretaceous strata (Gallup Sandstone and Crevasse Canyon Formation) (Fig. 1.32).

To the north, in Heaton Canyon and farther west, in Gibson Canyon outcrops of coal in the Cleary-Gibson of the Menefee and Crevasse Canyon formations (undivided) were extensively mined from the 1880s into the mid-1900s. Several of the largest underground mines in the Gallup area were located in these canyons and west at the town of Gamerco (Fig. 1.30). The Gallup-Gibson mine in Gibson Canyon operated from 1888 to 1904. The Heaton mine at the head of Heaton Canyon operated from 1904 to 1922. Southwest of the Heaton, the Weaver mine began operations in 1899 and closed in 1924. The Gamerco (Navajo No. 5) mine was one of the last large underground mines in the Gallup area, operating from 1921 to 1951. These mines extracted coal from seams within the Cleary-Gibson coal member.

FIGURE 1.32. The monocline at Stop 5 is steeply dipping strata of the Gallup Sandstone and Crevasse Canyon Formation.

The Gallup field is southwest of the shoreline turnaround of the marine Point Lookout Sandstone, which divides the coastal deposits of the Crevasse Canyon and Menefee formations in most of the San Juan Basin (Fig. 1.31). In the Gallup field, the transgressive paludal sequence of the Gibson Coal Member is directly overlain by the regressive sequence of the Cleary Coal Member, creating a thick (200-250 ft) coal-bearing unit containing as many as 16 coal beds. Several of these beds are economic and have significant lateral continuity. Sears (1925) summarized the coal beds named by the early miners. Both the Weaver and Heaton mines extracted coal from the Nos. 3 and 31/2 beds, ranging in thickness from 3 to 5 ft. The Gibson mine

removed coal from 5-6 ft thick beds in the Nos. 3, 31/2, and 5 seams. The Gamerco mine also extracted coal from the Nos. 3 and 5 beds that averaged 5 ft thick at this operation. The No. 5 is the lowest economic coal bed in the Cleary-Gibson sequence and thins to the northeast. Approximately 80 ft above the No. 5 at the Gamerco mine is the No. 3 bed, the most extensive coal in the sequence. The earlier mines started at the coal outcrop and went underground. At the surface, the Gamerco mine is in the overlying Allison Member of the Menefee Formation, and this mine was one of the first in the area to be delineated from drill holes. The Gallup American Coal Company or a predecessor owned the Weaver, Heaton, and Gamerco mines. Total production was 3.65 million tons from the Weaver, 1.47 million tons from the Heaton, and 3.56 million tons from the Gamerco (Nickelson, 1988).

A few hundred meters east of here is the principal reference (type) section of the Gallup Sandstone (Figs. 1.33-1.34). Here, the Gallup is 332 ft thick and consists of offshore marine sandstones and marine shale in the lower part and grades up to shoreface/coastal shoreline sandstone in the middle part capped by nonmarine carbonaceous shale and fluvial sandstone in the upper part (Molenaar, 1983). The upper fluvial unit is the Torrivio Member. The Gallup was deposited during a regional marine regression during the late Turonian-early Coniacian.

The town of Gallup (population 20,209 by the 2000 census) owes its origin to a fortuitous location on the route of a major east-west railroad and close proximity to abundant supplies of coal. Sheep and cattle ranchers occupied the Gallup area, when, in 1879, two mining engineers were sent to evaluate coal supplies for the anticipated route of the Atlantic and Pacific Railroad. At this time, a small settlement consisting of a general store, the Blue Goose Saloon, and a stage station

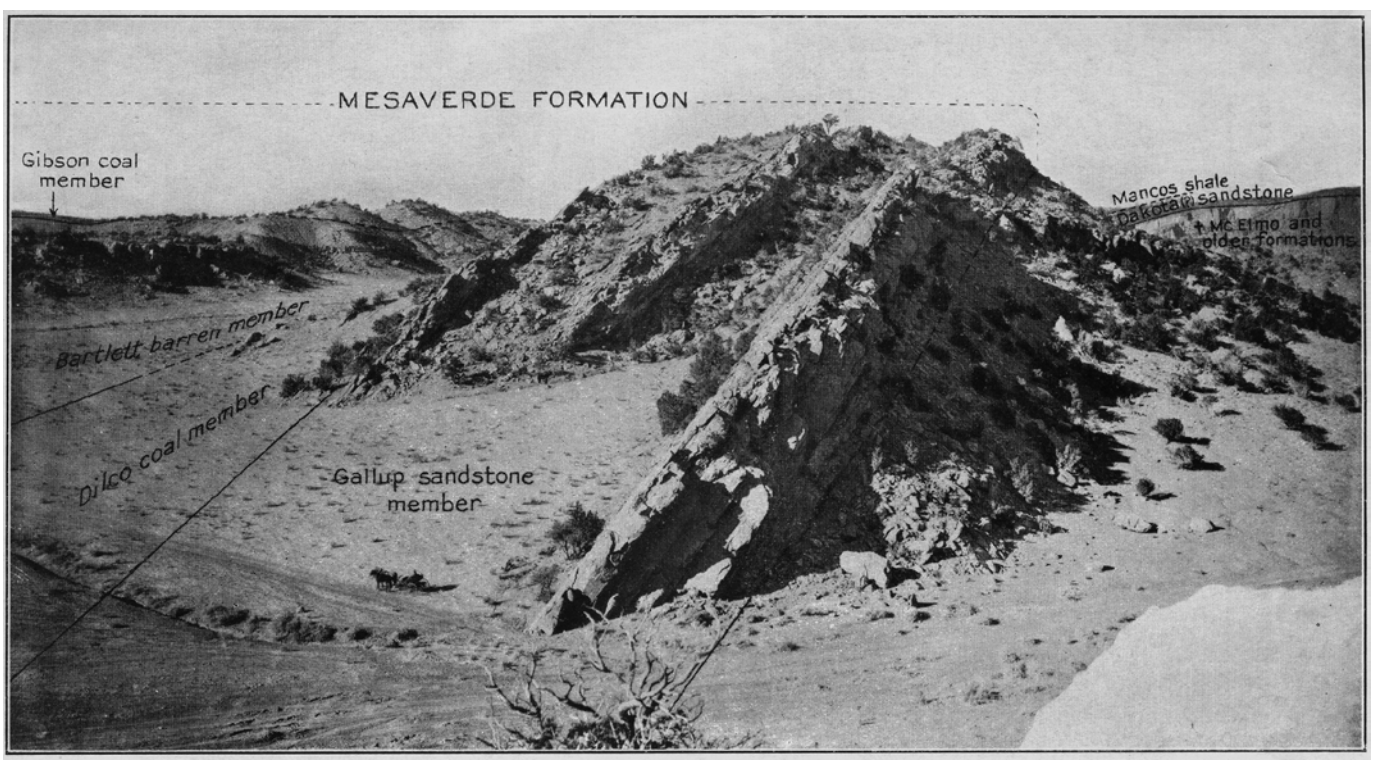

FIGURE 1.33. Sears' (1934, pl. 7) photograph of the type section of the Gallup Sandstone.

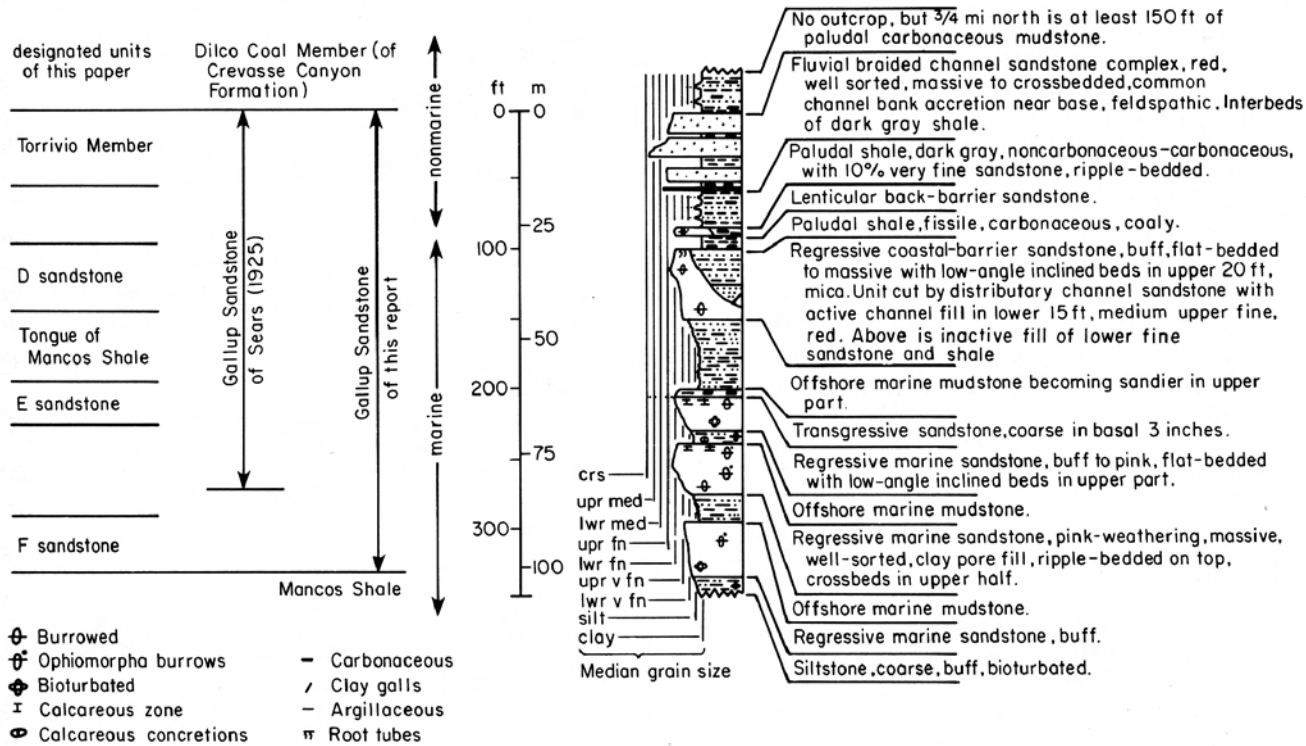

FIGURE 1.34. Molenaar's (1983) columnar principal reference section of the Gallup Sandstone.

existed near the site where Gallup was to develop. The A & P Railroad began building its western segment westward from Albuquerque towards southern California in April, 1880, and by the following April tracks had been laid over the continental divide into the Gallup area. At this time, David L. Gallup was auditor and paymaster for the A & P, and on payday the railroad workers would "go to Gallup" to collect their money, and the name stuck when the post office arrived in 1882.

The arrival of the railroad stimulated the mining of the coal in the area; most of it was sold directly to the A & P. In 1882, the Gallup district produced about 33,000 tons of coal (Myrick, 1970) and mining accelerated in subsequent years (Fig. 1.1). By 1886, Gallup was the largest coal-producing district in New Mexico, and by 1903 some 569,000 tons were mined from more than a half-dozen mines (Schrader, 1906). Growth of the town paralleled growth in coal production, and it became a division terminal for the railroad in 1889, incorporated in 1891, and in 1901 became the county seat of newly created McKinley County. In 1900, Gallup, with a population of nearly 3000, was the fifth largest town in New Mexico Territory (after Albuquerque, Santa Fe, Las Vegas, and Raton). A photograph of early Gallup (Myrick, 1970, p. 30) shows the town to have many well-constructed, substantial homes and buildings, including schools and churches.

The A & P Railroad did not fare so well, going into receivership in the depression of 1893 and eventually (1902) becoming part of the Atchison, Topeka, and Santa Fe Railroad. In the early part of the 20th century as many as eight spur lines connected the main line to various coal mines in the vicinity, and several small satellite coal camps, now mostly vanished, flourished around Gallup. Several of the spur lines were built by the American Fuel Company (later Victor American Fuel Company), which sold its Gallup coal properties to

the Gallup-American Coal Company (Gamerco) in 1917.

As Gallup grew, its economic base diversified beyond coal mining and railroad traffic. The town became the main shipping point and buying center for Navajo wool, thousands of pounds being shipped annually, and it was also a buying center for a growing piñon-nut industry. Wool combing and packing, and the shipping of sheep and cattle from the grazing lands in the Zuni Mountains, also became important industries in the 1920s and 1930s. Gallup has long been the main trading point for the Navajo and Zuni people, and a major center for the wholesaling of Indian arts and crafts. From 1922 to 1978, Gallup was the site of the annual Intertribal Indian Ceremonial, which now takes place in Red Rock Park a few miles to the east.

The proliferation of highways and great increase in truck transportation of goods contributed to the decline of the railroads after World War II. In the l940s, as many as 22 passenger trains passed through Gallup daily, but only one or two do so today. The coal industry also declined rapidly during this time as a result of the conversion of the railroads from coal to diesel fuel, and the replacement of coal by fuel oil and natural gas for space heating and in smelters, both in New Mexico and neighboring states, that had once been steady consumers of Gallup's coal. The coal mines closed down in 1950 for a time, before an increasing demand for electric power from coal-fired generating stations led to the opening of several underground mines as well as the enormous McKinley strip mine northwest of Gallup in the early 1960s. The McKinley mine has operated continuously since that time, producing on a scale (5.2 to 7.2 million tons per year in 1998-2000: McLemore et al., 2002) that dwarfs the Gallup district's mostly underground production during the boom years of 1900 to 1930.

Partially compensating for the decline in the railroads and coal production in the late 1940s was a large increase in traffic along old Route 66 that brought an influx of tourists to and through Gallup, and tourism continues to be an important staple of the local economy. The city's boundary coevolved with this post-war tourist traffic; the town stretches for more than 10 miles along former Route 66, and for most of that distance east and west of the downtown area there is little development away from the highway. The construction of Interstate 40 along a route bypassing most of Gallup's businesses caused some concern, which may be the reason why the Gallup segment of the interstate was among the last portions of that highway in New Mexico to be completed in the late 1970s (WPA, 1940; Myrick, 1970; Chilton et al., 1984; Fugate and Fugate, 1989; Julyan, 1996).

JULIAN SEARS AND CRETACEOUS TRANSGRESSIVE-REGRESSIVE DEPOSITION

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1801 Mountain Rd. N. W., Albuquerque, NM 87104

Students of Cretaceous strata of the Western Interior seaway readily accept the idea of marine transgression and regression, and the distinctive pattern of intertonguing lithofacies it produces. Indeed, since the 1940s, the Interior Cretaceous has been touted as a classic example of intertonguing transgressive-regressive deposits. This understanding began with Hatcher (1904), but prior to the 1940s only a few geologists had grasped the model of transgressive-regressive Cretaceous sedimentation now regarded as commonplace. It was largely because of work in west-central New Mexico that the model gained wide acceptance (Waage, 1975).

"The Upper Cretaceous formations of the Rocky Mountain region present widespread examples of intertonguing of marine and continental deposits which, recognized as formed in or adjoining a shallow epicontinental sea, indicate repeated advances and retreats of that sea" (Sears, 1933, p. 397). Thus began an article by Julian Sears (1891-1970), a U. S. Geological Survey geologist, in which he proposed a mechanism by which the transgressive and regressive deposits of the Western Interior Cretaceous sea were formed. Key to Sears' model were subsidence rates (accommodation in the Newspeak of sequence stratigraphy) (Fig. 1.35).

This model received full expression in one of the little hailed classics of North American geology, a 1941 U. S. Geological

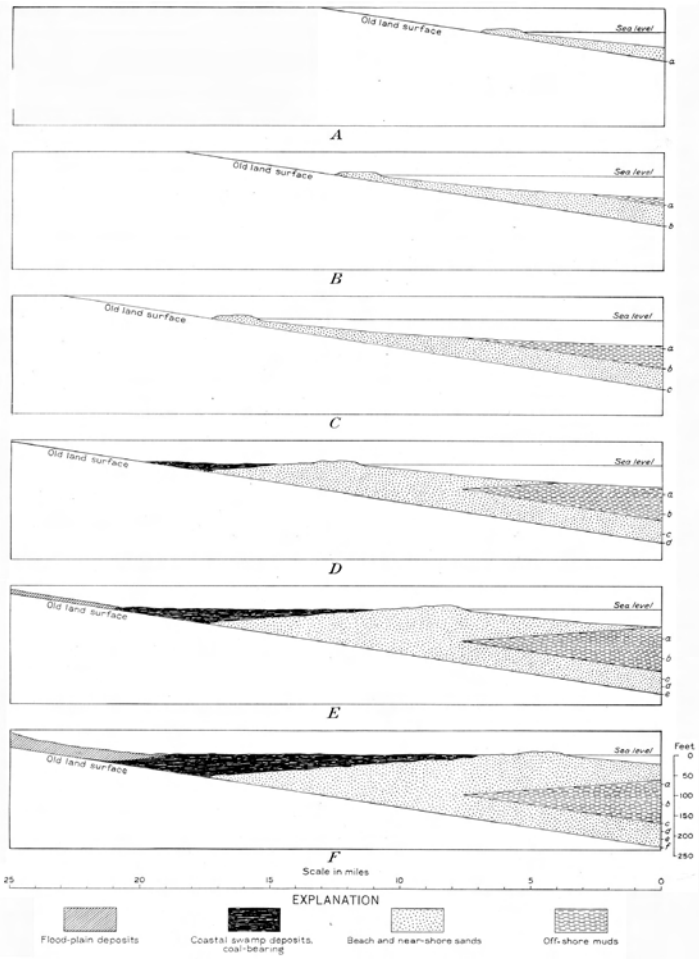


FIGURE 1.35. Plate 25 of Sears et al. (1941) had a brief caption: "Diagram showing change from transgressive to regressive deposition through decrease in rate of trough subsidence."

Survey Professional Paper by Sears, C. B. Hunt and T. A. Hendricks. Sears et al. (1941) developed the idea that regressive deposits accumulated during a slowdown in subsidence: "during periods when the sinking of the trough, though continuing, was at a slower rate the conditions would be favorable to the accumulation and preservation of regressive deposits" (p. 103). Or (p. 104) "…the formation of transgressive and regressive deposits depends upon relative rates of sinking and sedimentation. When sinking predominates, there is transgression; when sedimentation prevails, regression and regressive deposits are the result. Thus (p. 104), "during periods when subsidence of the trough was fairly rapid, the deepening of the sea was too fast for the supply of debris; the water advanced gradually over the land, and the position of the four zones [offshore, nearshore, coastal and landward] shifted progressively landward."

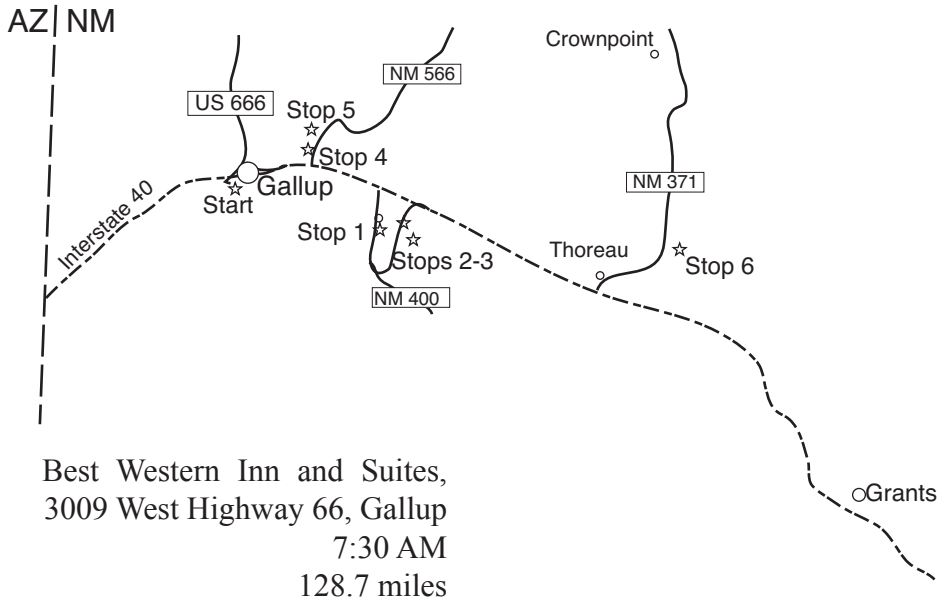
Sears et al. (1941) rejected the then popular idea that rising and falling of the trough caused transgression and regression. Furthermore, they demonstrated their model by detailing the intertonguing relationships of the Mancos Shale and Mesaverde Formation in west-central New Mexico, a set of stratigraphic relationships they documented in exemplary fashion.

Sears et al. (1941) placed sole emphasis on changes in subsidence rate, and I doubt that any geologist today would accept the idea that subsidence alone drove transgression-regression in the Interior Cretaceous seaway. Nevertheless, Sears et al. (1941) is not just a classic of New Mexico geology that first elucidated Cretaceous stratigraphic relationships in west-central New Mexico; it also is a key paper in the history of sedimentary geology.

End of Day 1 road log.

SECOND-DAY ROAD LOG, FROM GALLUP TO FORT WINGATE, SIXMILE CANYON, CINIZA, RED ROCK PARK, CHURCH ROCK, WHITE MESA, THOREAU AND GRANTS

SPENCER G. LUCAS, ANDREW B. HECKERT, WILLIAM R. BERGLOF, BARRY S. KUES, LARRY S. CRUMPLER, JAYNE C. AUBELE, VIRGINIA T. MCLEMORE, DONALD E. OWEN AND STEVEN C. SEMKEN



Assembly Point: Best Western Inn and Suites, 3009 West Highway 66, Gallup
Departure Time: 7:30 AM
Distance: 128.7 miles
Stops: 6

SUMMARY

The second day road log focuses on a detailed examination of the Triassic-Jurassic section of sedimentary rocks exposed on the northern flank (dipslope) of the Zuni Mountains. This is a classic section, first described in detail by Clarence Dutton in 1885. Though long studied, many aspects of these rocks remain controversial, and we explore some of these controversies.

Stop 1 dives right into debate about the base of the Chinle Group near Fort Wingate. Here, rocks of the Chinle Zuni Mountains Formation ("mottled strata") are a paleoweathering profile riddled with large, vertical, tubular structures that have been variously identified as lungfish or crayfish burrows or as rhizoliths. We let you resolve this one.

Stop 2, a few miles to the east, in Sixmile Canyon, examines an unusual feature first described by Clay T. Smith—a paleokarst developed on top of the Permian San Andres Formation and filled with Triassic Moenkopi Formation debris. This lesson in "paleogeomorphology" is followed by Stop 3, farther down Sixmile Canyon, in extensive exposures of the lower part of the Chinle Group. Topics of discussion include Chinle sedimentation, basinwide unconformities and paleontology.

Stop 4 moves us up section into the Jurassic rocks at Red Rock Park. Here, we discuss controversies regarding regional stratigraphy and sedimentation of the Wingate, Entrada, Todilto, Summerville and Bluff formations. Stop 5, a few miles north, at White Mesa, exposes the top of the Jurassic section and the base of the Cretaceous Dakota Sandstone, which here is a spectacular, incised-valley fill.

The trip then continues east to Grants, with Stop 6 north of Thoreau at a quarry developed in limestone of the Jurassic Todilto Formation. Here,

we discuss Jurassic sedimentation and industrial mineral production. The day ends at Grants.

Mileage

0.0 Start in parking lot of Best Western Inn and Suites on west side of Gallup. **Turn left** and proceed west on West Highway 66. **Get in left lane. 0.3**

0.3 Pass through traffic light at Rico Street. **0.5**

0.8 **Turn left** onto onramp for Interstate 40 East, before bridge (I-40 overpass). **0.2**

1.0 Merge left on I-40. **0.1**

1.1 Cross bridge on Interstate 40 eastbound looking down dip into the Upper Cretaceous Crevasse Canyon Formation, Bartlett Barren Member. **1.4**

2.5 Cross bridge over Rio Puerco. **0.2**

2.7 Good outcrops of the Crevasse Canyon Formation to the left next 0.2 miles. **0.6**

3.3 Coal-bearing and clinkered outcrops of the Upper Cretaceous Menefee Formation in roadcuts to left and right. **0.8**

4.1 Sign for Exit 20; hogback forms skyline ahead. More Menefee Formation outcrops to left. **0.6**

4.7 Mile marker 20. **0.5**

5.2 Exit 20, Muñoz Boulevard and US Highway 666. Roadbed on Upper Cretaceous Crevasse Canyon Formation. **1.6**

6.8 Roadcuts in Menefee Formation sandstone. **0.4**

7.2 Exit 22; Miyamura Drive on right, Miyamura Park on left. **1.2**

8.4 Road passes under powerline. Note the Hogback ahead formed at top of Gallup Sandstone with Crevasse Canyon Formation outcrops to left. **0.7**

9.1 Stop 5 from first day on left across frontage road. **0.3**

9.4 Pass through Gallup Sandstone coals in the Hogback. **0.3**

9.7 Cuesta developed in Upper Cretaceous Dakota Formation above Jurassic Morrison strata to left (Fig. 2.1). Red Rocks and Pyramid Mountain at 10:00. **0.3**

10.0 Hogback to south displays top of the Upper Triassic Chinle Group and a complete Jurassic section capped by the Dakota Sandstone. **0.6**

FIGURE 2.1. At mile 9.7, cuesta north of highway is Dakota Formation above Jurassic strata.

10.6 Exit 26 to East Gallup; leave Gallup by staying on Interstate 40. **1.1**

11.7 Cross bridge. Quaternary dunes and Rehoboth Mission on right. Note Pyramid Mountain at 10:00 (Fig. 2.2). We are driving through a strike valley developed in the upper Chinle Group that persists from here to the village of Bluewater, 25 to 30 miles to the east. Dipslopes south of the highway are generally developed in the Sonsela Member of the Petrified Forest Formation. **0.7**

12.4 Wingate Natural Gas plant on left. **0.6**

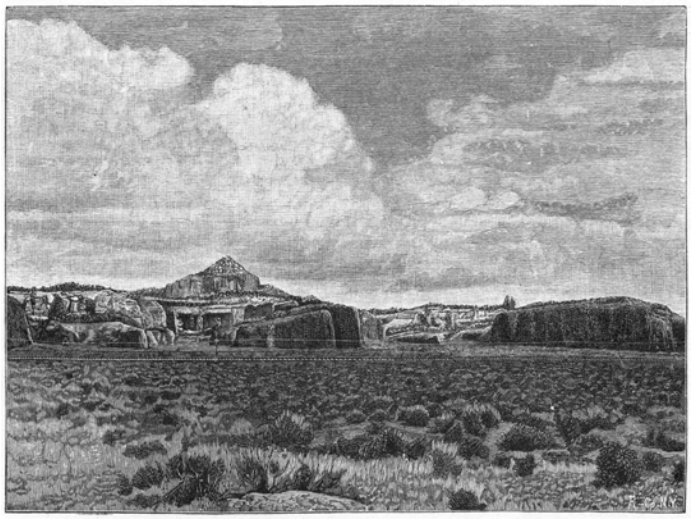


FIGURE 2.2. Dutton's (1885) woodcut photograph of Pyramid Mountain (Rock).

13.0 Cross bridge with good view to left of Red Rocks and Pyramid Mountain at 9:30, and the Jurassic section. **1.2**

14.2 Upper Triassic Owl Rock Formation roadcuts for the next 0.7 miles. **0.2**

14.4 Red Rock Park to left. **0.8**

15.2 Bridge over rail lines to Fort Wingate Army Depot. Originally a cavalry outpost established in 1862, Fort Wingate was deactivated in 1911, and was reopened as Wingate Ordnance Reserve Depot in 1918 and essentially closed again in 1992 (see Heckert et al. minipaper below). Fort Wingate is now run principally by White Sands Missile Range and serves to launch missile tests to White Sands. Note hogback exposure at 4:00. 0.5

15.7 Bridge over road to headquarters of Fort Wingate Army Depot. Note prominent tree-covered dipslope developed in the Upper Triassic Sonsela Member of the Petrified Forest Formation (Chinle Group) ahead and to the south of the highway. Strike valley is in the overlying Painted Desert Member. Dozens of above ground ammunition storage facilities called "igloos" dot the dipslope and are separated by depressions (bunkers). **1.3**

17.0 Sign for McGaffey, exit 33. **Prepare to exit to right. 1.1**

18.1 **Take exit 33**, NM Highway 400 to McGaffey. **0.2**

18.3 Stop sign. **Turn right** to go south on NM-400. **0.1**

18.4 Go straight south past turn for I-40 eastbound. **0.2**

18.6 Cross South Fork Creek. **0.7**

19.3 New entry road to Fort Wingate Army Depot on right. Drive up Sonsela dipslope. **0.3**

19.6 Crest cuesta, town of Fort Wingate ahead. Roadcuts developed in the Sonsela Member. **0.2**

19.8 Contact (Tr-4 unconformity of Lucas, 1993) between the Sonsela Member and the underlying Blue Mesa Member on right. Today's trip will focus on the Triassic section through stop 3 (Fig. 2.3). **0.2**

20.0 White sandstone to right is base of the Blue Mesa Member over redbeds of the underlying Upper Triassic Bluewater Creek Formation at the Fort Wingate Army Depot's small-arms shooting range (Fig. 2.4). **0.4**

20.4 Note Hogback near Gallup to right in distance. **0.2**

20.6 Enter town of Fort Wingate. The town (population about 950) grew up next to the military installation of the same name in the 19th century and has continued to the present, long after the fort ceased to host soldiers. The town's schools and other facilities serve the surrounding rural areas (Julyan, 1996). **0.6**

21.2 Historical marker on left for Fort Wingate. The old cavalry fort is to left behind Fort Wingate Veterans Park. Fort Wingate's history (Fig. 2.5) is detailed in the accompanying minipaper. **0.3**

FROM BEAR SPRING TO FORT WINGATE

Andrew B. Heckert[1], Barry S. Kues[2], and Steven C. Semken[3]

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The area known today as Fort Wingate has had a long and complicated history of multicultural occupation and conflict. Nearby springs were frequented by traveling and war parties of Zuñi and Diné (Navajo) people, and the Zuñi referred to the place as "Anshe Kyana." Bears were often sighted at the springs as well, so this locality was known to Navajos as "Shash bitoo," and later to New Mexicans as "Ojo del Oso" (Van Valkenburgh, 1941).

The fort was first established at Bear Spring near the present-day town (mile 21.2 of the road log) and named Fort Fauntleroy by its commanding officer, Colonel Thomas T. ("little lord") Fauntleroy in 1860. When the Civil War began, however, Colonel Fauntleroy cast his lot with the Confederate Army, and the fort was quickly renamed Fort Lyon in 1862, after Brigadier General Nathaniel Lyon, an early casualty of the fighting on the Union side. Later that year the fort was abandoned, and Union troops pulled back to a site near Ojo del Gallo, about 5 mi south of present Grants, near the town of San Rafael, where they established Fort Wingate, named after Captain Benjamin Wingate, who had died earlier in the year at the Battle of Valverde, trying to repulse

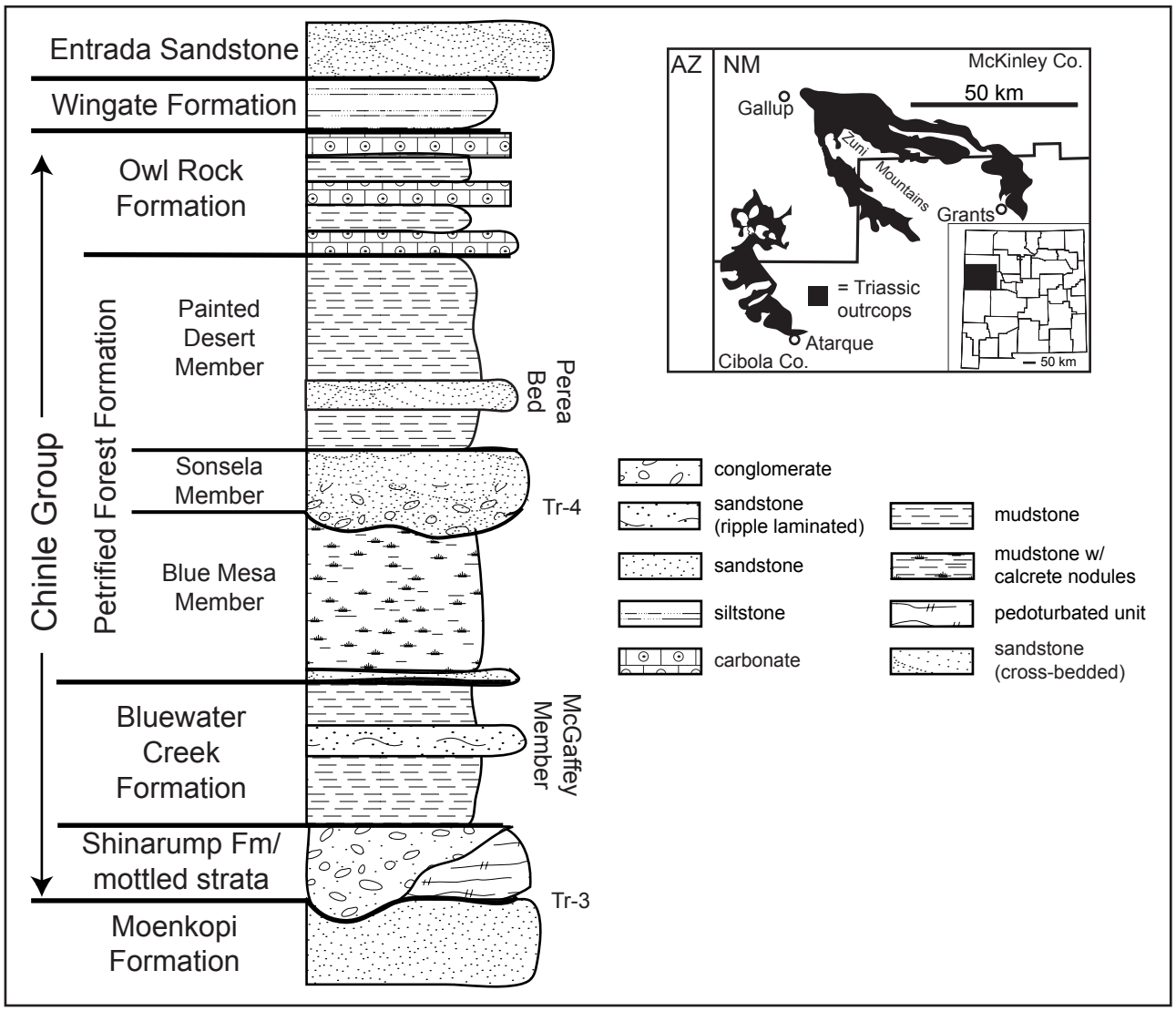

FIGURE 2.3. Generalized stratigraphy of the Upper Triassic Chinle Group in west-central New Mexico; total Chinle thickness is about 1900 ft.

the Confederate invasion of New Mexico. Ojo del Gallo had been an important watering place for centuries (it appears, for example, on the 1776 map of the Dominguez-Escalante Expedition).

FIGURE 2.4. Lower Chinle Group section at mile 20.0.

The fort at Ojo del Gallo was built a few months after the Confederate forces had been defeated and expelled from New Mexico, for the expressed purpose of dealing with the Navajo. The Navajo had used the preoccupation of the territory's military forces with the Confederates to strike at the villages, mines, and ranches of settlers they viewed as intruders. Once the Confederate threat had ended, Colonel R. S. Canby, military commander of New Mexico, began a plan to build a series of forts near Navajo territory, and to move the Navajo to a reservation far distant from the territory's population centers, both to protect New Mexicans against further raiding, and, perhaps, to prevent the Navajo from being exterminated. Before Canby could act, however, he was replaced by Brig. General James H. Carleton.

Carleton immediately implemented Canby's plan, and the construction of Ft. Wingate at Ojo del Gallo commenced. The location afforded excellent pasturage and was near the intersection of two major trails – the Spanish highway to Zuni Pueblo and the old military roads to Ft. Defiance, to the west. The site suffered, however, from its swampy surroundings and water table

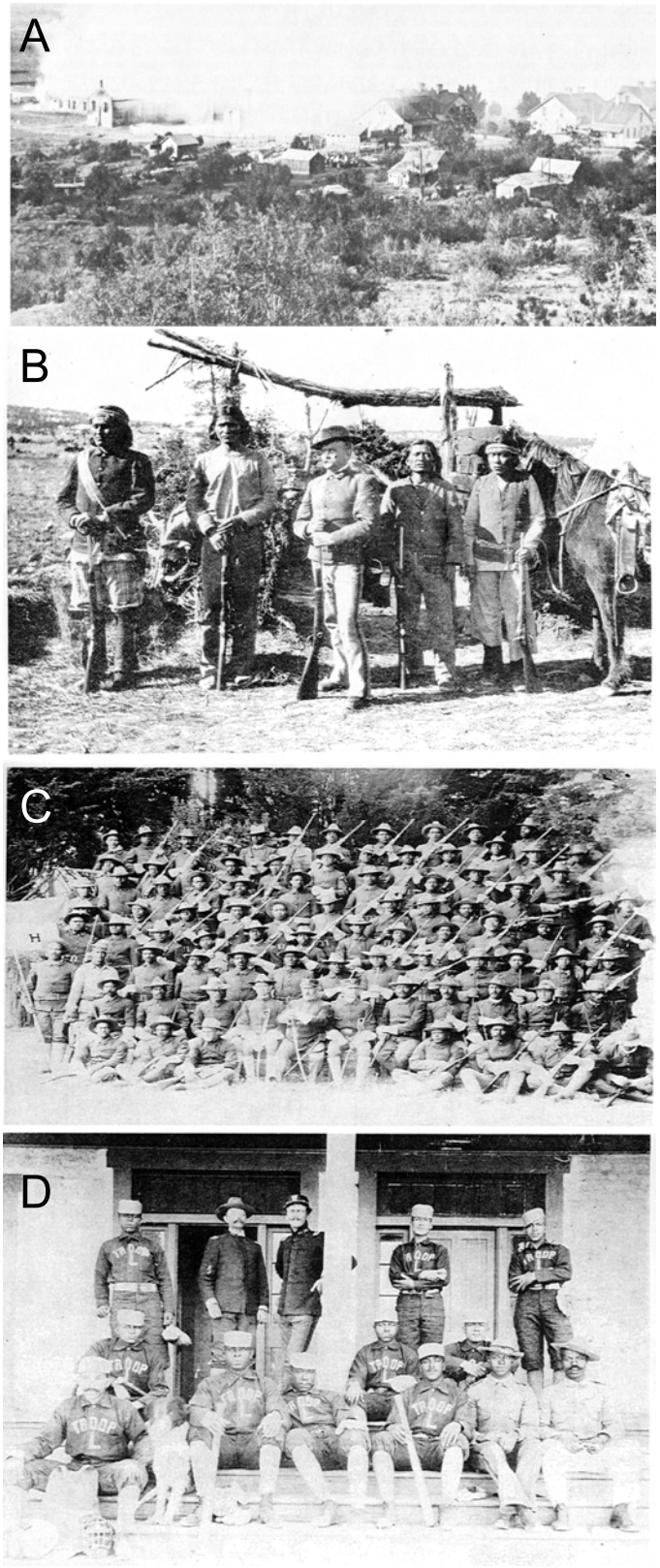

FIGURE 2.5. Historical photographs of Fort Wingate in the 19th century. A. Fort Wingate burning on July 2, 1896; B. Navajo (Diné) Scouts, Troop K, 4th Cavalry, ca. 1881-1884; C. "Buffalo Soldiers" of Troop H, 9th Cavalry, ca. 1899-1900; D. Baseball team of "Buffalo Soldiers," Troop L, 9th Cavalry, ca. 1899. Photos from Smith (1967) and Daniel (1997), Museum of New Mexico negatives 15773, 86944, 98372 and 98374.

near the surface. The fort was built of adobe, with a wooden stockade. Shortly after it was constructed, the fort served as a staging area and supply depot for Kit Carson's war against the Navajo, begun in 1863, which was designed to end the Navajo threat once and for all. His scorched-earth campaign effectively ended the Navajo resistance, and the Navajo people were forcibly resettled in the Bosque Redondo reservation near Fort Sumner, in central New Mexico, in 1864. Ft. Wingate served as a temporary detention center, from which the Navajo made "the Long Walk" to Hwéeldi, their name for Bosque Redondo. The resettlement plan was an egregious failure, and in 1868 the surviving Navajo were allowed to return to their homeland.

As the Navajo returned to northwestern New Mexico, Ft. Wingate at Ojo del Gallo was abandoned; it had fallen into decay during the Civil War and was too far removed from the new Navajo Reservation. The soldiers of Ft. Wingate moved west, to take up quarters at the site of the previous Ft. Lyon, which was then renamed Fort Wingate. There, in 1868, the fort was re-established in the present-day town of Fort Wingate, and again served as a temporary detention center for 7000 Navajos, now traveling from Fort Sumner on to Fort Defiance and the newly established Navajo Reservation.

Fort Wingate remained an important facility throughout the remainder of the 19th century. In 1877, Victorio's Chiracahua Apaches surrendered there, and in 1881-1882 Douglas MacArthur's father, Major General (at the time Captain) Arthur MacArthur commanded Company K of the 15th Infantry at the fort, and a very young Douglas (b. 1880) lived there briefly. "Buffalo Soldiers," (African-American cavalry units, with white officers, including a young John J. Pershing), principally of the 9th Cavalry, were stationed at Fort Wingate in 1876-1881 and again in 1899-1900 (Fig. 2.5C-D). With the arrival of the railroad in 1880, logging operations begun earlier by officers at the fort enjoyed great success. On July 2, 1896, much of the facility was destroyed by fire, but was rebuilt at the same site (Fig. 2.5A). Consequently, the oldest buildings at the original site only date to 1906.

One of the regular duties of the Ft. Wingate troops was to provide entertainment at the New Mexico Territorial Fair in Albuquerque. According to Fugate and Fugate (1989), in 1903 the manager of the Fair arranged a mock battle between cavalry troops and Navajo men. Both sides were issued blank cartridges, and the "battle" was scheduled for Old Town. However, some of the Navajo substituted real ammunition for the blanks, planning to shoot cavalry and escape in the confusion. The plot was discovered, however, and the Ft. Wingate contingent rode soberly back to its post. A short time later, the War Department issued orders banning any future mock battles between cavalry and Indians.

Troops were stationed at Ft. Wingate until 1911, when it was deactivated, but it was reopened in 1912 for several years in order to house about 4000 Mexican troops and their families who had fled from Pancho Villa's army into Texas during the Mexican civil war. General John J. Pershing returned to the fort during his campaign against Pancho Villa, although he was not formally stationed at Fort Wingate at that time.

In 1918, the U. S. Army Ordnance Department assumed control of the Fort for munitions storage, and by 1920 it was the largest storage facility of munitions in the world. Around 1925, Congress

appropriated $500,000 for a Navajo School; the barracks were converted to dormitories, and the parade grounds became a ball field. By the 1930s, more than 100 ordnance storage buildings were familiar sights to travelers on old Route 66, and many of the hogans and houses in the area are constructed from ammunition crates left over from that era. The present-day administrative compound for Fort Wingate (entrance under the bridge at mile 15.2 of the road log) was built in 1941, and it was during World War II that the Fort took on its present-day appearance with multiple railway spurs and hundreds of concrete "igloos" covering dipslopes developed on Chinle Group sandstones.

Fort Wingate continued to serve as a conventional ordnance storage and disposal facility throughout the Cold War. In the 1960s, the base was also used as a testing facility for rockets for the Pershing-1 missile. In the late 1980s, Fort Wingate was listed as one of the military facilities to close under BRAC (Base Realignment and Closure) 1988. As part of BRAC 1988, many munitions stored at Fort Wingate were removed and eventually disposed of in Iraqi and Kuwaiti deserts in early 1991. Others were disposed of on-site in somewhat less spectacular fashion.

Fort Wingate has long had a substantial economic impact on the region. In the 1870s and 1880s many of the officers stationed there augmented their paychecks by running logging and cattle companies. The former supplied railroad ties, and the latter often sold beef back to the government to supply the fort. Fort Wingate has long had a substantial civilian work force as well. In the 1880s, the fort employed male Navajos as scouts (Fig. 2.5B) and as laborers for facility construction, and female Navajos often worked as laundresses. Indeed, from 1868 through World War II, Navajos comprised the largest civilian workforce at Fort Wingate. During World War II the Fort employed over 1500 civilians (90% of them Navajo) loading and unloading munitions, especially TNT. By the late 1980s the fort had only a single military employee, the commanding captain, and the rest of the workforce was civilian. Since the drawing down of the facility, over $23 million has been spent to clean up a variety of "contaminants," including unexploded ordnance (UXO), explosive compounds, PCBs, heavy metals, pesticides, asbestos and (gasp!) lead-based paint. Much of this cleanup was contracted to TPL, Inc., which has a substantial facility employing as many as 85 people on-site. (Sources: WPA, 1940; James, 1967; Chilton et al., 1984; Fugate and Fugate, 1989; Julyan, 1996; Daniel, 1997; Mangum, 1997; Defense Technical Information Center, 2002; Global Security, 2002).

21.5 **Road to right** to Cibola National Forest Wingate Office; begin ascent of Chinle dipslope developed primarily on the Zuni Mountains Formation (formerly the "mottled strata") (see Heckert and Lucas, this volume). **0.3**

21.8 Outcrops of the Zuni Mountains Formation on left. **0.1**

21.9 Cattleguard. Enter Cibola National Forest. **0.2**

22.1 **STOP 1.** Pull off on dirt roads to left to look at the base of the Chinle Group.

At this stop, we focus on the early depositional history of the Chinle Group. Here, thick deposits of pedogenically modified strata overlie the unconformable surface between the Upper Triassic Chinle Group and the underlying Middle Triassic Moenkopi Formation (Fig. 2.6). These basal Chinle strata encompass a wide range of lithotypes, including conglomerates, sandstones, and mudrocks, some of which have been altered to the point where they have become "porcellanites." These strata are intensively color-mottled and turbated. Historically, these strata have been called the "mottled strata," both here and throughout their outcrop distribution from eastern Arizona to the Lucero uplift in central New Mexico (e.g., Stewart et al., 1972a; Ash, 1978; Lucas and Hayden, 1989; Heckert and Lucas, 2002a). Similar strata in east-central Utah were termed the Temple Mountain Member of the Chinle Formation by Robeck (1957). The turbation has been attributed to lungfish (Dubiel et al., 1987), crayfish (Hasiotis et al., 1993), or pedogenesis (Lucas and Hayden, 1989; Lucas and Anderson, 1993; Heckert and Lucas, 2002a). In this volume, Heckert and Lucas introduce the term "Zuni Mountains Formation" for these strata.

Here, at Stop 1, these strata are as thick or thicker than on any other locality on the southern Colorado Plateau (~65 ft). Indeed, these strata are so thick (and the underlying Moenkopi Formation so thin) that they are mapped with the Moenkopi Formation on Anderson et al.'s (2003) geologic map of the Fort Wingate quadrangle that accompanies this volume.

Our emphases here are threefold: (1) a thin remnant of the Moenkopi Formation is present; (2) above the Moenkopi Formation an unconformable surface (Tr-3 unconformity of Pipiringos and O'Sullivan, 1978) is overlain by a complex array of deposits; (3) these deposits

themselves have a complex depositional and post-depositional history.

Regarding the Moenkopi Formation, these strata are thinly bedded sicliciclastics, principally sandstones and siltstones with minor intraformational conglomerates. Moenkopi Formation strata are relatively thin (generally <30 ft) throughout the western Zuni Mountains, and typically overlie an erosional surface developed on underlying Permian strata. Indeed, there is a significant amount of paleotopography developed on the unconformable surface below Moenkopi strata regionally, so that, although the Moenkopi overlies the San Andres Formation throughout much of the Zunis, the San Andres is locally absent and Moenkopi strata rest on the underlying Glorieta Formation as well. Moenkopi Formation red beds typically weather to grayish red, with some unweathered outcrops light greenish gray. These strata are flaggy to ledgy with minor, low-angle crossbeds. Moenkopi red beds are readily differentiated from the overlying Chinle red beds by the absence of bentonitic mudstone in the Moenkopi. Locally, uppermost Moenkopi strata are pedogenically modified, with color bleaching and reduction spots, but little change in lithology or sedimentary fabric. Where changes are more profound, these strata are usually assigned to the overlying Zuni Mountains Formation.

At Stop 1, complex valley-fill deposits overlie the Tr-3 unconformity. These strata are siliciclastics that were extensively pedogenically modified. In many places this modification destroyed the primary sedimentary fabric, sometimes overprinting it with abundant rhizoliths, some of which are up to 2 m in length and as much as 20 cm in diameter. Dubiel (1987, 1989) argued that these structures were lungfish burrows, but we follow McCallister (1988) and Lucas and Hayden (1989) and consider them rhizoliths. Hasiotis et al. (1993) posited that they were instead crayfish burrows linked to the fluctuating water tables believed responsible for the color mottling. Although the simple (non-branching) nature of these structures is more similar to that of some burrows, Lucas and Hayden (1989) noted that they could well represent the non-branching roots of primitive tree-like plants such as *Neocalamites*.

Where most stratigraphers agree, however, is that whatever one terms the post Tr-3 deposits, they represent a complex valley infill of paleotopography generated between the end of Moenkopi deposition in the early Anisian and the onset of Chinle deposition during the Carnian, approximately 8 to 10 million years later. Accordingly, primary (unmodified) channel-fill fluvial deposits at the base of the Chinle are generally assigned to the Shinarump Formation (present in thin, discontinuous ribbons of conglomerate in the Fort Wingate area) or to the Zuni Mountains Formation ("mottled strata" of previous usage). There is little doubt that much of the Zuni Mountains Formation represents pedogenically modified Shinarump strata. At Nazlini near the type section of the Chinle on the Navajo Reservation there are outstanding outcrops documenting that pedogenic and diagenetic alteration of the Zuni Mountains Formation took place in Shinarump Formation deposits.

After stop return to NM-400 and continue southward. 0.2

22.3 Note outcrops of the Bluewater Creek Formation to right. **0.1**

22.4 "Monitor Butte facies" on left in roadcuts. This is lithofacies assemblage 3 of Heckert (1997) and Heckert and Lucas (2002a). **0.2**

22.6 Sandstone on left is low in Bluewater Creek Formation. A similar or equivalent sandstone to the east bears tetrapod tracks, including a footprint of an early dinosaur (Lucas and Heckert, 2002) (Fig. 2.7). **0.4**

23.0 Outcrops to right are the Bluewater Creek Formation capped by the McGaffey Member. **0.2**

23.2 McGaffey Member roadcut on left, so

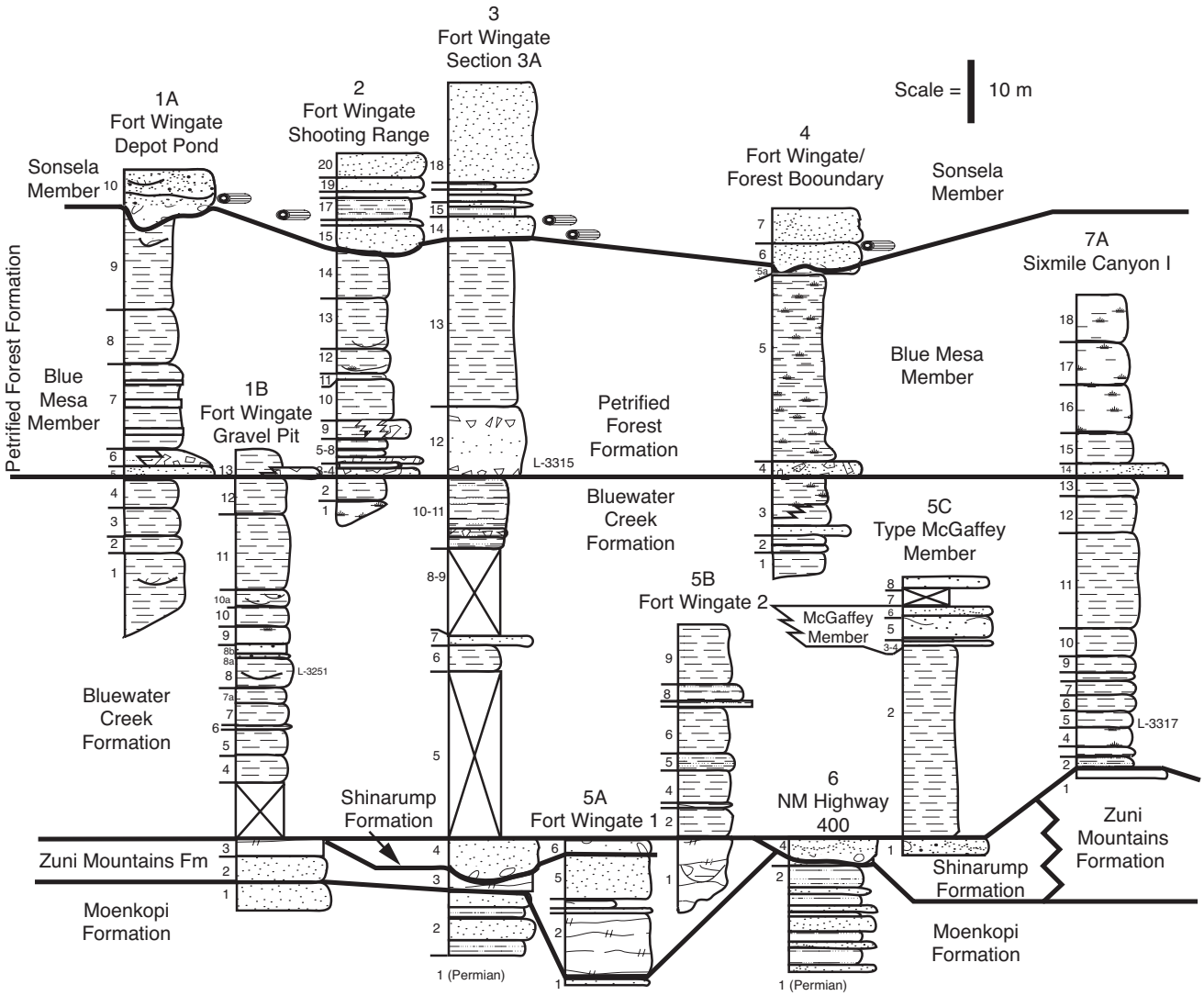

FIGURE 2.6. Lower Chinle Group stratigraphic sections in the western Zuni Mountains.

this is the top of the McGaffey cuesta. Roadbed now descends through the lower Chinle to the Middle Triassic Moenkopi Formation. **0.5**

23.7 Zuni Mountains Formation ("mottled strata") outcrops at curve in road. **0.2**

23.9 Cattleguard. **0.2**

24.1 Cibola National Forest entrance sign. Moenkopi Formation redbeds up to Shinarump Formation bench on left (Fig. 2.6, section 6). The bench below and to the right is in the Lower Permian Glorieta Sandstone. Note that the Lower Permian San Andres Formation is not present here. **0.1**

24.2 Moenkopi Formation redbeds exposed in roadcuts for the next 0.3 miles. **0.4**

24.6 Cliff to right across creek is the Glorieta Sandstone. **0.1**

24.7 Roadcuts for the next 0.2 miles are in the San Andres Formation. **0.1**

24.8 Cliff of San Andres Formation on left. Note here that patchy upper Paleozoic outcrops are present across the Zuni Mountains. Also note the equivalence of the New Mexico Glorieta with the Arizona Coconino and the New Mexico San Andres with the Arizona Kaibab. San Andres Formation outcrops on left for the next 0.2 miles. **0.9**

25.7 Zuni Mountains Formation outcrops on right. **0.2**

25.9 Milepost 3; campground on right. **0.4**

26.3 Cattleguard. We are now in ponderosa

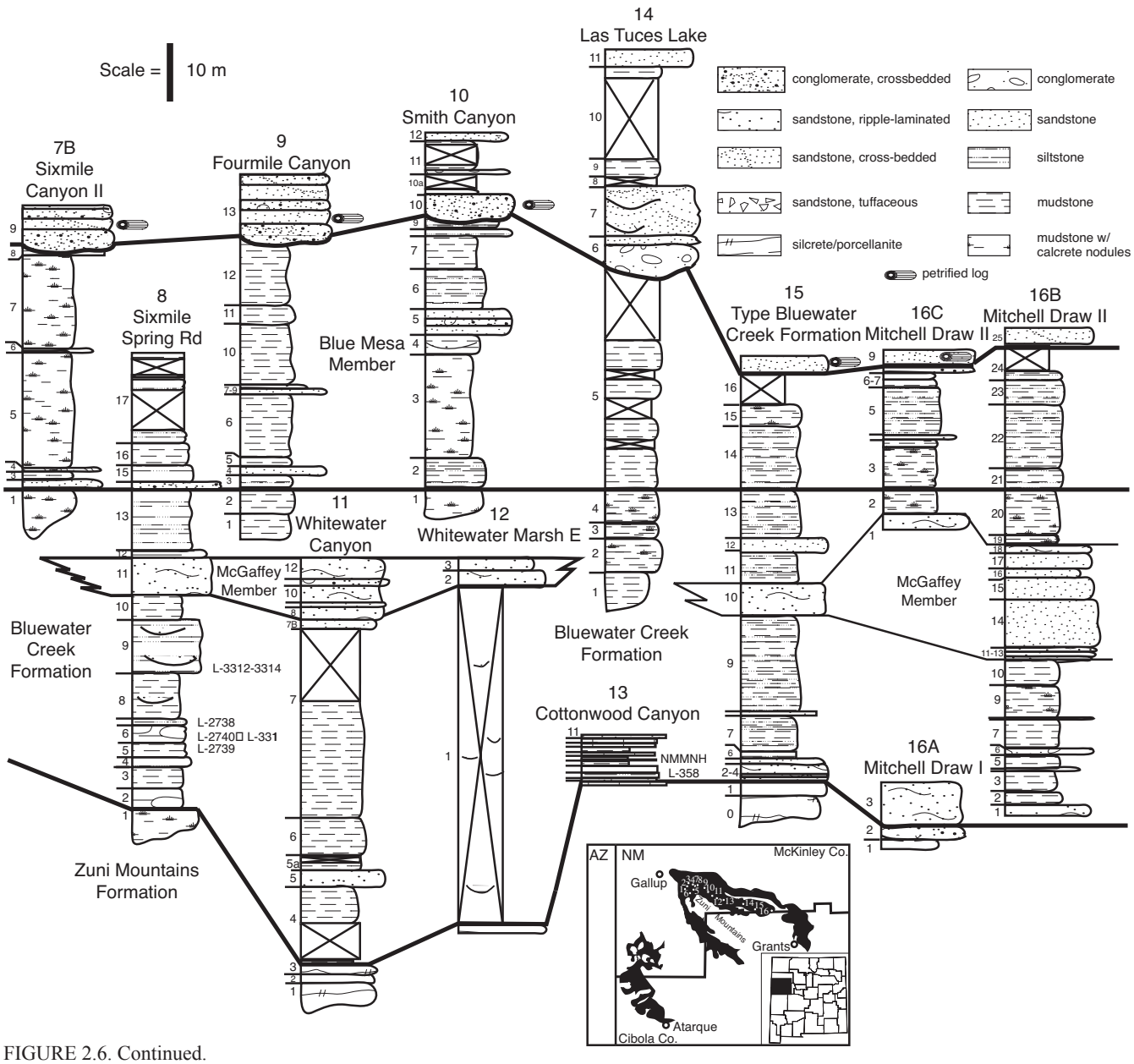

FIGURE 2.6. Continued.

pine-dominated forests. **0.1**

26.4 Quaking Aspen campground to right. **0.7**

27.1 Sign for McGaffey ahead, Grants to left. **Turn left onto dirt road and pass through gate.** (This route is closed from December 15 to March 31 each year and is nearly impassable when wet). McGaffey was established about 1903 as a timber town and was named after Amasa B. McGaffey, a trader at Thoreau who turned lumberman (Julyan, 1996). Cutting timber was a major industry in the Zuni Mountains during the late 1800s and the early 1900s. In the 1920s and 1930s, McGaffey was the largest of several Zuni Mountains lumbering towns, boasting 200 families, a five-room school, and a large town hall. It waned with the end of the lumber boom, but some residents still remain (Julyan, 1996). **0.4**

27.5 Sandstone on left is the Sonsela Member. **0.2**

27.7 Bluewater Creek Formation and Blue Mesa Member mudstone-dominated slope on left up to Sonsela Member capping ridge. **0.1**

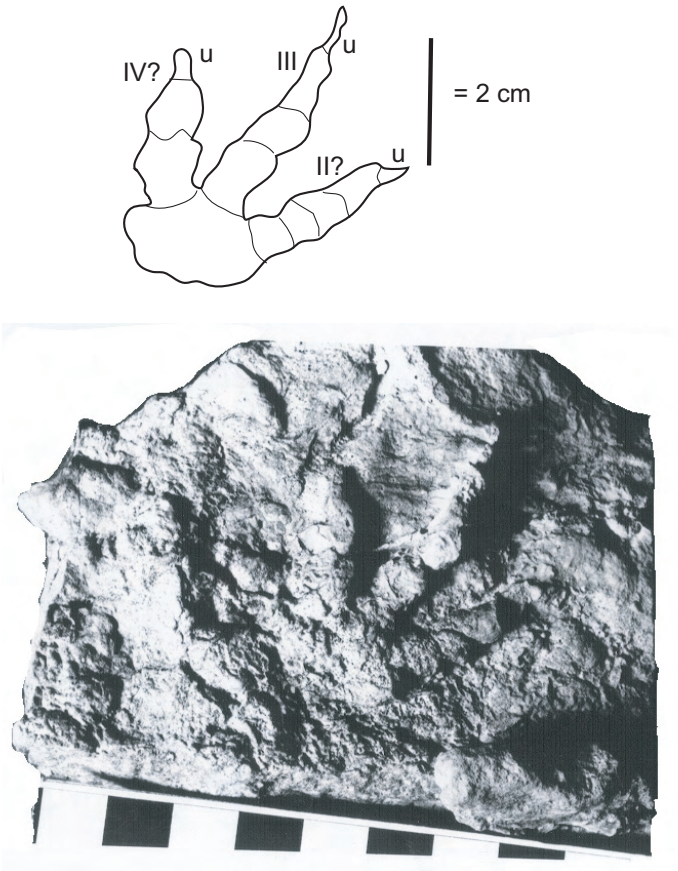

FIGURE 2.7. Dinosaur footprint from the Bluewater Creek Formation near Fort Wingate.

27.8 Blue Mesa Member bentonitic mudstones overlain by a Sonsela cuesta of tan/gray sandstones on left. **0.1**

27.9 Top of Sonsela; note its tripartite lithology—lower sandstone, middle mudstone, upper sandstone (see accompanying mini-paper). **0.2**

THE UPPER TRIASSIC SONSELA MEMBER OF THE PETRIFIED FOREST FORMATION IN THE ZUNI MOUNTAINS

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The Sonsela Member of the Petrified Forest Formation forms the long cuesta south of Interstate 40 that stretches from the Fort Wingate Military Depot east to the community of Bluewater. This sandstone- and conglomerate-dominated unit thus forms the south wall of the Chinle strike valley between Gallup and Grants. Following Dutton (1885), Darton (1928) mistakenly thought that the Sonsela represented the base of the Upper Triassic section in the Zunis, but subsequent workers, including Cooley (1957), Foster (1957), Stewart et al. (1972a,b), Ash (1978), Lucas and Hayden (1989), Heckert and Lucas (1996, 2002a), Lucas et al. (1997a,b) and Heckert (1997a,b) all identified it as a medial sandstone in the Upper Triassic section (Fig. 2.8).

The Sonsela Member rests disconformably on the Blue Mesa Member of the Petrified Forest Formation. This is the Tr-4 unconformity of Lucas (1993), and Heckert and Lucas (1996) documented as much as 23 m of erosional relief on this contact between thicker Blue Mesa Member sections to the west near Fort Wingate and thinner sections to the east near Prewitt. The upper contact of the Sonsela with the overlying Painted Desert Member is almost always covered at the base of the Sonsela dipslope, but appears to be gradational.

Sandstones dominate the Sonsela lithosome, although conglomerates are also common. A persistent mudstone interval is sometimes exposed in the middle of the unit as well. Basal conglomerates and conglomeratic sandstones of the Sonsela Member contain many pebble-to cobble-sized clasts. These clasts may include mudstone rip-ups but more commonly are siliceous extraformational clasts, apparently derived from Paleozoic limestones presumably exposed to the south during Late Triassic time. Higher in the Sonsela section, reworked calcrete nodules are more common. Sandstones are medium- to coarse-grained subarkoses, sublitharenites, and, rarely, quartzarenites. Mudrocks are not well-exposed, but are often bluish-purple and bentonitic, thus closely resembling the mudstones of the underlying Blue Mesa Member.

Trough-crossbedding is the most common bedform in the Sonsela, with some subordinate, principally low-angle, planar crossbeds present as well. Individual sets are typically 1-1.5-m-thick, with much scour-and-fill within the bed. Most of the conglomerates are concentrated at the bases of the sets. The predominance of scour-and-fill and laterally extensive coalesced sandstone bodies strongly suggests that Sonsela deposition was by low-sinuosity streams (Deacon, 1990).

The Sonsela Member is the principal petrified wood-bearing unit at the Petrified Forest National Park (PFNP) in Arizona (Heckert and Lucas, 1998, 2002b), and logs are relatively common in the Sonsela throughout the Zuni Mountains of New Mexico. These logs tend to be shades of yellow, white, and gray, and are not as abundant, large or as colorful as the logs at the PFNP. Still, trunks up to 10 m long have been recovered in places.

Heckert and Lucas (2002b) recognized three, bed-level units within the Sonsela Member at PFNP. They termed these the Rainbow Forest, Jim Camp Wash, and Agate Bridge beds, in ascending stratigraphic order. The Rainbow Forest and Agate Bridge beds are both predominantly sandstone and conglomerate. Both bear petrified logs, especially the Rainbow Forest Bed, host to most of the major "forests" in the Park. The Jim Camp Wash bed is a mudstone-dominated interval that separates the two sandstones. Akers et al. (1958) noted a similar interval at the type section of the Sonsela in the Chuska Mountains to the northwest (see also Lucas et al., 1997b). In the Zuni Mountains, the three units are only apparent on fairly close examination, as the Jim Camp Wash Bed strata are thin and typically covered. The Rainbow Forest Bed in the Zunis tends to bear most of the petrified wood and is

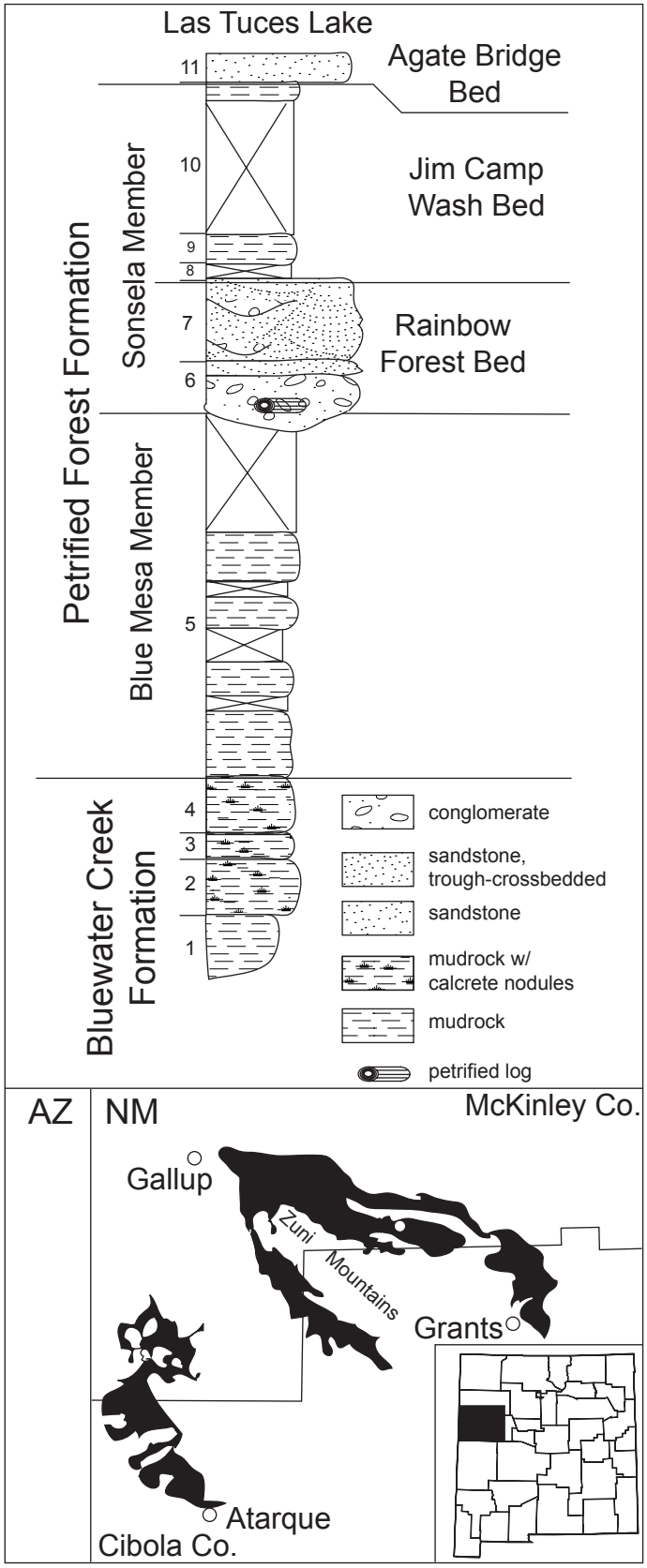

FIGURE 2.8. Representative section of the Sonsela Member in west-central New Mexico.

dominated by siliceous conglomerate clasts. The Agate Bridge Bed has less wood and more intraformational clasts.

Deacon (1990) reported paleocurrents in the Sonsela Member in the Zuni Mountains that are predominantly to the north or northeast at Fort Wingate, Continental Divide, and Bluewater. A section Deacon (1990) measured at Thoreau has easterly to southeasterly paleocurrents.

Within our broader understanding of the Chinle depositional system, Sonsela strata represent the deposits of fluvial systems draining highlands to the south (e.g., Stewart et al., 1972a; Lucas, 1993; Heckert and Lucas, 1996). These systems were themselves tributaries to a trunk drainage running southeast to northwest across the Four Corners area, where intraformational conglomerate is more common in the Sonsela interval, and correlative strata are termed the Moss Back Formation (Stewart et al., 1972a; Lucas, 1993; Lucas et al., 1997b).

Diverse lines of evidence, including palynology (Litwin et al., 1991) and tetrapod biostratigraphy (e.g., Lucas and Hunt, 1993; Lucas, 1997, 1998; Heckert and Lucas, 2002a) indicate that the Sonsela is Revueltian (early-mid Norian in age). Underlying Blue Mesa Member strata are Adamanian (latest Carnian). This contact is sharp and, locally, 1-2 m of erosional relief are visible. Heckert and Lucas (1996) and Heckert (1997a) documented as much as 23 m of erosion by comparing a 44-m-thick Blue Mesa section on the Fort Wingate Military Depot in the west to a 21-m-thick section of equivalent strata near Bluewater in the eastern Zuni Mountains. Farther to the east, in the Lucero uplift, the Blue Mesa Member was apparently removed during the development of the Tr-4 unconformity (Lucas and Heckert, 1994; Heckert and Lucas, 1996; Heckert, 1997a). This transect is one of the few well-constrained indications of the degree of erosion associated with the development of the Tr-4 unconformity.

28.1 Road forks, **go right. 0.4**

28.5 T-junction and sign; road to right goes to McGaffey, road to left to Sixmile Canyon. Debris from the Sonsela litters roadsides. Nearby McGaffey Lake (a large pond) and Forest Service campgrounds are popular fishing and camping destinations. **Turn left. 0.1**

28.6 West-dipping Sonsela Member sandstone outcrops on right; the road is on an old wagon grade used to pull logs out of the forest down to a railroad grade in Sixmile Canyon ahead. **0.3**

28.9 Cattleguard; red beds here are the Bluewater Creek Formation for next 0.3 miles. **0.4**

29.3 Sonsela Member conglomeratic debris on right. **0.1**

29.4 Blue Mesa Member mudstones in roadcuts for next 0.3 miles. **0.3**

29.7 Note slumped Sonsela up hill to left. **0.3**

30.0 Road forks; **go straight**. Sonsela cuesta at 10:00 across valley; floor of Sixmile Canyon ahead. **0.2**

30.2 "Porcellanite" of Zuni Mountains Formation on left. **0.1**

30.3 Road to left; go straight. Zuni Mountains Formation strata on right. **0.1**

30.4 Cuesta to left in Zuni Mountains Formation. **0.1**

30.5 Ripple-laminated sandstone cuesta to left is the base of Bluewater Creek Formation (lithofacies 2 of Heckert and Lucas, 1996). **0.1**

30.6 Red beds on both sides of the road are Moenkopi Formation. **0.4**

31.0 Road to right; go straight. **0.3**

31.3 Zuni Mountains Formation-Bluewater Creek Formation contact on left (red beds above blue mottled limestone). **0.3**

31.6 **STOP 2.** Typical Moenkopi sandstone on left opposite smaller road leading to east. A paleokarst is developed in the drainage here in the top of the Lower Permian (Leonardian) San Andres Formation and is filled with slumped and brecciated siliciclastic red beds of the Middle Triassic (early Anisian) Moenkopi Formation (Fig. 2.9). Smith (1954) first described and mapped this feature. The principal "dolein" is in the creek bottom just east of the road. Here, the San Andres outcrop is ~10 ft thick and consists mostly of medium light gray, thick-bedded, fossiliferous limestone; fossils are mostly heavily recrystallized shells of brachiopods and, rarely, nautiloids. Parts of this limestone, however, are brecciated, and the interstices and voids of the limestone breccia are filled with grayish red and pale reddish brown Moenkopi sandstone and conglomerate. A large boulder of this breccia sits in the arroyo floor. Just south of it is a striking red-bed fill about 6-7-ft-thick of sandstone and siltstone excavated into the San Andres bedded limestone. These features suggest that the creek bed exposes a sinkhole-like feature developed in the San Andres that has a map area of about 1800 ft^2.

Immediately east of the road are two outcrops of San Andres limestone surrounded by alluvium of the Moenkopi. These outcrops are 12 or more ft higher than the top of the San Andres in the creek bed. We suggest that this reflects paleotopography developed on top of the San Andres prior to Moenkopi deposition. The two San Andres outcrops at the road thus are "islands" surrounded by and buried over by the Moenkopi redbeds.

Here, the Moenkopi Formation is at least 20 ft thick and consists of red-bed siltstones and fluvially-deposited sandstones with minor lenses of intraformational conglomerate and conglomeratic sandstone. The Chinle Zuni Mountains Formation ("mottled strata") disconformably overlies the Moenkopi up the hill west of the road. Its base is marked by a prominent, color-mottled sandstone; colors include pale yellowish orange, very pale orange, very dusky purple and brownish gray.

Note also that the bluff to the northeast is part of the drainage divide between Sixmile and Fourmile canyons and displays red Bluewater Creek Formation overlain by purplish Blue Mesa Member capped by gray Sonsela Member on ridge crest.

After stop, continue north on main road. 0.1

31.7 Cut to right is also on the San Andres Formation (karsted) and is the location of Sixmile Spring. **0.2**

31.9 Cattleguard. **0.1**

32.0 Moenkopi on left with mottled strata above. Road to the right leads to Fourmile Canyon. **Continue straight. 0.1**

32.1 Sign for Sixmile Canyon Forest Road 547. **0.2**

32.3 Dark blue bentonitic mudstones are near the base of the Bluewater Creek Formation. Note Bluewater Creek Formation section to left. **0.9**

33.2 Note section to left of Bluewater Creek

Formation and Blue Mesa and Sonsela members of the Petrified Forest Formation. **0.2**

33.4 **Before culvert turn left onto 2-track road. 0.1**

33.5 **Stop at wash. STOP 3.** At this stop, a relatively complete lower Chinle Group section is exposed (Figs. 2.10-2.11). Only locally exposed in the valley floor are pedogenically modified siliciclastics of the Zuni Mountains Formation. The widespread red beds that are the most accessible outcrops are the Bluewater Creek Formation. Overlying the Bluewater Creek Formation are the purple, mudstone-dominated beds of the Blue Mesa Member of the Petrified Forest Formation—the contact is at the easily mapped, persistent white sandstone with abundant volcanic detritus approximately 50 m above the valley floor (Fig. 2.10). Disconformably overlying the Blue Mesa Member are the conglomerates and sandstones of the Sonsela Member.

Heckert (1997a; Heckert and Lucas, 2002) measured 50.5 m of Bluewater Creek Formation here. Throughout the Zuni Mountains the Bluewater Creek Formation consists of three primary lithofacies assemblages: (1) interbedded mudstone and siltstone with scattered calcrete nodule hori-

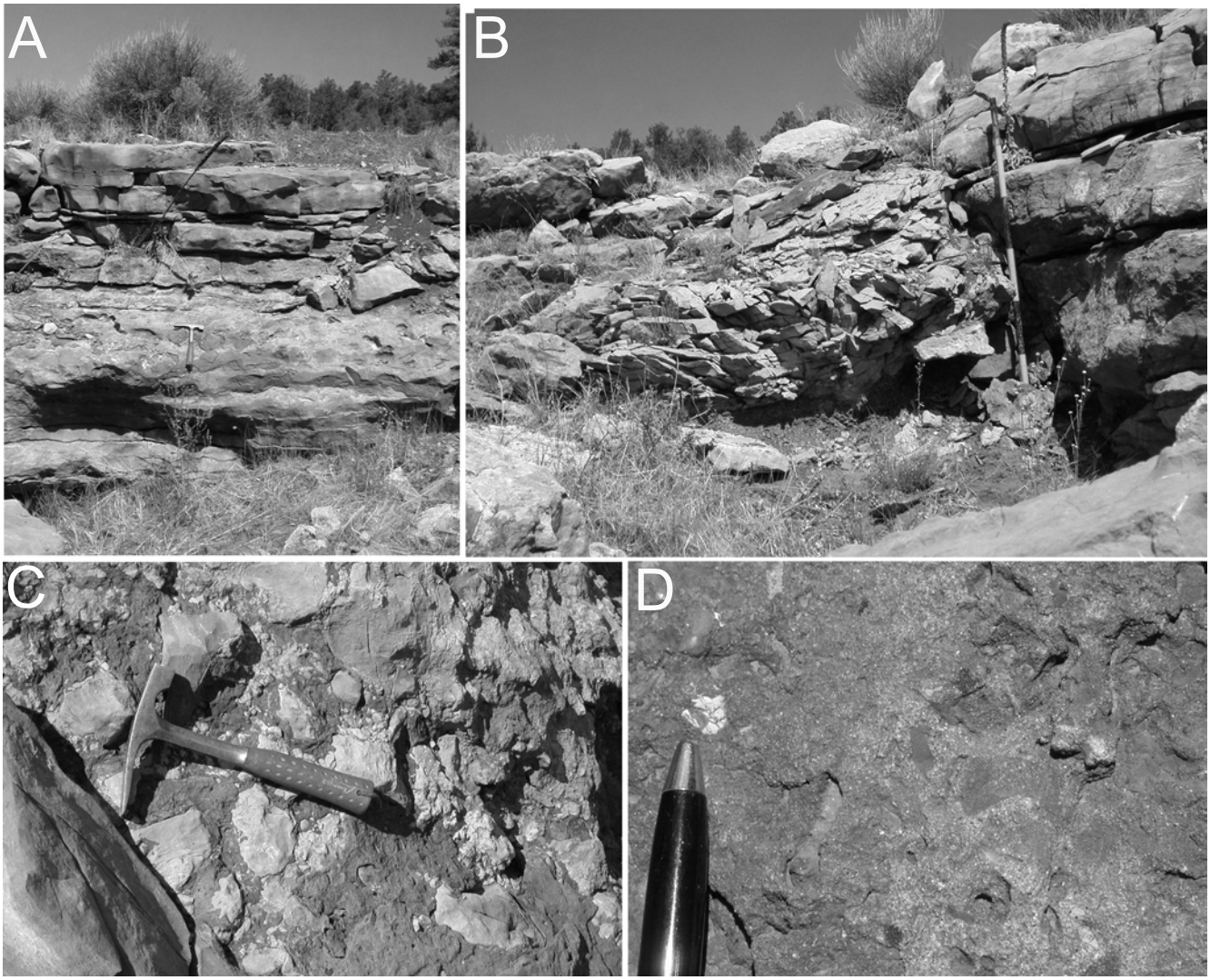

FIGURE 2.9. Photographs of Triassic Moenkopi Formation karst developed in the Permian San Andres Formation limestone at Stop 2. A-B. Overviews of the karst. C-D. Close-ups of the breccia that fills the karst. Pen in D points to a fossil bone fragment.

zons, (2) ripple laminated to plane-bedded sandstone with minor intraformational conglomerate, and (3) greenish bentonitic mudstone and black shale. These represent red-

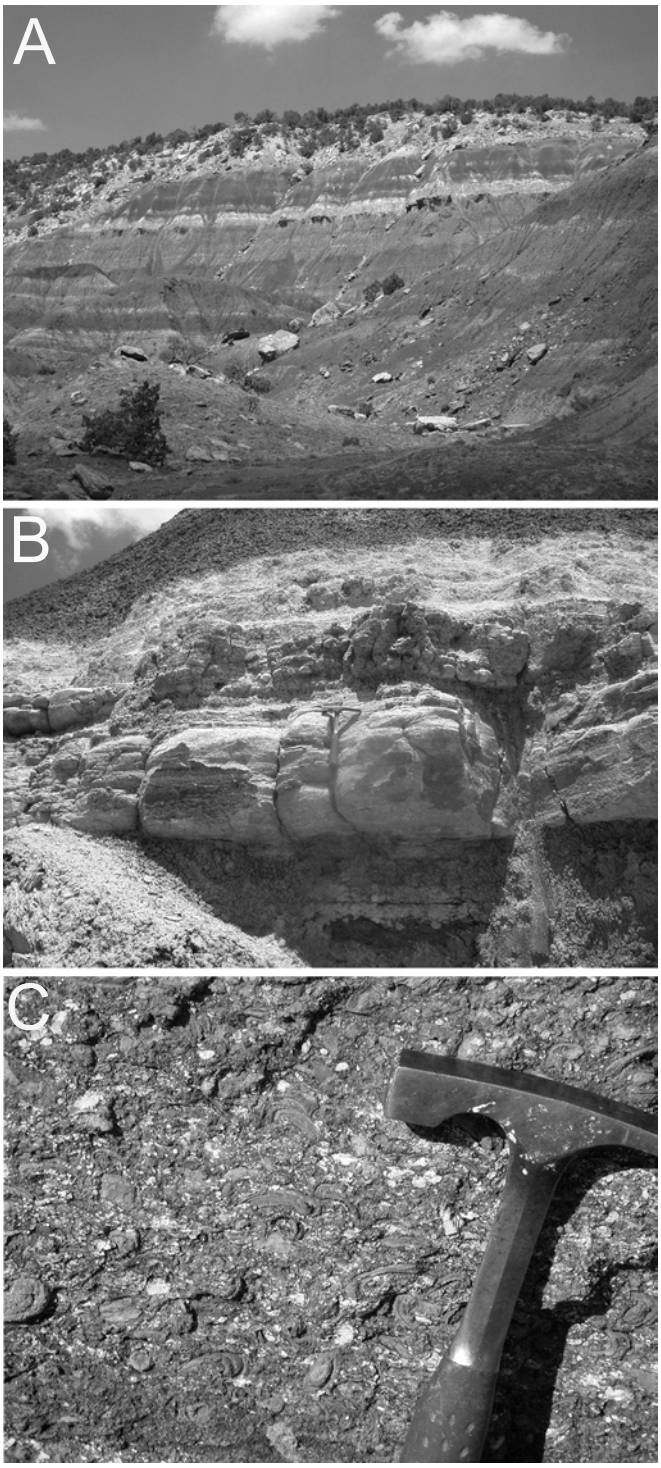

FIGURE 2.10. Lower Chinle Group outcrops at Stop 3. A, Overview of section. B, Close-up of sandstone at contact of Bluewater Creek and Petrified Forest formations. C, Unionid bivalve coquina in Sonsela Member.

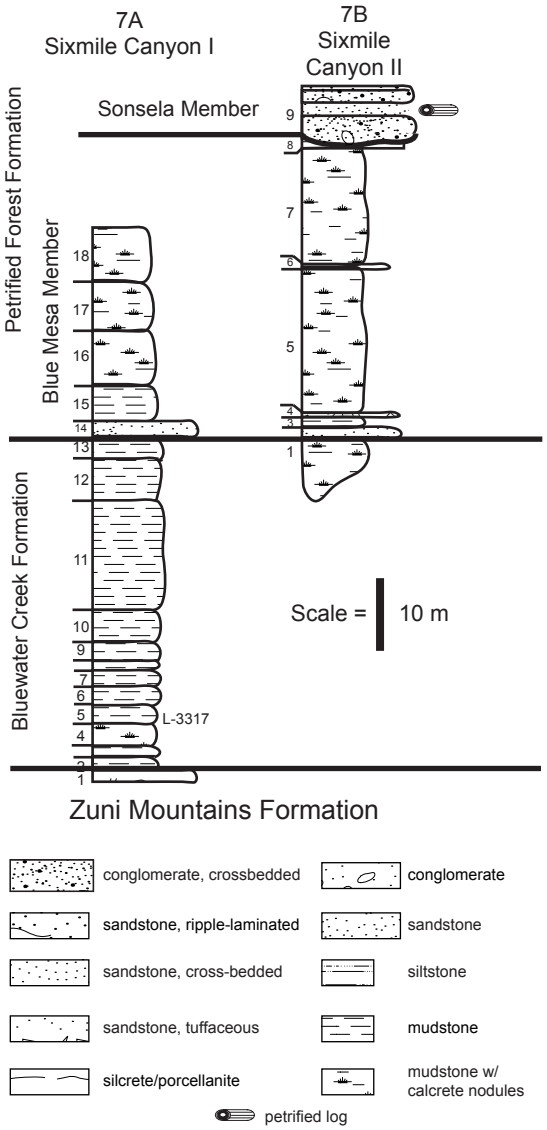

FIGURE 2.11. Stratigraphic section of the lower Chinle Group at Stop 3.

bed floodplain and overbank, low-sinuosity fluvial, and lacustrine deposits, respectively. This outcrop is relatively atypical in that it is almost exclusively the first lithofacies. However, we just drove through extensive outcrops of the third lithofacies (restricted to the bottom of the unit generally), and the second, sandstone-dominated lithofacies is evident just south of this stop where the McGaffey Member pinches out.

Throughout much of the Zuni Mountains the contact of the Petrified Forest Formation and the Bluewater Creek Formation is marked by a white, tuffaceous sandstone of the Blue Mesa Member that rests on

uppermost red-beds of the Bluewater Creek Formation (Figs. 2.6, 2.10-2.11). The upper contact is covered by colluvium here, but Heckert (1997a) measured 44 m of Blue Mesa strata north of here at his Sixmile Canyon II section (Fig. 2.6). The Blue Mesa Member clearly represents predominantly floodplain deposits, and calcrete (siderite) nodules frequently occur in discontinuous horizons, indicating paleosol development.

The top of the Blue Mesa Member is bleached out and irregularly weathered (scoured). Filling these scours are conglomerates and conglomeratic sandstones of the Sonsela Member of the Petrified Forest Formation. Lucas (1993) termed this surface the Tr-4 unconformity, and Heckert and Lucas (1996) documented 20 m of erosion on this surface across the Zuni Mountains. The Sonsela thus represents base-level recovery and the aggradation of channel deposits following this hiatus. Regionally, the Sonsela bears more petrified wood than any other Chinle unit, including the vast majority of the petrified wood at the Petrified Forest National Park (Heckert and Lucas, 1998). Here, in Sixmile Canyon the petrified wood is much less spectacular, but some logs approach 1 m in diameter and several m in length, although they are not as brightly colored as much of the wood in the Petrified Forest National Park. Although the Sonsela may appear inaccessible here, large toreva blocks litter the valley, and several of these preserve thick (0.3-0.5-m-thick) beds of unionid bivalves preserved as a sort of freshwater coquina (Fig. 2.10).

After stop turn around and go back to Forest Road 547. 0.2

33.7 Turn left onto Forest Road 547. **0.2**

33.9 Crest hill with good view of Sonsela on right. View ahead to red rock cliffs of the Entrada Sandstone in the distance. Section on left is Sonsela overlying Blue Mesa Member. **0.8**

34.7 Good view down canyon of red rock cliffs with Entrada Sandstone above Chinle Group strata. Note thick Sonsela cliffs in foreground ahead on left. **0.4**

35.1 Blue Mesa Member next to road on left. **0.6**

35.7 Road curves left; Sonsela just above road level on left. **0.3**

36.0 Sonsela to left with overturned crossbeds (Fig. 2.12). **0.1**

36.1 Road curves left; Sonsela on left with Interstate 40 traffic visible ahead. **0.2**

36.3 Road on top of Sonsela dip slope at cattleguard, looking north into entire Jurassic section up to the Upper Cretaceous Dakota Formation. Section (Fig. 2.13) is Painted Desert Member of Petrified Forest Formation (strike valley), Owl Rock Formation (pinkish bluffs low on far side of valley), Wingate Sandstone (locally exposed below Entrada), Entrada Sandstone (ribbed slopes and massive red cliffs), Todilto, Summerville, and Bluff formations (variegated slopes), overlain by Morrison Formation and capped by Dakota Formation. Here, we leave the Zuni Mounatins to travel along their northern dipslope for the rest of today's trip (Fig. 2.14). **0.1**

36.4 Jurassic section at I-40 in foreground. **0.3**

36.7 Gate and cattleguard. Leave National Forest. Note that the route we just drove through is closed from December 15 to

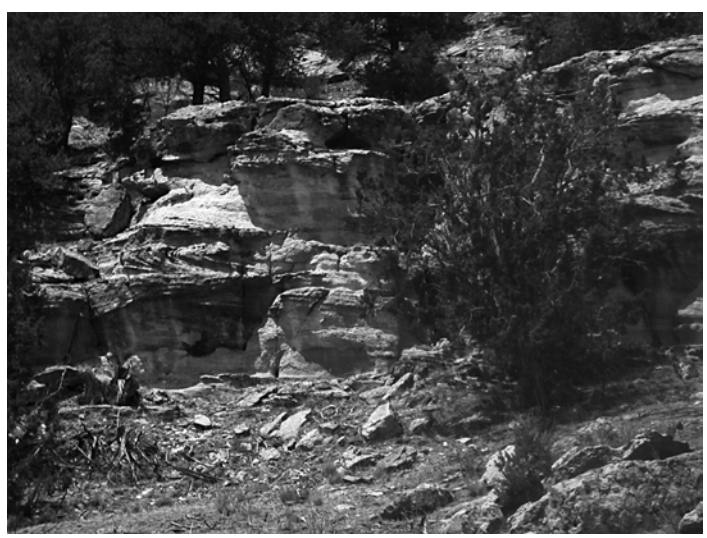

FIGURE 2.12. Sonsela Sandstone at mile 36.0 with overturned crossbeds (in left center of photo).

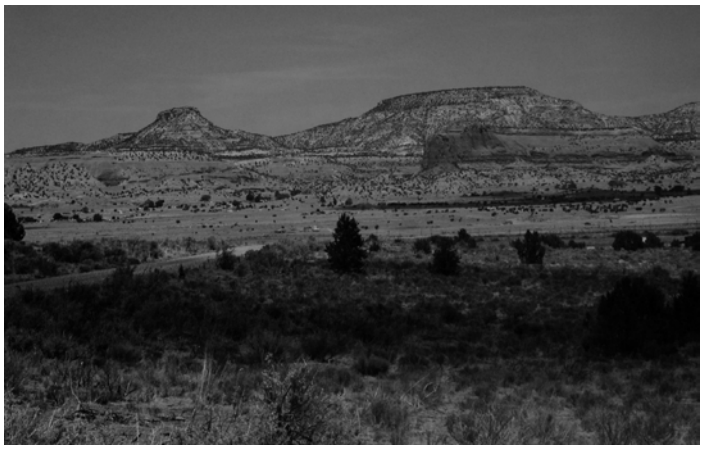

FIGURE 2.13. View north of the Mesozoic section from mile 36.3.

March 31 and is essentially impassable when wet. **0.3**

37.0 Cross major El Paso Natural Gas pipeline. **0.2**

37.2 Road turns hard right. **0.1**

37.3 Cross wash (Sixmile Canyon) at dip in road. **0.3**

37.6 Cattleguard. **0.7**

38.3 Road turns hard right. **0.1**

38.4 **Turn left onto pavement** (Whispering Cedars Road). **0.2**

38.6 Stop sign. Settlement of Ciniza on right. **Turn left** and proceed across Interstate 40 bridge. Ciniza derives its name from the Spanish word for ash, "ceniza," and is now the site of the Giant Industries oil refinery and one of the nation's largest truck stops. **0.1**

38.7 **Turn left onto Interstate 40 westbound. 0.2**

38.9 **Merge left** on I-40 westbound. **1.0**

39.9 Bridge over Sixmile Canyon. **0.8**

40.7 Midget Mesa and Mesa Butte on skyline to north. **0.9**

41.6 Exit 36 to Iyanbito--from the Diné 'Ayání bito': Buffalo Springs (Young and Morgan, 1987). 'Ayání, buffalo, literally means "the one that is always grazing." (Julyan, 1996). Type "Iyanbito Member of Entrada" (actually Wingate Sandstone) to right. **0.7**

42.3 Sonsela dipslope on left. **0.5**

42.8 Cuesta to right is developed in the Perea Bed of the Painted Desert Member of the Petrified Forest Formation. This is the type area of the Perea Bed (Cooley, 1957; Lucas et al., 1997b), discussed in the accompanying minipaper. **0.9**

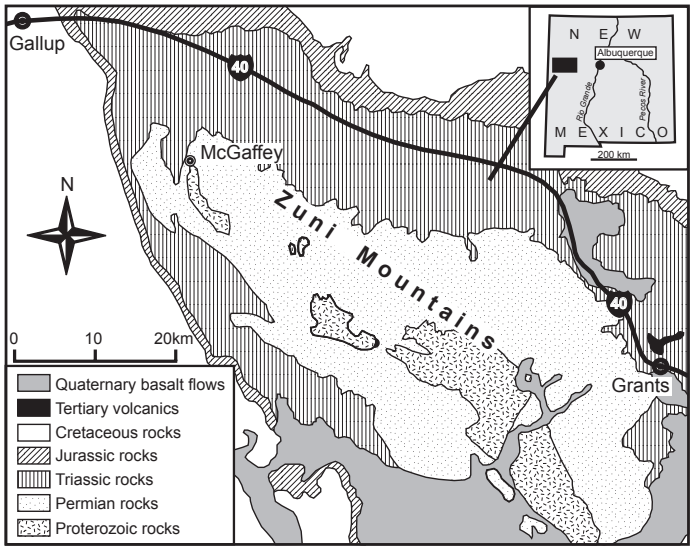

FIGURE 2.14. Simplified geologic map of the Zuni Mountains (courtesy of Karl Krainer).

THE UPPER TRIASSIC PEREA SANDSTONE BED (PETRIFIED FOREST FORMATION, PAINTED DESERT MEMBER) IN THE ZUNI MOUNTAINS

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Historically, many workers have refused to even attempt to correlate units within larger "red-bed" lithosomes such as the Chinle Group, arguing that fluvial facies are too ephemeral and laterally discontinuous to correlate across long distances. A more enlightened understanding of lithostratigraphy and sedimentation, however, recognizes that in a vast depositional system such as the Chinle basin, laterally persistent facies yield important information regarding sedimentation and base-level change, often at a regional level. Thus, Gregory (1917) was well ahead of his time when he correctly subdivided the Upper Triassic Chinle Formation into four regional subdivisions, his A, B, C, and D (in descending order). During the uranium boom of the 1950s, many other geologists made significant contributions to our understanding of Chinle lithostratigraphy, especially Cooley (1957) and Akers et al. (1958), who would further refine interval "C," the Petrified Forest Formation of current usage. Here, we build upon this work to develop a greater understanding of the Painted Desert Member of the Petrified Forest Formation.

After Akers et al. (1958) recognized the Sonsela Member (Sonsela Sandstone or Bed of their usage), the Petrified Forest Forma-

tion was informally divided into "upper" and "lower" members, and this usage persisted for more than 30 years (e.g., Stewart et al., 1972a; Lucas and Hayden, 1989). Lucas (1993) elevated the Chinle to group status, concomitantly raising members to formation rank and beds to member rank. Thus, Lucas (1993) divided the Petrified Forest Formation into the (ascending order) Blue Mesa, Sonsela and Painted Desert members. When Lucas et al. (1997a) reinvestigated the Triassic stratigraphy around Fort Wingate they identified the Perea Bed of Cooley (1957) as a valid lithostratigraphic unit in the Painted Desert Member, and designated unit 12 of Stewart et al.'s (1972a) NM-3b section as the type section (Fig. 2.15). Cooley, himself, did not actually measure the Perea near the type area, and instead relied on descriptions provided to him by J.W. Harshbarger (Cooley, 1957, p. 108).

The type section of the Perea Bed is part of a persistent cuesta arcing around the northern flanks of the Chinle outcrop belt on the Fort Wingate Army Depot. Perea itself is an abandoned railway station just north of I-40 approximately 10 mi (6 km) to the east. The name Perea is an old New Mexican family name (Julyan, 1996). Stewart et al. (1972a) documented 7 m of Perea Bed strata at the type section, and Lucas et al. (1997a) measured 4 m at another section on the Fort Wingate Army Depot. Exposed Perea strata within view of Interestate 40 are typically 4 to 8 m thick.

Regionally, there are many persistent sandstones in the Painted Desert Member. Cooley (1957) recognized several in the Petrified Forest National Park itself, named two in New Mexico (Perea and Taaiylone sandstones) and two more in Arizona outside the Petrified Forest (Chambers and Zuni River sandstones), each in a distinct outcrop belt. Laterally persistent planar-crossbedded sandstones crop out at multiple stratigraphic levels within the Petrified Forest National Park and have been referred to as "Flattops" and "Painted Desert" sandstones (Billingsley, 1985a,b; Ash, 1987) and are now formalized as Flattops and Lithodendron Wash beds (Heckert and Lucas, 2002b). These sandstones typically occur in the lower half of the Painted Desert Member and are much less common at higher stratigraphic levels. Presently, our biostratigraphic database is unable to support more detailed correlations in this interval. However, the lithologic similarity of some of these beds and their apparent homotaxial position in the lower 100 m of the Painted Desert Member suggests that at least some of them may be correlative. Specifically, the Perea Bed likely correlates to the Taaiylone bed in the south near Zuni Pueblo and to the Flattops Bed 2 and Lithodendron Wash beds in the Petrified Forest National Park (Heckert and Lucas, 2002b). The Perea may also be equivalent to Cooley's (1957) Chambers and Zuni River sandstones, but we have not reexamined those strata to the same level of detail. On an even broader scale, a similar sandstone (Saladito Point Bed) crops out low in the homotaxial Bull Canyon Formation in east-central New Mexico (Lucas et al., 2001). These strata are all stratigraphically lower than the lithologically similar Correo Bed, a persistent sandstone high in the Painted Desert that crops out throughout central New Mexico (e.g., Lucas and Hayden, 1989; Lucas and Heckert, 1994; Lucas et al., 1999).

Locally, the base of the Perea exhibits little (~1 m) stratigraphic relief. Presently we are unable to determine if there is greater stratigraphic relief on a more regional scale. The upper contact of

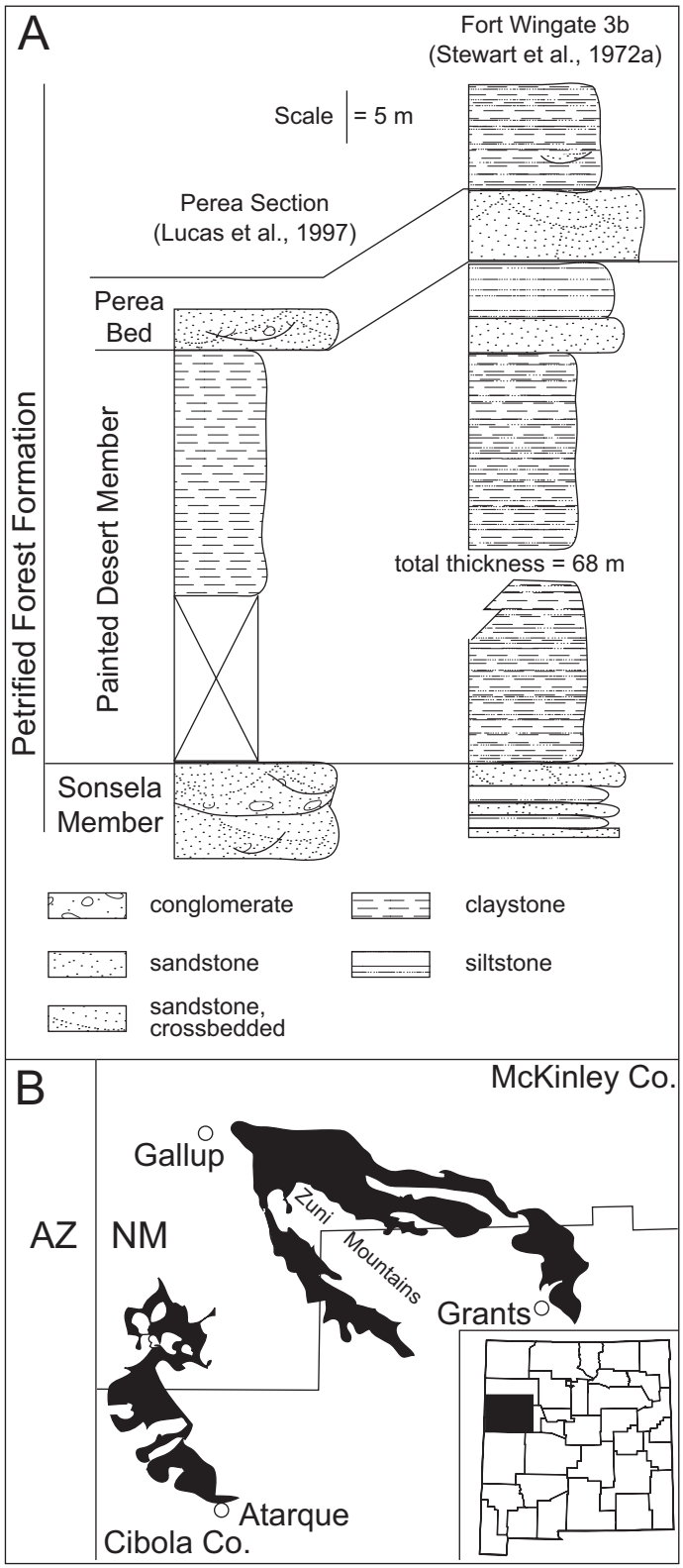

FIGURE 2.15. Measured sections of the Perea Bed of the Painted Desert Member of the Petrified Forest Formation.

the Perea Bed is, like many Chinle sand bodies, difficult to determine, as the contact is usually covered at the base of a dip slope. These sandstones appear to grade upward into the overlying mudstone-dominated interval. Perea strata are never very thick, and typical sections are only 5-10 m. The maximum thickness we have observed is approximately 12 m. Locally, the bed may pinch out.

The Perea Bed typically consists of fine- to medium-grained sublitharenites that are banded reddish brown and pale green. Conglomerates are relatively uncommon in the Perea Bed and are generally restricted to mudstone and calcrete rip-ups < 2 cm in diameter flooring individual crossbed sets. There are both planar- and trough crossbed sets in the Perea. Planar crossbeds, however, predominate, and are lithologically similar to those of the Painted Desert Member studied by Espegren (1985). The predominance of planar crossbedding suggests that a high-sinuosity fluvial system was responsible for Perea Bed deposition.

To date we have not recovered any fossils from the Perea Bed, although Stewart et al. (1972a) reported some unidentifiable bone fragments from the Perea Bed at the type section. Similar beds in the Petrified Forest National Park yield abundant unionid bivalves, but these fossils are not age-diagnostic within the Late Triassic.

We initially formalized the Perea Bed because we saw it as a useful mapping unit present on the Fort Wingate, Church Rock and Pinedale 7.5-minute quadrangles. However, reconnaissance for this guidebook revealed several additional outcrops that extend the known distribution of the Perea Bed eastward to the vicinity of Prewitt. Cooley (1957) thought that sandstone beds in the eastern portion of the Zuni Mountains might pertain to the Correo, but we note that their stratigraphic position is much more similar to that of the Perea than the Correo, so we assign them to the Perea Bed. Thus, the Perea has almost 25 mi (40 km) of strike between Gallup and Grants.

The prevalence of widespread, persistent sand bodies in the lower Painted Desert Member is an interesting phenomenon. Even if these sand bodies are not, strictly speaking, correlative, their nearly homotaxial position suggests that, early in Painted Desert time, depositional circumstances favored the widespread aggradation of sand bodies. Whether this apparent change in base level is a reflection of local, regional, or global conditions is unclear. The stratigraphically lower Sonsela Member clearly reflects base level rise following an interval of erosion and non-deposition that we suspect was driven by eustasy (Lucas, 1993, 1997; Heckert and Lucas, 1996). Whether or not the Perea Bed and its apparent correlatives represent a lower-amplitude change in base level is not clear, but possible.

To date, the Perea Bed has not held any economic significance. However, Native Americans from the Pueblo II-III periods (AD ~900-1250; Schutt, 1997) utilized the Perea both for building materials and as an elevated area above the mudstone-dominated strike valleys in the vicinity of the Fort Wingate Army Depot.

43.7 Sign for exit 33 to McGaffey. **0.6**

44.3 Roadcuts of the Perea Bed. **0.3**

44.6 **Turn right**, taking exit 33 to McGaffey. **0.2**

44.8 Stop sign. **Turn left** onto NM Highway 118 (old US Highway 66) and continue west on frontage road. **0.2**

45.0 Junction with NM-400 to left; continue straight on NM-118. **0.2**

45.2 Fort Wingate historical marker on right. **2.4**

47.6 Road to Fort Wingate Army Depot to left; continue straight. **0.5**

48.1 Cross railroad tracks. **0.1**

48.2 Cross second set of railroad tracks leading to depot. **0.7**

48.9 Owl Rock outcrop on right; see accompanying minipaper. **0.1**

DEPOSITION OF THE UPPER TRIASSIC OWL ROCK FORMATION, WEST-CENTRAL NEW MEXICO

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One of the most distinctive units of the Upper Triassic Chinle Group is the Owl Rock Formation, as much as 150 m of red-bed siltstone, sandstone and mudstone interbedded with laterally persistent limestone beds exposed on the southern Colorado Plateau. These limestones provided the primary basis for some workers (especially Blakey and Gubitosa, 1983; Dubiel, 1989a, b) to conclude that the Owl Rock Formation was deposited in an extensive lake. Dubiel (1989a) even suggested that subsidence along the "Zuni lineament" created the lake basin, and that the Rock Point Formation, which overlies the Owl Rock, represents the shoreline and landward facies that eventually prograded over the lake as it disappeared.

Lucas and Anderson (1993), however, pointed out that most Owl Rock limestone beds appear to be pedogenic calcretes, not lacustrine carbonates. Features indicative of pedogenesis in these limestones include great lateral persistence and thickness (up to 4 m thick), extreme induration, tabular to platy structure, pisolitic and multilaminar internal fabrics, common secondary silica and zones of dissolution, brecciation and recementation. Many vertical, tube-like structures in the Owl Rock limestones claimed to be lungfish burrows (e.g., Dubiel, 1989a, b) are actually rhizoliths (Tanner, 2002). Most Owl Rock limestones thus represent stage III to stage VI calcretes (Gile et al., 1966; Bachman and Machette, 1977) according to Lucas and Anderson (1993).

A more detailed analysis of Owl Rock deposition by Tanner (2002) further undermined the model of Owl Rock deposition in a large lake. Instead, Tanner (2002) concluded that Owl Rock deposition took place in a low-gradient floodbasin during a period of increasing aridity. Owl Rock limestones are pedogenic calcretes or palustrine-lacustrine limestones formed in ponds and ephem-

eral lakes that developed in topographic lows on the floodplain.

Significantly, the Owl Rock Formation lacks a fossil assemblage of a lacustrine macrofauna; indeed, few body fossils are known from Owl Rock limestones. In Moenkopi Wash, Arizona, Kirby (1989, 1991, 1993) reported a tetrapod fauna from clastic rocks in the Owl Rock Formation that is essentially identical to that of the underlying Painted Desert Member of the Petrified Forest Formation. This fauna includes the phytosaur *Pseudopalatus* and the aetosaur *Typothorax coccinarum*, both of which indicate a Revueltian (early-mid Norian) age (Lucas, 1998).

The excellent outcrop of the Owl Rock Formation in the roadcut of the I-40 frontage road just south of Red Rock Park (Fig. 2.16) was key to the conclusions of both Lucas and Anderson (1993) and Tanner (2002). The roadcut exposes ~ 8 m of Owl Rock strata that include four laterally persistent limestone beds. These beds display many of the classic diagnostic features of pedogenic calcretes, including uneven bedding, brecciation, pisolites, concentrically zoned silica replacement and a general lack of primary laminae.

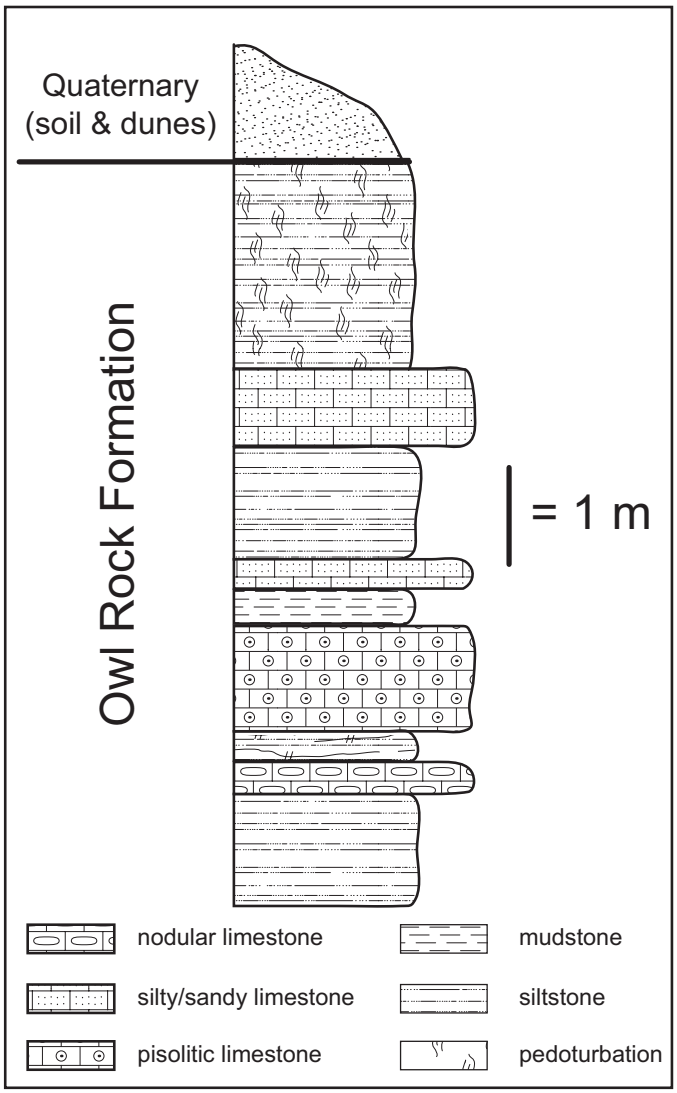

FIGURE 2.16. Measured section of Owl Rock Formation at mile 48.9.

49.0 **Turn right** on NM Highway 566, paved road to Red Rock Park. **0.1**

49.1 Bridge over railroad tracks. **0.2**

49.3 Enter village of Church Rock (population 1077 by the 2000 census; post office from 1952); chapter house on right. Church Rock, also known as Navajo Church, has long been a local landmark, even appearing on Marcou's (1858) geological map of New Mexico. Dutton (1885, fig. 12) provided a wonderful illustration of Church Rock (Fig. 2.17), noting that the rocks "are the upper members of the Jura-Trias, and strongly cross-bedded." Some Diné people referred to it as Tsé'íí'ahi, Standing Rock (Van Valkenburgh, 1941); not to be confused with the community of the same name farther north. **0.2**

49.5 **Turn left into Red Rock Park**. The park, which covers one square mile, includes

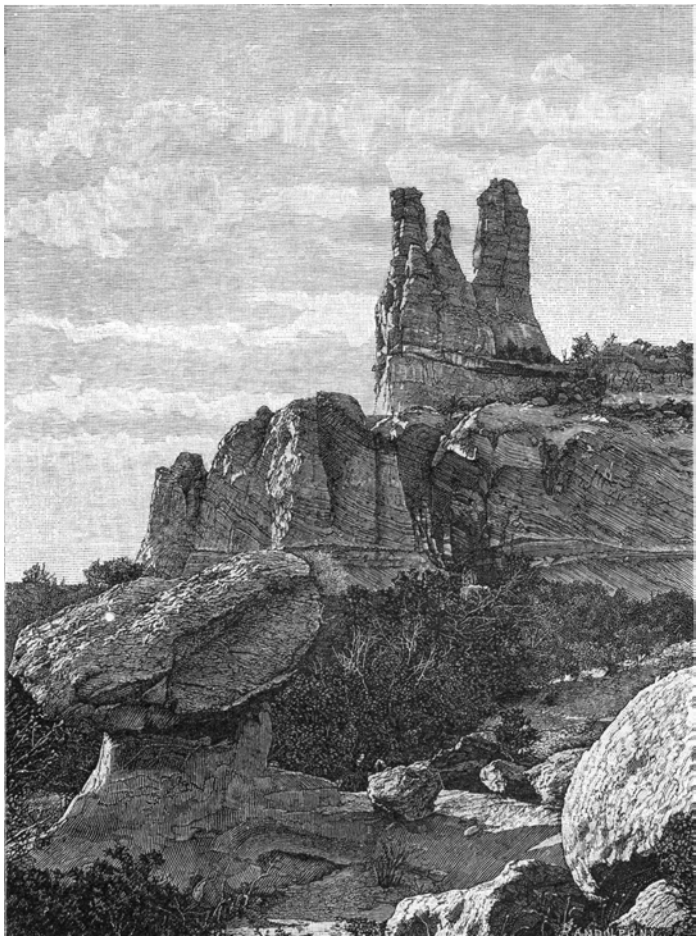

FIGURE 2.17. Dutton's (1885, fig. 12) illustration of Navajo Church.

a large arena seating 8000, an exhibition hall and arts and crafts pavilion, a convention center, auditorium, campground, and information center (see accompanying minipaper by McLemore). **0.2**

RED ROCK PARK

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Red Rock Park takes its name from the spectacular red sandstone cliffs surrounding the impressive array of public facilities, including a rodeo arena, convention center, museum, and camp grounds. The 640-acre park offers excellent scenery for balloonists, hikers, campers, and other visitors. Red Rock Park opened in 1972 as a state park at a cost of $6 million (McLemore, 1989), but in 1989 the park was turned over to the Navajo Nation.

The main attraction in Red Rock Park is an 8000-seat outdoor arena used for various events ranging from rodeos to Motocross competitions to outdoor concerts. Some 25 rodeos and numerous Native American dances are held from June until mid-November. The Inter-Tribal Indian Ceremonial and All-Indian Rodeo are held at the arena every year in August. The Lions Club rodeo in June is one of the state's finest. The Red Rock Balloon Rally in December attracts balloonists from all over the world.

Additional public facilities at the park include the Red Rock Convention Center, which can accommodate conventions, meetings, concerts, shows, weddings, and private parties. The outdoor plaza area can be used for barbecues, square dances, and trade shows. A restaurant is open on a seasonal basis and for special events. The Inter-Tribal Indian offices are housed at the convention center.

At the Red Rock Museum, visitors throughout the year can view exhibits and displays depicting the history and culture of local and regional Native American tribes, including Navajo, Rio Grande Pueblo, Zuni, Acoma, Hopi, and Plains Indians. Pottery, rugs, crafts, and paintings are on display. The museum includes a collection of Zuni Kachina dolls. Another exhibit is dedicated to the Navajo code talkers, who served as Marine Corps communication specialists during World War II (Brown, 1977). Eventually, 420 Navajos served in the group, and their code was the only one never broken by the Japanese (Paul, 1973). The museum features an art gallery where paintings by local and national artists are periodically displayed. Wild flower gardens just outside the museum offer colorful glimpses of the desert vegetation. Corn, beans, and squash are grown during the summer in a Pueblo "waffle garden," the traditional method of agriculture in the area.

Two campgrounds offer campers modern conveniences, including restrooms with showers, picnic tables, electrical and water hookups, and a sanitary dump station. Stables for boarding horses also are available. The main campground features the Outlaw Trading Post, a log cabin built in 1888 and now used as a general store, laundry, U.S. Post Office, and information center for camping arrangements and listings of daily events. Picnic areas and a playground are located at the main campground. Hiking along the one-mile nature trail north of the Outlaw Trading Post takes the visitor into undeveloped portions of the park.

Jurassic and Quaternary rocks are exposed in Red Rock Park, and Triassic rocks are seen from the park (Fig. 2.18). The oldest and most prominent rocks within Red Rock Park are the red sandstones of the Upper Triassic Wingate Sandstone and the Jurassic Entrada Sandstone. The spectacular massive cliffs forming the background for the public facilities in the park belong mostly to the Entrada. The Entrada Sandstone is divided into two members: Dewey Bridge Member and overlying Slick Rock Member. The Dewey Bridge Member consists of 40–60 ft of reddish-brown to reddish-orange silty sandstone and siltstone that form slopes at the base of the massive cliffs. The Slick Rock Member forms the spectacular cliffs and consists of 100–400 ft of reddish-orange,

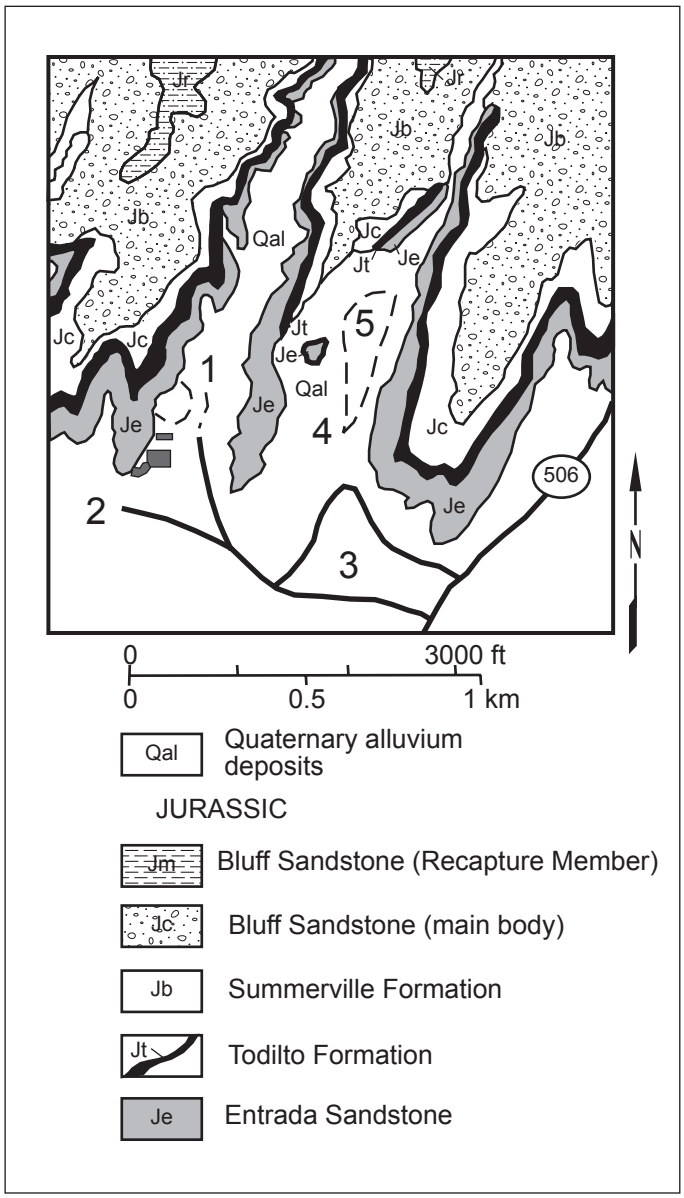

FIGURE 2.18. Geologic map of Red Rock Park.

well-cemented, thick-bedded, well-rounded sandstones, typical of ancient sand dunes. High-angle crossbeds or layers are seen in the sandstone. The sand dunes were cemented by silica and calcite from ground water and compacted to form the massive rock cliffs seen today.

The Jurassic Todilto and Summerville formations overlie the Entrada Sandstone. The Todilto Formation is the older unit and forms a thin, white to gray, resistant cap on top of the Entrada Sandstone. It consists of as much as 10 ft of fine-grained limestone that was deposited in a saline lake. Overlying the Todilto are slopes of interbedded white, pink, and reddish-brown sandstone, siltstone, and shale belonging to the Summerville Formation. The Summerville Formation is locally as much as 50 ft thick and was deposited in a shallow-water coastal plain.

The Jurassic Bluff Sandstone overlies the Summerville Formation and consists of 190 ft of green-gray to pink, well-cemented sandstone (Green and Jackson, 1975). The lower, main body, was deposited in an arid environment as sand dunes (Condon and Peterson, 1986). The overlying Recapture Member consists of 100 ft of reddish-brown to brick-red siltstone interbedded with white to green to yellow sandstone (Green and Jackson, 1975). The Recapture Member is well exposed at the base of Navajo Church, seen from the Outlaw Trading Post. The Recapture Member was deposited in both fluvial and eolian, sand-dune environments. The overlying Acoma Tongue of the Zuni Sandstone is the prominent eolian sandstone with east-dipping crossbeds at the base of Church Rock (Anderson, 1993).

The Jurassic Morrison Formation overlies the Acoma Tongue and consists of two members: Salt Wash and overlying Brushy Basin members. The Salt Wash Member is not exposed within the park boundaries, but it is visible on some of the mesas north of the park and at the top of Navajo Church. This unit consists of 130–230 ft of red to orange sandstone with thin lenses of siltstone and shale (Green and Jackson, 1975). It was deposited in a fluvial environment and is host to most of the uranium resources in the Gallup-Grants area.

The Brushy Basin Member also is not exposed within the park boundaries but crops out north of the park (Green and Jackson, 1975). It consists of green to purple to gray shale, siltstone, and sandstone.

The rocks were subsequently eroded, mainly by wind and rain, to form mesas and spires such as Navajo Church. Erosion of the rock continues today and contributes to Quaternary alluvium and unconsolidated wind-blown (eolian) sand and silt deposits in the park.

49.7 **Turn right** onto one-way "post office" road. **0.2**

49.9 **Go to right** around post office, following signs to hiking trail. **0.1**

50.0 **STOP 4.** Church Rock Post Office, trading post, and Red Rock nature trail parking lot.

At this stop we see the bold, red cliffs of the Entrada Sandstone in the vicinity of Red Rock Park. The valley here, on which the Interstate highway and railroad are built, is formed in the thick, nonresistant Chinle Group, which directly underlies the Entrada. The Wingate/Entrada contact, mostly covered here, is the J-2 unconformity.

The Church Rock trail takes us up through the Slick Rock Member of the Entrada Sandstone to closely examine the Todilto, Summerville, and Bluff formations (Figs. 2.19-2.20). Key features to note are: (1) the Todilto Formation is thin-bedded kerogenic limestone that forms a single ledge (bed) typically about 1 m thick; (2) the Summerville Formation here is very thin, about 1.5-4.0 m thick and generally poorly exposed; (3) the Summerville consists of water-laid siltstones and sandstones and shows much evidence of soft-sediment deformation; (4) the Bluff Sandstone is strikingly different from the Entrada Sandstone: Entrada bedforms are dominantly large-scale trough crossbeds

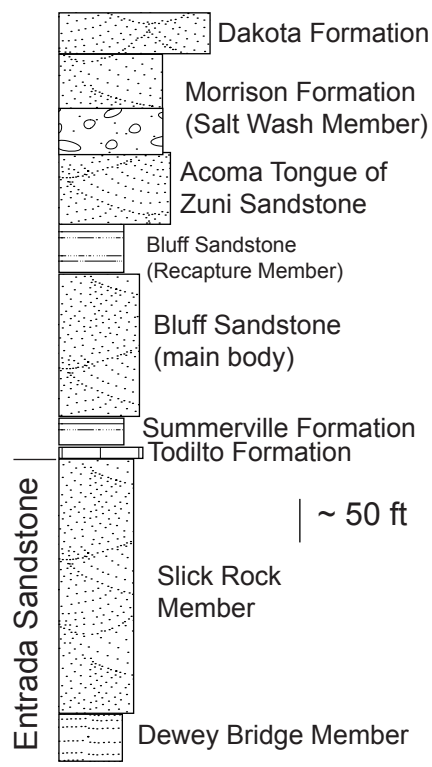

FIGURE 2.19. Schematic Jurassic stratigraphic section on Church Rock trail.

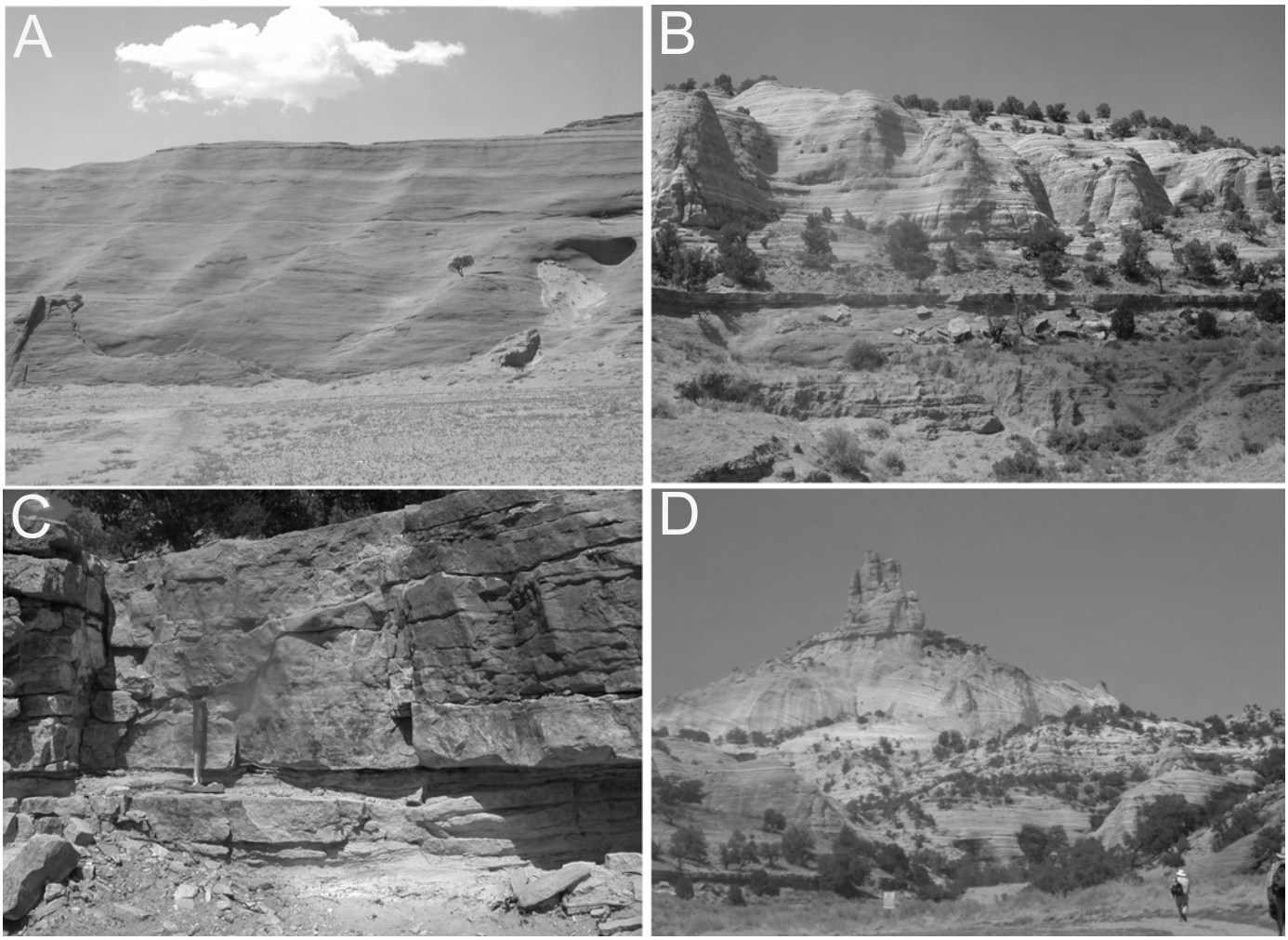

FIGURE 2.20. Photos of Jurassic outcrops on Church Rock trail. A, Crossbedded Slick Rock Member of Entrada Sandstone. B, Section Entrada-Todilto-Bluff. C, Closeup of Todilto Formation. D, Prominent Acoma Tongue of Zuni Sandstone is the crossbedded unit at the base of Church Rock.

indicative of eolian duneforms, whereas Bluff bedforms are mostly horizontal laminae in thick sets, characteristic of eolian sheet sands; (5) lower Bluff sets are broken by rhizolith horizons suggestive of a "wet" eolian system; (6) the Bluff consists of two members, a lower interval of eolian sandstone (main body) overlain by red-bed siltstone and sandstone (Recapture Member); and (7) above the Bluff is a prominent eolianite with easterly-dipping crossbeds, the Acoma Tongue of the Zuni Sandstone (Anderson, 1993).

How the red, cliff-forming, eolian sandstone here came to be called Entrada is an interesting (and confusing) story. It was originally named the Wingate Sandstone by Dutton (1885), who thought it to be of Triassic age. Stratigraphic work continued in the Colorado Plateau during the 43 years following the Wingate naming, especially in Arizona and Utah by U.S. Geological Survey geologists. In the San Rafael Swell of Utah, several groups of geologists found a red, cliff-forming, eolian sandstone unconformably overlying the Chinle Group and assumed it to be the Wingate Sandstone, as in New Mexico. They also found two other similar eolian sandstones higher in the stratigraphic column. The next higher was named Navajo Sandstone from Navajo County, Arizona, by Gregory (1915). The next sandstone above that was named Entrada Sandstone by Gilluly and

Reeside (1928), from Entrada Point in the northern San Rafael Swell, Utah. Later, Heaton (1939) correlated the Entrada of Utah through Colorado into New Mexico, where it could be traced to near the type Wingate at Fort Wingate. Baker et al. (1947) recognized that the type Wingate in New Mexico was, indeed, what had been later named Entrada in Utah, contradicting their earlier correlation (Baker et al, 1936). They proposed to solve this problem by acknowledging that the names Wingate and Entrada had been widely used for many years, and, rather than correct the miscorrelation and follow priority, recommended that the Wingate Sandstone at Fort Wingate, New Mexico and its lateral equivalents be called Entrada. They also recommended that the misidentified Wingate Sandstone of Utah and its lateral equivalents be called Wingate, although they recommended abandoning the Wingate type locality in New Mexico because the type Wingate was now called Entrada! Their recommendations have been generally followed since 1947. So, after 62 years of these red cliffs before you being the legally designated stratotype of the Wingate Sandstone, they have been called Entrada Sandstone for the last 55 years, and the Wingate Sandstone has no real stratotype! This story is perhaps the most spectacular stratigraphic nomenclature foul-up due to miscorrelation in the U.S., all courtesy of the U. S. Geological Survey.

After stop retrace route to NM-566. 0.2

CLARENCE DUTTON

Spencer G. Lucas
New Mexico Museum of Natural History, 1801 Mountain Road N.W.
Albuquerque, New Mexico 87104

Clarence Edward Dutton (1841-1912) (Fig. 2.21) was born in Wallingford, Connecticut and graduated from Yale College in 1860. He then entered the Yale theological seminary, but the Civil War interrupted his studies when, in 1862, he joined the 21st Connecticut Volunteers and was commissioned as a second lieutenant. During the war, Dutton served at Fredericksburg, Suffolk, Nashville and Petersburg. After the Civil War, he remained in the army and ultimately advanced to the rank of major. Dutton began to study iron technology and geology in 1865, and in 1875 he began service in Major John Wesley Powell's surveys of the Rocky Mountain region, working especially on the high plateaus of central Utah and in the Grand Canyon country of northern Arizona.

Dutton's writings about this work indicate his clear interest in volcanology and seismology, and in 1882 he was able to study volcanic phenomena in the Hawaiian islands. In 1884, Dutton worked in west-central New Mexico and paid particular attention to the monoclinal flexures near Gallup and the volcanic rocks of the Mt. Taylor region.

Dutton subsequently worked in the coastal ranges of California, Oregon and Washington, and he also studied the Charleston, South Carolina earthquake of 1886. Elected to membership in the National Academy of Sciences in 1884, Dutton is most famous today for coining the term isostasy to express the idea that the crust is floating on a very plastic or liquid substratum. Indeed, this concept was a major contribution by Dutton to the late nineteenth century debate over global tectonics, most of which focused on the contraction of the planet as an underlying mecha-

FIGURE 2.21. Portrait of Clarence E. Dutton (from Merrill, 1924).

nism (Greene, 1982). Dutton's work on the Colorado Plateau was instrumental to the isostasy concept, as it was clear the Plateau had been significantly uplifted (largely, Dutton believed, because of the removal by Cenozoic erosion of thousands of cubic kilometers of sediment) without being laterally compressed, as was the case with many mountain ranges.

Dutton's 1884 work in west-central New Mexico was published in 1885 as an 85-page-long, illustrated article in the Sixth Annual Report of John Wesley Powell's young U. S. Geological Survey. It provided the first detailed description of the geology of west-central New Mexico and included: (1) a geologic map at a scale of 1:640,000 (pl. 14); (2) a series of structural cross sections through the map (pl. 18); (3) a composite stratigraphic section of the entire rock column exposed from the Zuni Mountains to the Chuska Mountains (pl. 16); and (4) a series of remarkable woodcut ("photographed on wood and engraved") images of outcrops and other geological features of west-central New Mexico (pls. 20-22, figs. 1-4, 6, 8-13, 17-25). Dutton's report thus stands as one of the first detailed studies of regional geology in New Mexico, and this classic work is the real beginning of our knowledge of the geology of the west-central portion of the state.

50.3 Stop sign; **turn left. 0.2**

50.5 Stop sign; **turn left** onto NM-566 northbound. **0.1**

50.6 Road comes in from right. Contact between Dewey Bridge and Slick Rock members of the Entrada Sandstone (white line) on left. **0.5**

51.1 Outstanding exposures of crossbeds in the Slick Rock Member on left. Note generally southwesterly dip of most Entrada crossbeds (Fig. 2.22). **0.2**

51.3 Gray limestone on left is Todilto Formation. **0.1**

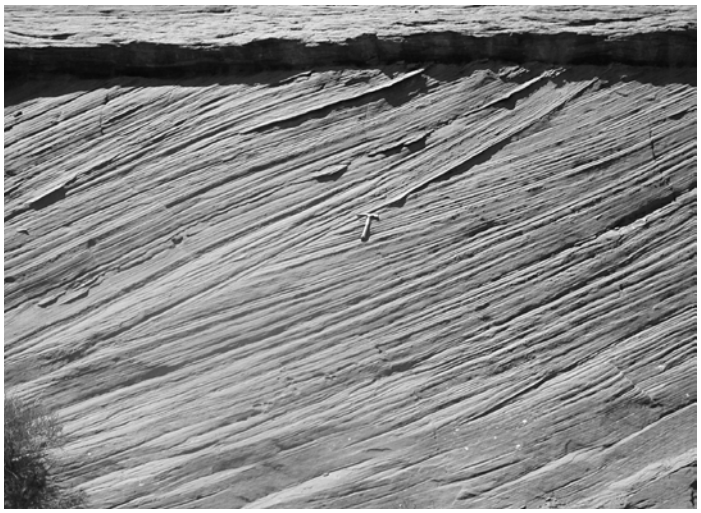

FIGURE 2.22. Southwest-dipping Entrada crossbeds at mile 51.1.

51.4 Microfaults in Bluff briefly visible high above road to left. Middle Jurassic Todilto Formation is thin limestone above well-exposed crossbeds of the Entrada Sandstone. Microfault horizon also contains sandstone pipes, generally small. **0.1**

51.5 Entrada-Todilto contact at about road level left; Bluff Sandstone outcrops overlie the Todilto. When present in this area, the Summerville Formation is a very thin (<10 ft) series of water-laid sandstones and siltstones between the Todilto and Bluff. Road continues north through Bluff Sandstone. **0.3**

51.8 Sandstone pipes in the Bluff Sandstone on left with more microfaults. **0.3**

52.1 Contact between main body of Bluff Sandstone (below) and Recapture Member of Bluff (above) on left. **0.2**

52.3 Contact between red Recapture Member and gray-green Acoma Tongue of the Zuni Sandstone on right. **0.3**

52.6 At crest of hill note inset alluvium on right; Church Rock at 9:00. White Mesa ahead at 10:00. **0.1**

52.7 Excellent exposure of Acoma Tongue on right with crossbeds. Note southeast-dipping foresets. **0.4**

53.1 **Turn left** on McKinley County Road 43 (weathered sign is barely legible). Note Acoma Tongue-Morrison contact on right before turn. **0.3**

53.4 Steeply inclined southeast-dipping foresets characteristic of the Acoma Tongue on right. At first glance this outcrop appears to be a slump, but the crossbeds are at their original attitude. **0.3**

53.7 **STOP 5.** Here, we will examine strata of the Upper Cretaceous (Cenomanian) Dakota Sandstone deposited in an incised valley in the Salt Wash Member of Morrison Formation at the west end of White Rock Mesa (Fig. 2.23). After Jurassic fluvial deposition ceased here, no sediment accumulated (or was preserved) for ~50 million years. Then, early in Late Cretaceous (Cenomanian) time, the West-

ern Interior seaway transgressed through west-central New Mexico, and the marginal marine to shallow marine Dakota sandstone was deposited. Here, we see a striking example of the Dakota-Morrison unconformity in the form of a well exposed, incised valley fill.

Note the bleached white color of the Salt Wash sandstones below the carbonaceous Dakota to the east on White Rock Mesa. The valley fill is in the part of the Dakota known as the Dakota main body. Additional valley fills and channel fills may be seen in the Dakota main body and the overlying Paguate Member of the Dakota to the east along the Second Canyon Road. Note that the Cretaceous section to the north above the marine Twowells Sandstone Tongue of the Dakota Sandstone is the lower tongue of the Mancos Shale in the valley overlain by Gallup Sandstone with interbedded Tocito Sandstone, which forms Nose Rock Point Mesa on the skyline.

After stop turn around and retrace route to highway 566. 0.6

54.3 Stop sign at intersection with NM-566. Acoma Tongue-Morrison contact ahead with brown fluvial sandstone on eolian sandstone. **Turn right** to retrace route to Interstate 40 frontage. Enjoy driving through the entire Jurassic section yet again! **0.5**

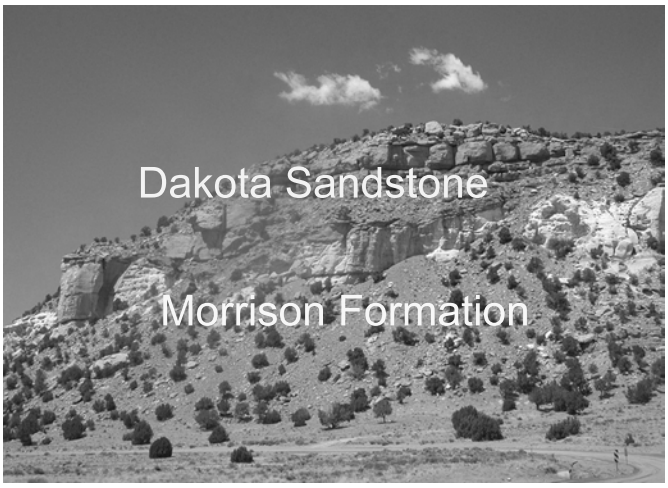

FIGURE 2.23. Incised valley in Morrison Formation filled with Dakota Sandstone at Stop 5.

54.8 Alluvium on left cut into Acoma Tongue. **0.3**

55.1 Acoma Tongue-Recapture Member contact on left. **0.1**

55.2 Recapture Member-Bluff Sandstone contact on right. **0.7**

55.9 Summerville Formation-Todilto Formation-Entrada contacts on right. **0.8**

56.7 Contact between Slick Rock and Dewey Bridge members of Entrada on right. **0.7**

57.4 Stop sign. Owl Rock Formation ahead with thick alluvial fill overlying it. **Turn left** on old U.S. 66 frontage road (NM-118). Owl Rock Formation on left (see minipaper at mile 48.9). Retrace route to McGaffey exit. 0.7

58.1 Cross railroad tracks. 0.1

58.2 Cross second set of railroad tracks. **0.6**

58.8 Entrance to Fort Wingate Army Depot on right. **2.3**

61.1 Historical marker on left for Fort Wingate. Note that cliffs to left are the section we just examined (Jurassic strata and Dakota Formation). **0.2**

61.3 **Turn right** onto NM-400, cross bridge, and prepare to turn left to go east on Interstate 40. **0.2**

61.5 **Turn left** onto Interstate 40 eastbound entry ramp. **0.2**

61.7 **Merge left** onto Interstate 40 eastbound. **0.2**

61.9 Perea Bed outcrops along highway roadcuts. **2.8**

64.7 Pass under bridge. Exit 36 to Iyanbito. **1.8**

66.5 Paralleling Sixmile Canyon road. Note bluffs to north, with a section from the upper Chinle to the Entrada. **1.0**

67.5 Exit 39 to Ciniza. Giant Truck Stop and refinery on left. **0.7**

68.2 We are driving obliquely up and across the Sonsela dipslope as we ascend toward Continental Divide. **0.7**

68.9 Cross Fourmile Canyon with good Sonsela outcrops. **1.7**

70.6 Cross Smith Canyon, also developed in

the Sonsela, with good view to left down into Painted Desert section. **0.9**

71.5 Cross Foster Canyon. Note flexure in Entrada to north. Rimrock to east of flexure is Cretaceous Dakota Formation. **1.0**

72.5 Exit 44 to Coolidge, historically the shipping point for Fort Wingate troops and infamous for its 14 rough-and-tumble saloons. Later came a guest ranch frequented by artists and ethnologists (Van Valkenburgh, 1941). **1.5**

74.0 Just before the continental divide, the peak topped with radio towers at 10:00 is Mount Powell, a Tertiary diabase intrusion above a lower tongue of the Cretaceous Mancos Shale and a complete Dakota Formation section, including the Paguate Member, which forms the rimrock. Mount Powell (K-Ar age = 32.7 $\pm$ 1.2 Ma: Robertson, 1990) may be a southern outlier of the Navajo volcanic field. **1.6**

75.6 Exit 47 to town of Continental Divide (population about 250 in 2000; post office from 1949). **0.5**

76.1 Cross physiographic continental divide; elevation 7275 feet. This pass was long called Campbell's pass, after Albert H. Campbell, the surveyor attached to the Whipple Expedition of 1853. Mount Taylor at 11:00 in distance. **3.9**

80.0 Sign for exit 53 to Thoreau. **1.0**

81.0 **Exit right** at exit 53 to Thoreau; El Paso Natural Gas station to right. **0.2**

81.2 Stop sign. **Turn left** onto frontage road. **0.1**

81.3 Stop sign, **turn left** onto NM-371 and proceed under interstate. **0.1**

81.4 Stop sign, go straight. **0.2**

81.6 Bridge over railroad tracks. **0.2**

81.8 Enter Thoreau (population 1863 by the 2000 census). Diné people refer to this locale as Dlǫ́' áyázhí, Little Prairie Dog (Young and Morgan, 1987). The arrival of the Atlantic and Pacific Railroad in 1881 marked the beginning of the town, which was originally called Chaves, after a local family who maintained a store here. In 1890, the Mitchell brothers, Austin and William, bought some 300,000 acres of timber land in the Zuni Mountains and laid out a townsite (called, of course, Mitchell), which had attracted 150 residents by 1892. The Mitchells gave up their plan to become timber barons during the Panic of 1893, and departed, but the town soon afterward became the base for the Hyde Exploring Expedition (1896-1899), which conducted the first extensive archeological excavations of Chaco Canyon. At this time, the town also developed into an extensive Indian trading center. The Hyde brothers renamed the town for the philosopher Henry David Thoreau, and the town post office changed to that name in 1899. However, local traditions claim that the name came from a resident named Thoreau, (a railroad man, army paymaster, or bookkeeper for the Mitchell brothers; accounts vary). The pronunciation is not that of Henry David, but rather "tho-ROO" or simply "THROO" (Julyan, 1996). In 1903, the American Lumber Company acquired the Mitchell Brothers' large holdings, and in partnership with the A,T & SF Railroad, resurrected the timber industry. By 1910, the firm sawed some 60 million board feet of timber, employed more than 1500 people, and an average of 100 railroad cars of timber rolled eastward from Thoreau to Albuquerque each day. However, the American Lumber Company went out of business in 1913 (Mangum, 1997). **0.2**

82.0 Post office to left; Entrada Sandstone red rock bluff in distance at 12:00. **0.7**

82.7 Leaving Thoreau; cemetery on right. **2.5**

85.2 Note section on point of mesa to left, exposing the Dewey Bridge and Slick Rock members of the Entrada Sandstone under a cap of gray Todilto Formation limestone. **0.3**

85.5 The 250-megawatt Plains Escalante Generating Station is visible at 1:00. It burns coal hauled by train from Peabody Energy's Lee Ranch surface mine 35 miles

northwest of Grants. **0.7**

86.2 Milepost 5; note Owl Rock-Wingate-Dewey Bridge-Slick Rock section exposed to left with Todilto on top. **0.7**

86.9 Red Mesa Bluffs Road on right; goes to local landfill. Continue straight. Road will now climb up through the Slick Rock Member of the Entrada. **0.8**

87.7 Outcrops of Slick Rock Member of Entrada Sandstone on left. Mesa on skyline to N at 12:00 is capped by Dakota Sandstone on Brushy Basin Member of Morrison Formation. Erosional truncation between here and STOP 6 gradually removes Brushy Basin so that basal Dakota unconformity is on Salt Wash Member of Morrison Formation. Note Dakota offset across fault (up to E) in gap with highway. **0.3**

88.0 Unpaved road to right. **Turn right. 0.1**

88.1 Enter Gallup Sand and Gravel Company Quarry. **0.1**

88.2 Road intersection; **go right. 0.1**

88.3 Road to right; go straight. **0.4**

88.7 **STOP 6.** Here, we will talk about limestone quarrying in the Todilto Formation, Summerville outcrops to the north, and Entrada stratigraphy (Fig. 2.24).

The Gallup Sand and Gravel Co. produces a variety of rock products from the Todilto Limestone. As noted in the first-day road log at Stop 2 (in Todilto Park), the Todilto Formation is an economically important unit in New Mexico. One example is the production of limestone from the lower, Luciano Mesa Member of the Todilto. The quarry visited at this stop is one of several that have been developed along the Todilto outcrop belt between Gallup and Grants. At this quarry, the Gallup Sand and Gravel Co. produces a variety of limestone rock products from the Todilto.

Quarrying begins with the removal of an average of about three ft of soil and overburden overlying the economic-grade limestone. The thickness of remaining limestone suitable for production may be up to about 15 ft. The rock is drilled and blasted and carried to a primary crusher. The crushed limestone is then screened and depending on the desired product

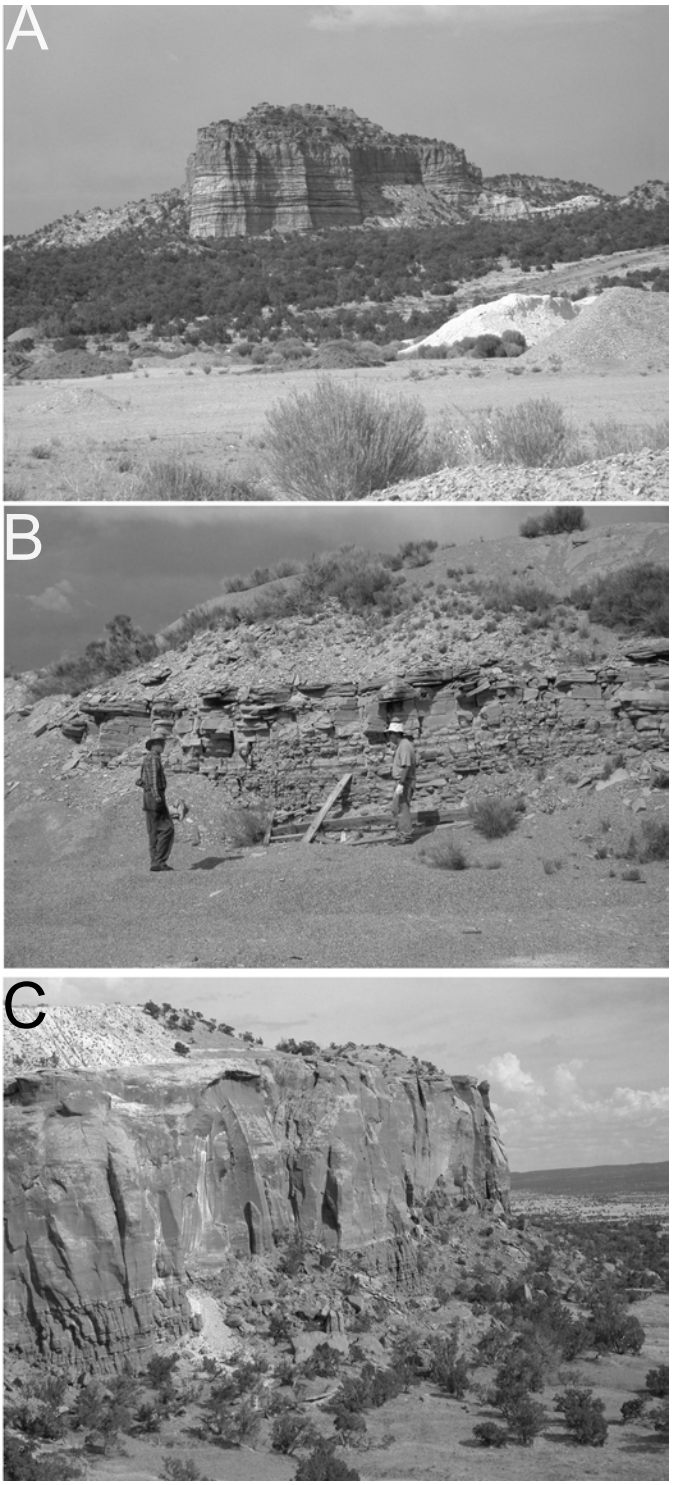

FIGURE 2.24. Jurassic outcrops at Stop 6. A, Cliff of Summerville and Bluff strata north of the stop. B, Limestone of the Todilto Formation at the stop. C, Wingate-Entrada section below the limestone quarry.

some may be conveyed to secondary crushers and then to a final screening.

The company adjusts the precise details of its operations according to the anticipated end uses of the limestone products. At various times the products may include riprap rock, filter rock, road metal aggregate, concrete aggregate, and various rock chip and specialty gradations. All are transported by truck from the quarry to the locations where they will be used.

We are now intimately familiar with the Jurassic section regionally. The flats below the quarry are developed in the upper part of the Triassic Owl Rock Formation. The cliff above is composed of the Wingate Sandstone and Dewey Bridge and Slick Rock members of the Entrada Sandstone (Fig. 2.24C). The quarry is developed in the Todilto Formation (Luciano Mesa Member) (Fig. 2.24B), and to the north are exposures of the Summerville Formation and Bluff Sandstone (Fig. 2.24A).

After stop, turn around and leave the quarry. 0.6

89.3 Stop sign. **Turn left. 0.5**

89.8 Crest of hill. A good view ahead of the dip slope of the Zuni Mountains. **0.5**

90.3 Note Entrada section to right. **3.9**

94.2 Highway divides; enter greater Thoreau. **0.4**

94.6 Thoreau village limit. **1.0**

95.6 Leave Thoreau. **0.1**

95.7 Bridge over railroad tracks. **0.3**

96.0 Stop sign. Go straight, under I-40. **0.1**

96.1 **Turn left** to enter I-40 eastbound onramp. **0.2**

96.3 **Merge left** onto I-40 eastbound. Mount Taylor (elevation, 11,301 ft, the highest mountain in New Mexico west of the Rio Grande) at 12:00. This mountain has tremendous cultural significance to the Diné people: it is the southern of their four principal sacred mountains, and figures prominently in many Diné creation stories and ceremonies, as well as in Navajo educational philosophy (Van Valkenburgh, 1941; Yazzie, 1971; Zolbrod, 1984; Benally, 1987; Aronilth, 1991). They refer to it variously as Tsoodził, Tongue Mountain (referring to a tongue of lava); Níłtsą́ dziil, Rain Mountain; and Dootł'izhii dziil, Turquoise Mountain (Young and Morgan, 1987).

Note Sonsela dipslope to right. The road is on colluvium near the base of the Painted Desert Member of the Petrified Forest Formation. The Sonsela in this region is an important aquifer. **3.4**

99.7 Mile marker 57. Haystack Mountain at 12:00; Mount Taylor at 1:00. Mount Taylor was named by Lieutenant James H. Simpson for Zachary Taylor, hero of the Mexican War and 12th president of the United States. In Simpson's (1850) words, this "is one of the finest mountain peaks I have seen in this country. This peak I have, in honor of the President of the United States, called Mount Taylor. Erecting itself high above the plain below, an object of vision at a remote distance, standing within the domain which has been so recently the theatre of his sagacity and prowess, it exists, not inappropriately, an ever-enduring monument to his patriotism and integrity." Although Taylor was president for only 16 months in 1849-1850, and never saw the mountain named for him, he had a profound influence on the subsequent history of New Mexico. As Julyan (1996) noted, Taylor strongly resisted attempts by Texas to annex the eastern half of New Mexico, and it was through Taylor's determination, against bitter southern opposition, that New Mexico remained a territory free of slavery. **1.0**

100.7 Mile marker 58. Note cuestas of Owl Rock Formation to left, Entrada red rock bluffs beyond, and mesas on northern skyline capped with Dakota Sandstone. **1.3**

102.0 Outcrops of upper part of Sonsela Member along road for next 1.7 miles. **3.0**

105.0 Outcrop on right of Painted Desert Member red beds. **0.9**

105.9 Exit 63 to Prewitt (NM-412) and Bluewater State Park. Note large fault to north that cuts out the Entrada bluffs and puts the Entrada against the Morrison. The Diné name for this area is Kin łigaaí, White House; earlier it was called Naaslah, White Clay Quarry (Van Valkenburgh, 1941). The 1882 USGS Map of New Mexico marked the locality as Ojo Negra (Van Valkenburgh, 1941). The community of Prewitt (population 460 by the 2000 census) was originally called Baca, after a local family. In 1916, Bob and Harold Prewitt arrived, established a trading post, and gradually the name Prewitt replaced Baca as the name of the town. **0.5**

BLUEWATER LAKE STATE PARK

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Bluewater Lake State Park (Fig. 2.25) is one of the oldest of 31 state parks in New Mexico, becoming a state park in 1955. The park lies 7 mi west of the village of Bluewater, south of Prewitt, at an elevation of 7400 ft in Las Tuces Valley, near the Continental Divide in the Zuni Mountains. The Navajos knew the area as T'iis Ntsaa Ch'éélí, "large cottonwood trees where water flows out horizontally" (Young and Morgan, 1987; Julyan, 1996), because a forest of cottonwoods, piñon pine, and juniper surrounds the lake. Bluewater and Cottonwood (Azul) Creeks feed the man-made lake.

The lake is formed by an arched dam, which is 90 ft high and 500 ft long (Robinson, 1994), and impounds 38,500 acre-feet of water. The last time water spilled over the dam was in 1941. The dam is convex in the upstream direction for increased strength, and it is at the mouth of Bluewater Creek, a steep-walled canyon. An overlook at the end of the road from the Visitors' Center and a primitive hiking trail into the canyon offer excellent views of the dam and canyon.

The New Mexico Department of Game and Fish maintains a permanent pool of water for fish and periodically stocks the lake with rainbow trout and channel catfish. It is well known to ice-fishermen during the winter. In addition to fishing, camping, picnicking, power and sail boating, hiking, water skiing, sail surfing, and swimming are other possible recreational activities (New Mexico State Parks, 2002). Developed facilities lie on the east side of the lake, north of the dam. Facilities include day-use picnic tables, a launch ramp, drinking water, modern rest rooms with showers, camping sites (some with electrical hookups), a playground, and a dump station. Primitive camping is allowed along the northwest side of the lake. A restaurant and store are available for visitors during weekends and other busy times of the year. Additional facilities are available in nearby Bluewater. Not all of the 25 mi of shoreline belongs to the state park; some land surrounding the lake belongs to private individuals, Indian tribes, and U. S. National Forest. All of the water is open to the public.

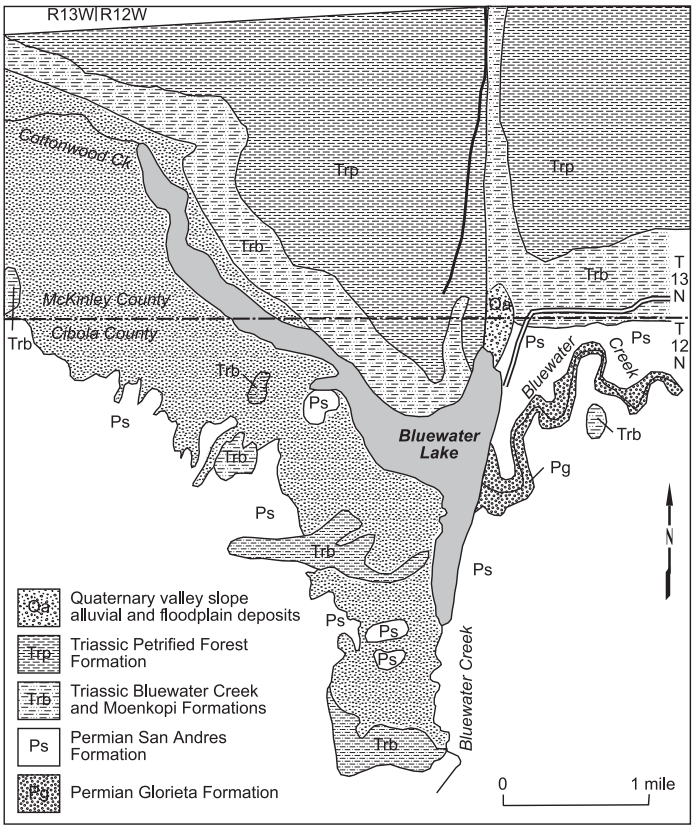


FIGURE 2.25. Geologic map of Bluewater Lake State Park (from McLemore, 1998 modified from Smith, 1954, using stratigraphic nomenclature of Lucas, 1995).

Few people permanently settled in the Zuni Mountains until the middle 1800s. Zuni, Acoma, and Navajo Indians hunted and traveled through the Zuni Mountains long before there was a Bluewater Lake. Spaniards traveled through the mountains on their way to the Zuni Pueblo. About 1756, Don Bartolome Fernandez built a ranch and settled approximately 25 mi east of Bluewater Lake. James H. Simpson of the U. S. Army and Adolph F. Bandelier traveled through the Zuni Mountains in 1849 and 1883, respectively (Robinson, 1994).

Although several earthen dams were built and rebuilt multiple times since about 1850 to impound water for local irrigation, recreational use, including hiking, picnicking, camping, swimming, fishing, boating, and water skiing, is important to most visitors today. The lake was originally impounded about 1850 by Martin Boure, a French settler, to irrigate his farm (Young, 1984); the original dam failed during a rare, torrential rain, one of a few recorded occurrences in the Zuni Mountains. In the 1870s, another Frenchman, Dumas Provencher, operated a stagecoach stop and sawmill near the present Bluewater Lake (Robinson, 1994). The settlement of Bluewater, also known as Bluewater Valley, was established in 1880-1881 by the Atchi-

son, Topeka, and Santa Fe Railroad and has had a post office since 1895 (Julyan, 1996). Provencher sold his operation to the Acoma Land and Cattle Co., who sold it in 1882 to James L. Latta. Latta formed the Zuni Mountain Cattle Co. in 1883 with its headquarters at Bluewater. In 1884-1885, more French settlers arrived, formed a cattle company, and built a dam at the junction of Cottonwood (or Azul) and Bluewater Creeks. That dam also failed. In 1894, a Mormon named Ernst Tietjen bought the Latta ranch, formed a partnership, the Bluewater Land and Irrigation Co., with local businessmen, and built another dam at the confluence of Bluewater and Cottonwood Creeks (Tietjen, 1980; Robinson, 1994). Other Mormon settlers soon found the area to their liking and, in 1896, established a community 3 mi west of the railroad camp called Mormontown. The railroad camp soon died, and Mormontown changed its name to Bluewater, which is still occupied.

Over the next few decades, dams were breached at least three or four times and then rebuilt at various places along Bluewater Creek (Tietjen, 1980; Robinson, 1994). Feuds occurred between the cattlemen and Mormon farmers over the destiny of the fertile valley. Finally, in 1925-1926, the Bluewater-Toltec Irrigation District was formed to build the current structure (Anonymous, 1983). About 1930, sportsmen with the help of the Game Protective Association, opened Bluewater Lake for recreational use. In 1936, the lake was stocked with trout, bass, perch, and crappie, and in 1937, the state of New Mexico purchased 160 acres along the lakeshore for recreational development (Robinson, 1994). Additional land was purchased in 1954-1955. In 1955, Bluewater Lake was added to the list of New Mexico State Parks, with a total acreage of nearly 2200 acres.

The Zuni Mountains are considered the southern boundary of the San Juan Basin and form the core of an elongated structural dome created by regional compressional tectonics during the Cretaceous and Paleogene. Rocks ranging in age from Proterozoic through Recent are exposed in and around the Zuni Mountains, but only Permian (Glorieta Sandstone, San Andres Formation) and Triassic (Moenkopi Formation and Shinarump, Bluewater Creek, and Petrified Forest formations of the Chinle Group) strata are exposed near Bluewater Lake; thin veneers of Quaternary alluvium fill valleys draining into the lake (Fig. 2.25; Smith, 1954; Hackman and Olson, 1977; Anonymous, 1983).

There is no stratigraphic evidence of a former natural lake in Las Tuces Valley; instead, it contains a thin veneer of Quaternary alluvium and finer-grained valley-fill deposits formed by ancient rivers or streams. This alluvium fills the bottom of the canyons and arroyos draining into the lake and lines some of its shores. Most of this alluvium consists of sand, silt, and clay derived from erosion of the surrounding ouctrops of the Bluewater Creek and Petrified Forest formations.

The Bluewater fault zone strikes north-south and locally separates Bluewater Creek and Petrified Forest beds from older San Andres beds. The Bluewater fault has a down-to-the-west stratigraphic throw of 100–400 ft (Smith, 1954). The dam is built along the west-facing fault-line scarp. The lake conceals portions of the en echelon fault pattern (Smith, 1954).

106.4 Roadcuts in sandstone of Painted Desert Member, possibly of the Perea Bed, on the left. **0.6**

107.0 Mount Taylor at 10:30; East Grants Ridge at 11:00; Horace Mesa at 11:00 to 12:00; and Haystack Mountain (or Butte) at 10:30. We will end day 3 near the base of Haystack Mountain at El Tintero volcano (visible as low rise capped with a small scoria cone at 11:30).

Mount Taylor forms the skyline behind El Tintero (Fig. 2.26).The right peak is Mount Taylor Peak. From the summit most of the central western part of New Mexico may be seen. The left peak is La Mosca Peak, a thick mass of latite (trachyandesite) lava that probably originated in a vent now truncated by the erosional amphitheater occupying the summit. The saddle between the two peaks is the western rim of this summit amphitheater. The profile from this angle and from the south near El Malpais is that of a mature composite volcano, a fact that did not escape Dutton (1885), who noted "…its volcanic nature is betrayed in every line and feature…"

The celebrated writer Mary Austin, in The Land of Journeys' Ending (1924), wrote this about Mount Taylor:

"Most sacred is the bulk of Tsotsil, blue as a summer rainstorm, where it watches, from its high and level plateau, the black caterpillar trains of the Santa Fé

FIGURE 2.26. Mount Taylor.

crawl across the cindery plain between the Río Grande and the Río Puerco. This is a rim-rock mesa, red sandstone, topping the softer stuff and weathering in huge blocks like a ruined wall. Like the teocalli of the Aztecs, it rises from the mesa platform, a pyramidal, solitary mass of broken cones, from whose top, streams cloud like smoke of accepted sacrifice, following the high wind river. For a whole day's travel, east and west, it dominates the landscape to the north of the railway, a semicircular volcanic mass, having a secondary cone within, one clear creek, and a giant's tongue of black lava protruded down the shallow red sandstone cañon where the railway follows the old trail past Acoma to Zuñi." **0.6**

107.6 Basalt of El Tintero volcano on both sides of road. **0.2**

107.8 Mile marker 65. Haystack Mountain at 10:00. **0.2**

108.0 Roadcuts in Sonsela Member. **0.3**

108.3 Cross wash. **0.5**

108.8 Mile marker 66. Cinder cone at 10:00 is El Tintero; Haystack Butte at 9:30. **0.8**

109.6 El Tintero (inkstand) at 9:30 is the source of the basalt flows (also known as the "Bluewater flow") that occur along the highway for the next 4 miles or so. El Tintero is a shield volcano similar to that common throughout the Southwest in which a small scoria cone is perched on the summit of a pile of lava flows. In the case of El Tintero, the regional slope away from the base of Haystack Mountain resulted in most of the flows spreading east-southeast, and south from the vent area. It is dated at between 57 ± 6 Ka (^{3}He surface dating) and 79 ka (U-series) (Laughlin et al., 1993). The younger date would imply that it is similar in age to Capulin Volcano in northeastern New Mexico, whereas the older date would imply that it is some 20,000 years older than Capulin. Judging from the overall similarity in preservation, yet drier local climate, either age is reasonable. The lava flows are tholeiites, similar in composition to the McCartys lava flow that constitutes the youngest flow within El Malpais National Monument farther east along I-40. These are the westernmost young eruptions in the Mount Taylor region. Refer to Day 3, last stop for more details. **1.1**

110.7 Lava flows of El Tintero occur along the right side of I-40. **0.7**

111.4 Pass under power line. An excellent exposure of the distal margins of the El Tintero flows is visible in the small valley on the right. Note that the valley has incised several meters subsequent to the emplacement of the flows due to constriction of the valley along the flow margin and adjacent sedimentary rock outcrops. The margin of the flow consists of a steep carapace of pahoehoe crust. Apart from loss of the glassy (tachylite) surface materials, the flow surface is eroded very little. This contrasts with the subdued appearance of the flows elsewhere, implying that mantling of fine materials blown in on top of the flow together with general accumulation of debris from the sparse vegetation account for the subdued appearance more than any actual disintegration and surface erosion. **0.4**

111.8 Cibola County line. **0.3**

112.1 Sonsela outcrops on right. **0.4**

112.5 Flats here are developed in Bluewater Creek Formation red beds. Mitchell Draw section (Fig. 2.27) to right is the easternmost Chinle outcrop in the Zuni Mountains. The red beds belong to the Bluewater Creek Formation. The substantial sandstone body in these beds is an exceptionally thick section of the McGaffey Member, as much as 60 ft thick here. The overlying Blue Mesa Member of the Petrified Forest Formation is only 63 ft thick here, about half the thickness of this unit in the western Zuni Mountains. Because underlying Bluewater Creek Formation strata have a relatively constant thickness throughout the Zuni Mountains of about 150-180 ft, Heckert and Lucas (1996)

argued that eastward thinning of the Blue Mesa Member is due to erosion at the Tr-4 unconformity, between it and the overlying Sonsela Member. **0.6**

113.1 Road cut through the basalt here reveals a soil overlying the upper vesicular zone. The upper vesicular zone of pahoehoe lava flows (Aubele et al., 1988) is characterized by a downward progression in which the average diameters of individual vesicles become larger while the number density (number per unit volume of lava) decreases. The origin of this pattern, which occurs in pahoehoe flava flows throughout the world, is a result of freezing-in of initial vesicle populations in the rapidly cooled outer portions of lava flows and continued growth and coalesence of vesicles within the flow interior. The actual volume of vesicles per unit lava flow volume decreases somewhat with depth (Cashman and Kauahikaua 1997; Crumpler et al., 1999) in accordance with ideal gas law behavior. **1.7**

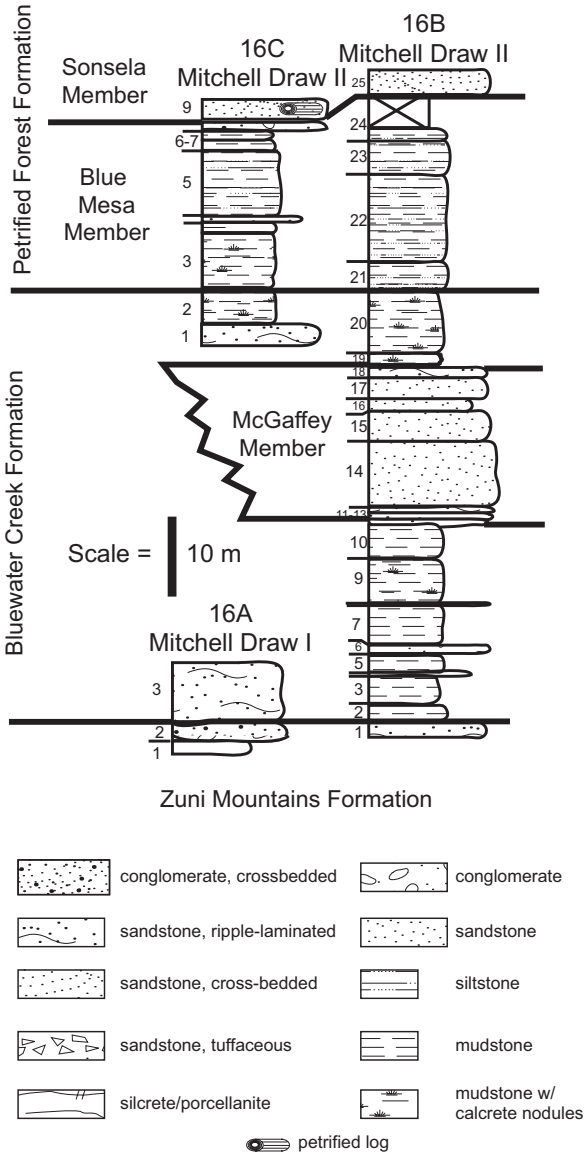


FIGURE 2.27. Mitchell Draw Chinle Group section at mile 112.5.

114.8 Exit 72 to T'iis Ntsaa Ch'éélį, Bluewater Village (population 500 in 2000). A town near the present Bluewater grew up along the Atlantic and Pacific Railroad in 1881. Mormon settlers arrived a few years later, constructed an earthen dam at the confluence of Bluewater and Cottonwood Creeks, and by 1896 a settlement, Mormontown, had arisen about 3 mi west of the railroad town of Bluewater. The railroad town eventually died, and the farming community adopted the name. Long before the town was established, this area was known as Agua Azul (literally "Blue Water"), and it was stipulated as the southern boundary of Navajo country in the Navajo-Spanish treaty of 1819 (Julyan, 1996). The geologist James Newberry, returning from the Ives Expedition to the Colorado River in 1858, passed through the area and produced (Newberry, 1861, p. 96) a simple stratigraphic section of the units encountered from Campbell's Pass (Continental Divide) eastward to Agua Azul. He collected a few fossils from the limestones at the base of the section, which he believed to represent the "summit of the Carboniferous formation;" we now know these fossiliferous limestones are the Lower Permian San Andres Formation. **1.5**

116.3 The grassy slope on the mesa immediately in front of Mount Taylor is the west flank of a scoria cone on East Grants Ridge. This same scoria cone is naturally half-sectioned in the west side of Lobo Canyon. The high mesa in the distance at 9:30 is La Jara Mesa, the western margin

of the Mount Taylor field. **0.8**

117.1 The road is now on Moenkopi Formation here, approaching the San Andres cuesta. **1.2**

118.3 Crest of hill; note Mount Taylor volcanic field to northeast. **0.4**

118.7 Begin roadcuts in Permian San Andres Formation. Note low amplitude folds in the limestone. **0.2**

118.9 Black Mesa (also known as West Grants Ridge) is at 11:00 and forms the backdrop for the towns of Milan and Grants. Its unusually symmetric map plan shape makes it a distinctive landmark from aerial and orbiting spacecraft perspectives. **0.7**

119.6 End San Andres roadcuts. Note Milan ahead with West Grants Ridge behind it. **2.1**

121.7 Exit 79 to Milan/San Mateo. Note basalt-capped West Grants Ridge (Black Mesa) to left. Milan (population 1891 by the 2000 census) developed as a result of the uranium boom of the 1950s. It is named for Salvador Milan, whose family had settled in the Gallup area in 1913 to work in the coal mines. He moved to the Grants area in 1932 and with his wife assembled large land holdings in the area. When Milan died in 1979, he had been the only mayor of the town since its incorporation in 1957 (Julyan, 1996). **2.0**

123.7 The lava flow along the margins of I-40 for the next several miles is known as either the Paxton Springs flow or the Zuni Canyon flow. The source vent is the Paxton Springs volcano, a small scoria cone located inside one of the canyons within the Precambrian crystalline terrain on the south side of the Zuni Mountains. From the Paxton Springs vent the lava flowed east to the head of Zuni Canyon, and from there northward down Zuni Canyon to emerge and spread out in the valley floor of the Rio San José. Most of the flow probably traveled within the confines of a lava tube during its traverse down Zuni Canyon. Upon emerging into the Rio San José, the flows were forced to travel in open channels and along a lower gradient. The tendency to develop a distributary lava delta at its terminus very shortly after entering the lower gradient of the Rio San José is evidence that the flow was near its maximum cooling-limited length at the time it entered the valley. Transition to aa characteristics in the valley here probably reflects the rapid emplacement. Although the Zuni Canyon flow appears to be a confused jumble of aa, from the air several distinct channels in the flow may be mapped within the terminal fan where it spread out over the valley floor. The El Calderon flow, on which the Zuni Canyon flow rests, flowed around the south side of the Zuni uplift. **0.1**

123.8 Grants city limit. **0.2**

124.0 Note aa lava to right. **0.5**

124.5 Exit 81A to San Rafael. Note Chinle outcrops to left in Grants along Santa Fe Avenue. **0.2**

124.7 Exit 81B to Grants. The highway now crosses part of the El Malpais lava field. Diné people called this flow Yé'iitsoh bídił, Giant's Blood (Young and Morgan, 1987). **0.5**

125.2 Note Jurassic-Cretaceous strata at 12:30-2:30 in distance. East Grants Ridge is at 9:00. The contrast between the white pumice of the East Grants Ridge rhyolite and the overlying dark cinder and basalt of the East Grants Ridge half-sectioned scoria cone is prominent in the distance. Mount Taylor is visible at 9:30 above Horace Mesa (9:00-11:00). **0.9**

126.1 End of Zuni Canyon lava flow. **0.7**

126.8 Impounded drainage on right. **0.2**

127.0 The El Calderon lava flow occurs adjacent to I-40 for the next several miles until the junction of I-40 and NM-117. **0.6**

127.6 **Exit 85** to Grants/Mt. Taylor; take this exit to leave I-40 and go to old 66. The Dinosaur Museum visible to the right is defunct. 0.4

128.0 Stop sign; **turn left. 0.2**

128.1 Cross bridge over I-40. **0.5**

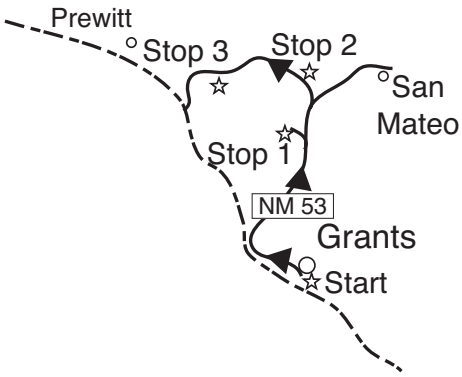
128.6 Traffic light at intersection with Naomi Road. Continue straight. **0.1**

128.7 **Turn left** into parking lot of Best Western Inn and Suites. The town of Grants (population 8806 by the 2000 census) began as a settlement along the Atlantic and Pacific Railroad in 1881, where three brothers named Grant established a construction camp. Earlier, prior to the Civil War, Antonio Chavez had settled in the area, and it was homesteaded in 1872 by Don Jesus Blea. The settlement named Grant (the name was changed to Grants in 1935, to reflect local usage) grew slowly, as a station, depot, and coaling station on the railroad. During this time it was overshadowed by the prosperous town of San Rafael, 5 mi to the south, an agricultural and livestock community that had formed shortly after Ft. Wingate was dismantled and moved west to its present location just east of Gallup. In the 1920s, an entrepreneur named George E. Breece shifted his lumbering operations from the western side of the Zuni Mountains, where 25 years of lumbering had depleted the resource, to the untapped forest areas south of Grants, and on the west side of Grants built company housing and a railroad roundhouse to serve his spur lines into the southern Zunis. The town got water and electricity in 1929, but the timber and livestock industries were hit hard by the Depression of the 1930s. By 1941, when Grants incorporated, residents numbered about 1000. Oil from the Hospah field to the west was piped to a refinery near Grants in the early 1940s, and the Army Air Force from Kirtland Base in Albuquerque used the malpais nearby as a bombing range during World War II. Large-scale farming in the Grants area began in the 1940s, with carrots as the main cash crop, but that industry crashed in the 1950s under competition from cheaper California produce. When Paddy Martinez discovered uranium west of town in 1950, Grants boomed, its population increasing from about 2250 to more than 10,000 from 1950 to 1960 with the opening of several large mines. The influx of people, and the substantial distance of Grants from the Valencia County seat in Los Lunas, led to the creation of Cibola County from western Valencia County in 1981. Since then the fortunes of the town have waxed and waned with the level of uranium mining. The closing of the large mines in the 1980s had an adverse impact on Grants' economy, and the town has more aggressively promoted the tourist industry in recent years (Chilton et al., 1984; Julyan, 1996; Mangum, 1997).

End of second-day road log.

THIRD-DAY ROAD LOG, FROM GRANTS TO MILAN, HOMESTAKE MINING COMPANY, DOS LOMAS, HAYSTACK MOUNTAIN AND EL TINTERO

SPENCER G. LUCAS, ANDREW B. HECKERT, WILLIAM R. BERGLOF, LARRY S. CRUMPLER, JAYNE C. AUBELE, BARRY S. KUES AND VIRGINIA T. MCLEMORE



Assembly Point: Best Western Inn and Suites, 1501 East Santa Fe Avenue, Grants
Departure Time: 8:00 AM
Distance: 29.6 miles (to old Highway 66 intersection); 36.1 miles to I-40 east on-ramp near Prewitt.
Stops: 3

SUMMARY

The field conference ends today, focusing on uranium mining, mill site and tailings reclamation and the late Cenozoic volcanic rocks to the northwest of Grants. Today's trip begins at Stop 1 with a tour and explanation of the Homestake Mining Company reclamation project near Grants. Homestake was a major producer of uranium ore from the Ambrosia Lake District to the north of today's route, milled the ore at this site, and has been reclaiming the mill tailings for more than two decades.

At Stop 2 near Dos Lomas (a topographic feature) we examine a well-exposed sandstone pipe in the Bluff Sandstone and discuss uranium deposits in the Todilto Formation, together with their mining history and the origin of the intraformational folds that localized the uranium mineralization in the Todilto.

We then move on to Stop 3, between El Tintero volcano and Haystack Mountain (also known as Haystack Butte). El Tintero, with an estimated age of 30-120 ka, was the source of an extensive series of lava flows (the "Bluewater flow"), some of which are crossed by I-40 west of Grants (see road log for Day 2). Uranium in the Todilto Formation was discovered for mining at Haystack Mountain, and one of the largest known Todilto deposits was mined there. Indeed, uranium mining in New Mexico began at Haystack Mountain.

Mileage

0.0 Start in parking lot of Best Western Inn and Suites on east side of Grants. **Turn left** and proceed west on Santa Fe Avenue. The view east as you leave the lot is directed toward Horace Mesa, a high, basalt-capped mesa that marks the southwestern edge of the Mount Taylor volcanic field. These basalts are dominantly nepheline hawaiites and are up to 30 m thick and locally columnar. Fault scarps cut the mesa surface in a northeast-striking orientation typical of most Quaternary structures throughout the volcanic field, as do several alignments and fissures of vents on the mesa (Fig. 3.1). Consequently, the flows covering Horace Mesa are incompletely mapped. Preliminary shallow geophysical studies for a planned (but never built) mesa-top astronomical observatory facility encountered several subsurface cavities within the basalt believed to be lava tubes. **0.4**

0.4 Bridge over Santa Fe railroad tracks. Directly ahead is West Grants Ridge (also called Black Mesa), with Chinle Group red beds capped by basalt of Black Mesa, prominent at 12:00 as the backdrop for

FIGURE 3.1. Aerial oblique view looking north centered on Grants area. Several fault scarps cut basalts of Horace Mesa on the right. Black Mesa, also known as West Grants Ridge, is the prominent symmetrical mesa to the left. East Grants Ridge is the upper ridge, where the half-sectioned scoria cone is highlighted by underlying bright pumice from the East Grants Ridge rhyolite dome. The terminus of the Zuni Canyon lava flow from the Paxton Springs vent on the south side of the Zuni Mountains fills the valley and is crossed by I-40. Diverging channels within the flow near its terminus are clearly visible. The moderately crenulated outline of the flow is typical of aa flows.

the town of Grants. Lava flows of Black Mesa may be traced to their source at the northeast end of East Grants Ridge, where the original scoria cone was half-sectioned during development of Lobo Canyon. A K-Ar age of the basalt lava flows capping Black Mesa is 2.57 ± 0.13 Ma (Laughlin et al., 1993), and there is a K/Ar age of 3.3 ± 0.3 Ma (Bassett et al., 1963a, b) for the rhyolite pumice underlying these flows. **0.2**

0.6 Enter Grants proper on old Highway 66. **1.0**

1.6 View ahead of U.S. Gypsum perlite processing plant. **0.2**

1.8 U. S. Gypsum Grants Plant. Perlite quarried from a dome-like volcanic mass at the northeast end of the East Grants Ridge was processed at this site and shipped by rail to other U. S. Gypsum plants. One of the more common uses of perlite is in the production of wallboard or "drywall." **0.2**

MINERAL RESOURCES OF EAST GRANTS RIDGE

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East Grants Ridge is prominently visible from I-40 as a topographic ridge northeast of Grants, New Mexico, marked by a large basaltic plug projecting through light-colored pumice beds (Fig. 3.2). Up to 900 ft of Jurassic and Cretaceous rocks form the base of the ridge and include (oldest to youngest) the Entrada Sandstone, Todilto Limestone, Summerville Formation, Bluff Sandstone, Morrison Formation, Dakota Sandstone, Mancos Shale, Gallup Sandstone, and Crevasse Canyon Formation (Fig. 3.2; Thaden et al., 1967; Barker et al., 1989). Volcanic rocks consist of an older rhyolitic dome, ash-flow tuff, and rhyolite flows overlain by younger basalt flows and plugs. These rocks contain deposits of uranium, pumice, and perlite that were mined in the past. Occurrences of scoria, limestone, topaz, garnet, and obsidian also are found on East Grants Ridge.

Uranium, used mostly as fuel for nuclear reactors, was produced from the F-33 mine on the northwest side of East Grants Ridge by Anaconda and United Nuclear-Homestake Partners. From 1954 to 1959 and 1971 to 1977, 205,000 short tons of ore grading 0.21% U_3O_8 were produced (Barker et al., 1989; McLemore, 1983). Uranium was mined from a cluster of deposits along northeast-trending intraformational folds in the middle and upper parts of the Todilto Limestone (McLemore and Chenoweth, 1989, 1991). Uranium and vanadium minerals included uraninite, pitchblende, coffinite, paramontroseite, häggite, carnotite and grantsite, in a gangue of calcite, barite, fluorite, and pyrite. Reserves were depleted in 1977, and Homestake Minerals Corporation reclaimed the mine in the 1990s.

Pumice is a lightweight, porous igneous rock that forms during explosive volcanic events. Pumice is used mainly as an aggregate in lightweight building blocks and assorted building products; other uses include industrial abrasive, absorbent, concrete aggregate and admixture, filter aid, filler, soap, horticulture (including landscaping), and the stonewashing of denim (Bolen, 2001). A pumice deposit on the south side of East Grants Ridge, near the prominent basaltic volcanic plug, was mined during World War II and from 1946 to 1952 (Barker et al., 1989). Pumice Corporation of America (PCA) produced 59,473 short tons of pumice from open pits from 1946 to 1952 (Weber, 1965); production during World War II is unknown.

Perlite is a weathered high-silica rhyolitic volcanic glass with 2.5% water. When sized perlite is rapidly softened in a commercial furnace, the water converts to steam bubbles that produce lightweight cellular foam when the perlite is cooled. This rock foam has many uses in construction, filtering, and horticulture. The U. S. Gypsum (USG) perlite deposit is about 9 mi northeast of Grants, mainly in sections 35, 36, T12N, R9W and sections 1, 2, T11N, R9W comprising 1144 acres (Fig. 3.2). The deposit is related to a local vent/plug in the Mount Taylor volcanic complex and is up to 177 ft thick in drill holes. The perlite is tan to gray,

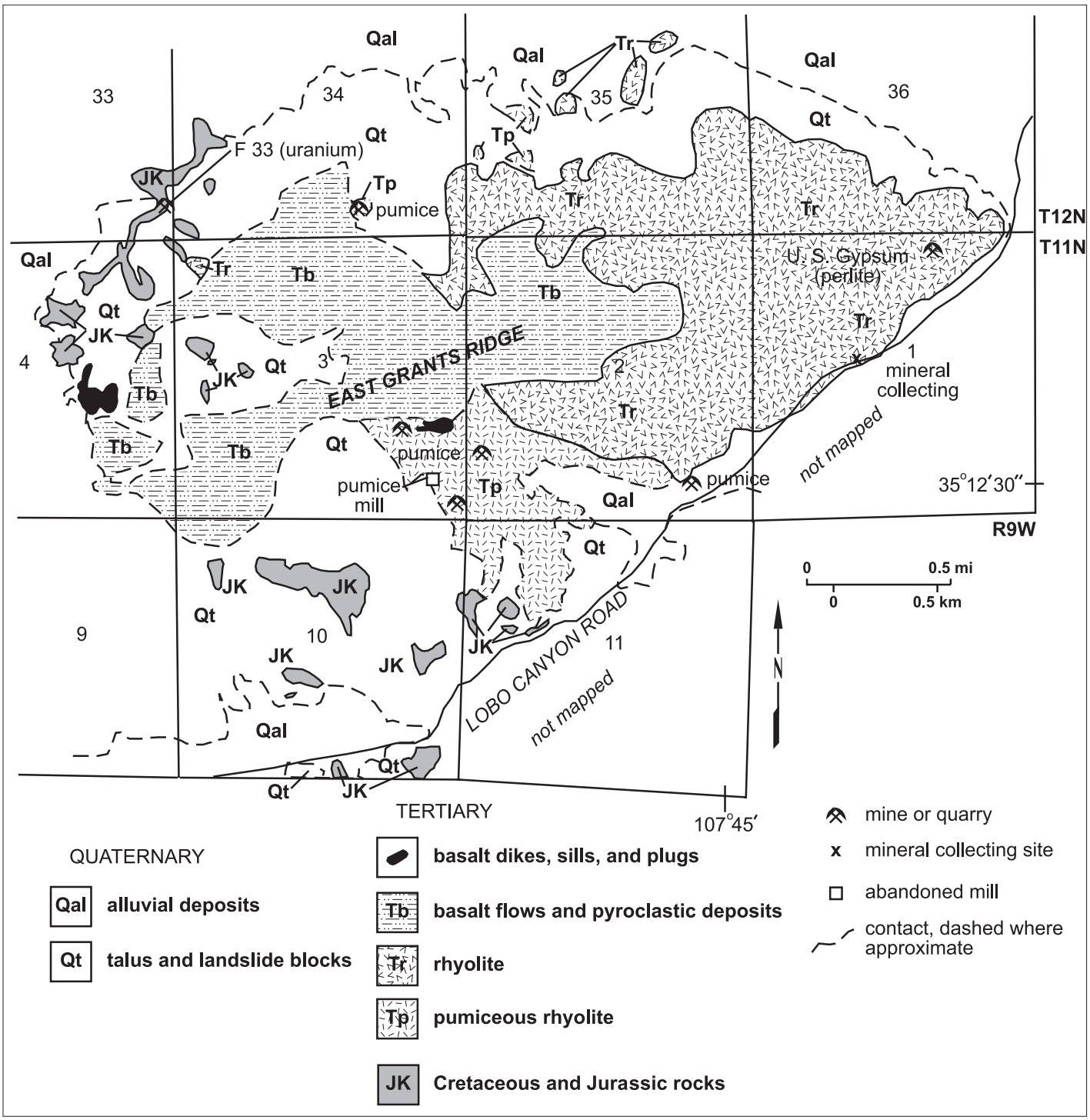

FIGURE 3.2. Geologic map of East Grants Ridge.

with flow banded and pumiceous portions and granular texture. USG operations began in 1953, after the company purchased the property from PCA and local claimholders, and terminated in the early 1990s. For many years, less than 10,000 tons were produced yearly by open pit methods, and a significant portion of the 6 to 10-million-ton reserve remains in place. Total production was a few hundred thousand tons. The mill is on a rail siding in Grants and has a permitted capacity of 20 tons per hour (116,000 tpy), but rarely operated at that level and needs a major overhaul. The property is currently for sale by USG.

Scoria and pumice are pyroclastic deposits formed as volcanic fragments ejected during explosive volcanic eruptions. Scoria (volcanic cinder) is red to black to gray, vesicular, basaltic (50–60% SiO_2) volcanic fragments. Most scoria deposits occur as loose, poorly consolidated, poor- to well-sorted cones or mounds of stratified fragments (Cima, 1978; Osburn, 1979, 1982; Peterson

and Mason, 1983; Geitgey, 1994). The ejected material ranges in size from minor quantities of volcanic ash or cinder (<2 mm in diameter), scoria (2–100 mm in diameter), and volcanic bombs (smooth-sided) and blocks (angular fragments), which are greater than 100 mm in diameter. Most volcanic cinder cones contain approximately 75% scoria (Cima, 1978; Osburn, 1979, 1982). Scoria is not to be confused with pumice. Scoria is denser and more coarsely cellular or vesicular than most pumice (Peterson and Mason, 1983). Pumice is light in color, ranging from white to gray to pale yellow, pink, or brown and also is vesicular but of a dacitic to rhyolitic composition (60 to 70% SiO_2) (Geitgey, 1994). The vesicular nature of scoria results in lower density and higher porosity than most rock types. These properties result in commercial use as lightweight aggregates, insulators, absorbents, and abrasives (Geitgey, 1994). Most scoria in New Mexico is used to manufacture cinder block and concrete. Scoria is found along East Grants Ridge as part of the basaltic flows (Fig. 3.2). Although no production of scoria is reported from East Grants Ridge, scoria is a potential resource. Similarly, limestone has not been quarried from East Grants Ridge, but the limestone from the Todilto Formation could be crushed and used for construction purposes.

Mineral collecting at East Grants Ridge is well known for excellent micromounts of clear to amber topaz (6 mm or more long) and red-brown to red spessartine garnets (less than 1 cm in diameter) found in cavities and lithophysae in the rhyolite flow (Barker et al., 1989; DeMark, 1989; McLemore et al., 1989). In addition, quartz (less than 1 mm long), Apache tears (obsidian, 3 cm in diameter), and cassiterite (less than 4 mm in diameter) have been found.

2.0 Traffic light at First Street. **0.1**

2.1 Traffic light at Second Street. **0.2**

2.3 Traffic light at Fifth Street. **0.1**

2.4 Grants Chamber of Commerce and Mining Museum on right. Hills beyond the museum forming the northwestern edge of the town of Grants and Milan are largely colluvial materials consisting of large blocks of basalt from Black Mesa in a surficial matrix of Chinle. The slopes of Black Mesa consist in part of several terraces or landslips in which the basalt cap is displaced down slope in disturbed sections. **0.1**

2.5 Grants Post Office on right. **0.4**

2.9 Chinle red beds to right. **0.4**

3.3 Traffic light; I-40 onramp to left (NM-53); **continue straight.** Chinle red beds on right. **0.2**

3.5 Malpais lava flows to left. The Precambrian-cored Zuni Mountains uplift is on the skyline at 10:00, and most of that skyline consists of Permian sedimentary units gently dipping to the north. At 9:00, near the western edge of Grants and the eastern edge of Milan, the relatively dark and rough Zuni Canyon lava flow fills the floor of the Rio San José valley along the course of I-40 (discussed in the road log for the end of Day 2). **0.4**

3.9 Red beds of Painted Desert Member of Petrified Forest Formation on right. **0.2**

4.1 Bridge over Santa Fe Railroad tracks. **0.2**

4.3 Welcome to Milan. **Get in right lane.** West Grants Ridge (Black Mesa) to right. **1.3**

5.6 I-40 access to left. Continue straight ahead. **Get to right and prepare to turn right**. **0.3**

5.9 **Junction 605; turn right** and cross railroad tracks to proceed north on NM-605. During the uranium boom this intersection merited a traffic light, but now, during the "bust," the traffic light has been removed. The view east along this route is largely of the west flank of East Grants Ridge. **0.7**

6.6 Note extensive colluvium of basalt boulders to right. **0.7**

7.3 Haystack Mountain at 9:30; low, broad mound at 10:30 is Homestake Mining Company reclaimed tailings pile, where we will soon stop. **0.2**

7.5 Mesa at 12:00 is La Jara Mesa, a part of the Mount Taylor volcanic field that projects westward from the base of Mount Taylor. At 1:00, the west flank of Mount Taylor is visible. Immediately in front of Mount Taylor is East Grants Ridge. The prominent grassy slope on East Grants Ridge is the west flank of a large scoria cone that is half-sectioned in the side of Lobo Canyon and visible from the Lobo Canyon road. **0.5**

8.0 Mile marker 2; Mt. Taylor at 1:00. **1.0**

9.0 Mile marker 3; Lobo Canyon and Mount Taylor volcano at 2:00. **Get in left lane. 0.7**

9.7 Tailings pile at 9:30-10:30 (Fig. 3.3). East Grants Ridge at 3:00. Note zigzag pattern of drill roads dating from the early 1950s,

FIGURE 3.3. The Homestake tailings pile, site of Stop 1.

developed at about the time of the discovery of a large uranium deposit (F-33 Mine) in the Todilto Formation at the base of East Grants Ridge. Little additional uranium was discovered despite the extensive drilling. **0.9**

10.6 Pass tailings pile on left, get into left lane **0.5**

11.1 **Turn left** on unpaved road to Homestake Mining Company facility offices. **0.3**

11.4 **STOP 1.** Homestake Mining Company facility. Note dip slope of Permian San Andres Limestone on Yeso Formation ahead (west). The facility is discussed in the accompanying minipaper by McLemore, and the information in the following text was provided by Alan Cox of Barrick Management Corporation.

Homestake Mining Company was one of the original pioneers in the uranium business in the Grants Mineral Belt-Ambrosia Lake District (Fig. 3.4), with operations beginning in the mid-1950's. Homestake was involved in the operation of two separate milling facilities and several underground mines in the Ambrosia Lake area.

Two mills were constructed in 1956-57 in conjunction with the U.S. Atomic Energy Commission to supply uranium to meet U.S. government needs. Yellowcake production from milling operations commenced in 1958. The smaller of the two mills, with a capacity of 750 tons per day (tpd), was owned by the Homestake-New Mexico Partners, and started processing

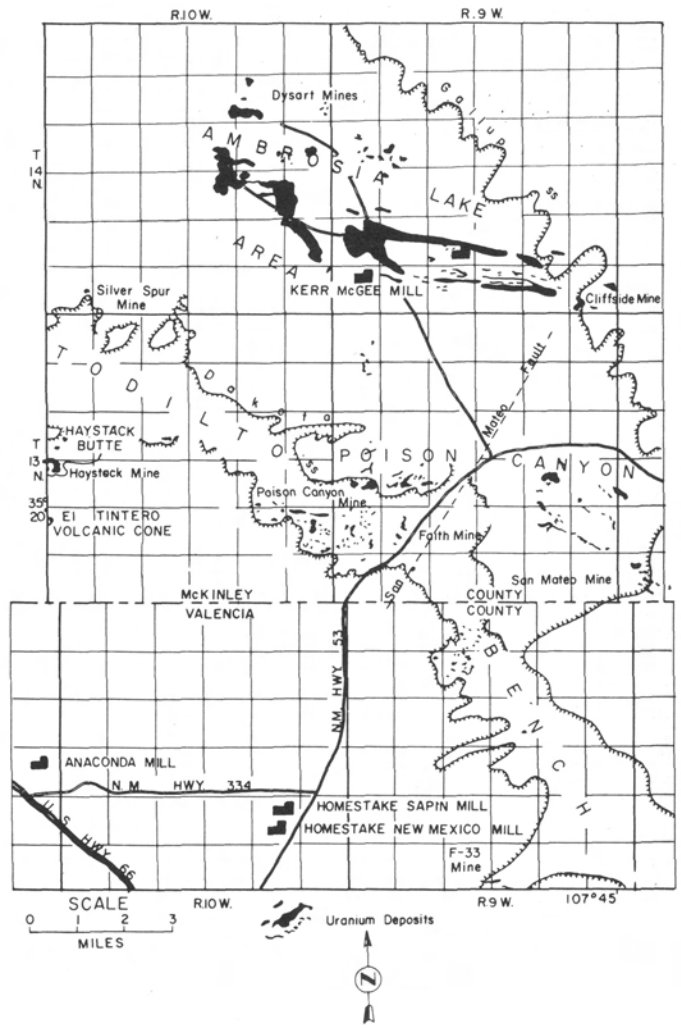

FIGURE 3.4. Map of uranium deposits in the Grants district (from Kittel et al., 1967).

ore in April 1958. The second Homestake-Sapin Partners mill commenced operating in May 1958 at an optimal capacity of 1750 tpd. The Homestake-New Mexico Partners operation closed in 1961 due to uranium market deterioration. In 1961, a consolidation of uranium properties occurred that involved the combining of the Homestake-New Mexico Partners, Homestake-Sapin Partners and Sabre-Pinon Corporation interests. The milling complex at Grants subsequently went through a series of modifications, with optimal production capacity increased to 3400 tpd. Production at the operation continued from that time period until May 1990, when milling operations were shut down.

Over the years, additional organization and ownership changes were made relating to the Homestake milling/processing operation. Homestake-Sapin Partners became the United Nuclear-Homestake Partners in 1968. This partnership was subsequently dissolved in February of 1981, and the operation became known as Homestake Mining Company-Grants.

The primary activities occurring at the site at present center around completion of a groundwater cleanup/restoration program that was commenced in the late 1970s and continues today. Seepage from the tailings piles at the milling site during operations introduced contamination into the water table underlying and downgradient of the pile locations. After final groundwater cleanup, final physical reclamation and closure of tailings piles and ancillary surface facilities related to the cleanup program will be completed with the site then scheduled to be turned over to the Department of Energy (DOE).

Initial groundwater investigations of the alluvial aquifer system underlying the United Nuclear-Homestake Partners tailings site started in 1975 with the drilling of approximately 40 wells. An initial report was developed in 1976 on the groundwater hydrology of the San Mateo alluvium at the Partnership site. Subsequent to 1976, numerous other wells in the area were also developed for use in further defining the groundwater system. Contaminants were found in two different aquifer systems. The primary aquifer is the alluvial system, which averages approximately 100 ft deep, and encompasses both the Lobo Creek and San Mateo alluvial aquifers. The alluvial aquifer flow gradient in the site area generally runs in a north to south direction. The second aquifer system is the Chinle Group. It is comprised of three separate aquifers, the Upper, Middle and Lower Chinle aquifers. The Upper and Middle Chinle sub-crop under the alluvial system near the project site. Low-level concentrations of some contaminants have been observed in the Upper and Middle Chinle aquifers near these sub-crops.

The present aquifer cleanup/restoration program underway at the Grants site consists of several freshwater and reverse osmosis (RO) product water injection systems utilized to develop a hydraulic barrier to the groundwater flow downgradient of the tailings pile areas. The injection system impedes the migration of contaminants in the aquifer system and enables the use of upgradient collection wells to retrieve contaminated aquifer water. The collected water is either sent to the RO treatment plant for processing and subsequent use in the ground water injection systems or to the on-site evaporation pond system.

The initial evaporation pond and spray system was commissioned in 1990 as part of the groundwater restoration program to provide a means of reducing the volume of collected contaminated water at the site. Toe drains were installed around the edge of the large tailings pile during 1993 to assist in collection of water from the tailings and reduce future contamination contributions to the alluvial aquifer system underlying the site. At present there are two main evaporation ponds in use in conjunction with two smaller collection ponds for ongoing management of water associated with the cleanup program.

Grants Reclamation Project Chronology/ Milestones:

- Mill Site and Tailings Pile reclamation activities began in 1993.
- Mill Site demolition and reclamation started in September 1993.
- The milling complex buildings and plant were dismantled and buried in deep pits, with demolition materials stabilized in place by addition of concrete slurry in the disposal pits. Demolition and disposal/ burial activities were completed in 5 months.

- The outer slopes of the large tailings pile were recontoured to 3-to-1 slopes for stability, then covered with a 3 ft compacted radon barrier clay cap. An 8-inch rock cap was then placed to protect the clay cap against erosion. This work was completed over a 24-month period.
- A groundwater restoration program started in 1977, continues at present, and is estimated to be completed around 2010-12.
- Final site reclamation is estimated to be completed by 2013. Upon completion of post-reclamation site monitoring, the site will be turned over to the Department of Energy (DOE) for long-term care.

After stop return to NM-605. The view as we drive back to NM-605 is directed towards the Mount Taylor composite volcano and East Grants Ridge. **0.3**

HOMESTAKE MILL

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The Homestake mill, 5.5 mi north of Milan, was the first uranium mill to process ores from the Ambrosia Lake area (Chenoweth, 1989) and actually consisted of two mills. The southern mill was known as the Homestake-New Mexico Partners mill. Homestake Company partnered with six additional companies and built the southern mill in 1957 and began production in February 1958, primarily from the Dysart, Hogan, and Section 32 mines in Ambrosia Lake to the north (Fig. 3.4). The mill used a carbonate-leaching process with caustic soda to recover uranium and had a capacity of 750 tons per day (tpd) (United Nuclear-Homestake Partners, 1968). In 1961, Homestake-Sapin Partners acquired the mill from Homestake-New Mexico Partners. That mill was closed in 1962.

A second, larger mill was built north of the first facility, also in 1957, by the Homestake-Sapin Partners, a partnership between Homestake and Sabre-piñon Corporation. Ore from the Sections 15, 23, and 25 mines was processed at this mill. This mill used a carbonate-leaching, caustic-precipitation process to recover uranium and had an initial capacity of 1650 tpd (United Nuclear-Homestake Partners, 1968). After acquiring the southern mill, Homestake-Sapin Partners expanded this mill to 3500 tpd.

In 1962, United Nuclear Corporation merged with Sabre-piñon Corporation but maintained the United Nuclear Corporation name. United Nuclear Corporation became the limited partner with Homestake, forming the United Nuclear-Homestake Partners, and continued operating the mill.

In March 1981, the United Nuclear-Homestake Partnership was dissolved, and Homestake became the sole owner. The partnership included five mines (Sections 13, 15, 23, 25, and 32) and the mill. The mill ceased production in 1981, but reopened in 1988 to process ore from the Section 23 mine and Chevron's Mount Taylor mine. The mill closed soon after and was decommissioned in 1990 and demolished in 1993. In 2001, Homestake Corporation merged with Barrick Gold Corporation.

The Homestake mill recovered 6,000,000 lbs of V_2O from 1973 to 1981 as a by-product (Chenoweth, 1989). Vanadium was removed to avoid contamination of the uranium concentrate.

Today, the mill site includes a large tailings pile covering 200 acres that is 100 ft in height, and contains 21 million short tons of tailings. The site also includes a small impoundment covering 40 acres that is 25 ft in height and contains 1.225 million short tons of tailings (U. S. Environmental Protection Agency, 2002). The tailings are built on alluvium that overlies Chinle and San Andres aquifers.

Between 1993 and 1995, under the direction and oversight of the Nuclear Regulatory Commission (pursuant to Source Materials License No. SUA-1471), the mill was demolished, and the surrounding area was reclaimed, including construction of radon barriers on the tailings piles. Surface reclamation activities included the excavation and disposal of contaminated soils and the construction of radon barrier (soil) covers and erosion protection covers (rock layers) on the perimeters of the tailings piles. Homestake continues to operate a groundwater extraction/injection system at the former mill site to dewater the large tailings impoundment and clean up groundwater contaminated by tailings seepage. It is estimated that cleanup will cost $23,292,000.

THE MOUNT TAYLOR VOLCANIC FIELD

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The Mount Taylor volcanic field (late Pliocene, 3.9 Ma to 1.7 Ma) (Fig. 3.5) is one of the many late Cenozoic volcanic fields located around the margins of the Colorado Plateau. Mount Taylor is typical of many composite cones; from a distance it appears to be a relatively simple accumulation of lava and ash around a vent. However, the symmetry of exterior form is not a good indicator of the geologic complexity. In reality, Mount Taylor, like many composite volcanoes, consists of a conglomeration of several volcanic centers of many different magma compositions, all more or less clustered around a small area. The large scale symmetry is principally a result of the accumulation of fairly thick and viscous trachydacitic and trachyandesitic lavas later in the history of the volcano and an outward-radiating apron of debris shed off of these domes mixed with late pyroclastic materials.

Early alkali basaltic eruptions initiated volcanism in the field. This was followed closely in time by eruptions of rhyolitic domes and ash. The ash in many road cuts includes large chunks of pumice that frequently bear fragments of the granitic deep crust. Basaltic volcanism occurred from isolated vents together with domes of trachyte and intermediate trachytic rocks. These

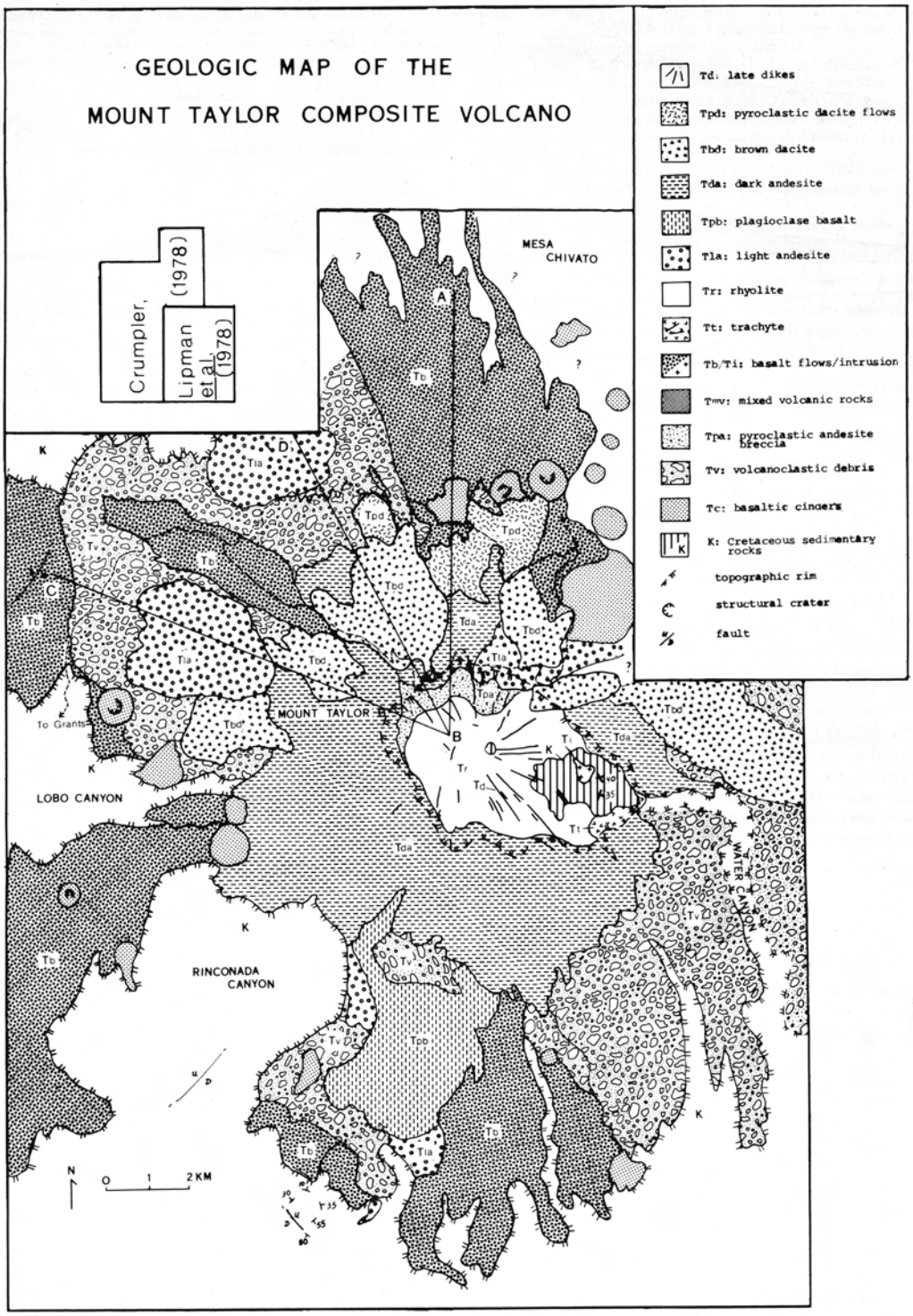

FIGURE 3.5. Geologic map of the Mount Taylor volcano, from Crumpler (1982).

began to accumulate as separate eruption centers distributed in time, but clustered near the site of the current main volcano of Mount Taylor. Continued eruption of isolated basaltic lava flows and scoria cones occurred even as the main cone of Mount Taylor had begun to take shape. As a result, thick trachydacitic lavas are interbedded on the outer slopes of the cones with aphyric and porphyritic alkali basalts bearing mantle nodules (Crumpler, 1982; Perry et al., 1990).

After the initial rhyolite eruptions, domes and thick viscous flows of trachyandesite and trachydacite began to erupt from various centers. Much of the late history involved emplacement of thick, viscous flows, and debris flows from flow domes of trachydacite near the summit. The extent to which a summit pyroclastic cone occupied the center of the volcano is undetermined. However, outcrops of intermediate composition ash and scoria on the amphitheater walls suggest that a pyroclastic cone may have

occupied the summit originally. Both erosion and late explosive modification could have played a role in its destruction.

The more viscous trachydacitic domes tended to be extruded high up on the accumulated volcanic mass. Consequently, their precarious perch on the higher elevations, together with the abundance of snow or water in the upper volcano, led to frequent collapse and avalanching of the hot and/or muddy debris down the flanks of the growing pile of volcanic material. There may have been a recurring pyroclastic cone near the center of this extrusive activity that also contributed to the abundant loose materials that now litter the lower flanks of the volcano with fine light-colored ash and large, house-size blocks of trachydacite. Radial dikes of trachydacite in the summit amphitheater were probably feeder dikes for many of the viscous extrusions. Collapse and extrusion of viscous flows, along with occasional basaltic lava flows, contributed to the final external accumulations to the volcano.

The current morphology of Mount Taylor is that of a truncated cone, centered on a point located at the head of Water Canyon within the large, summit, amphitheater-shaped valley and just east of Mount Taylor peak and La Mosca peak. This amphitheater has the shape of a large crater, although the relative contributions of erosion versus late-stage (Mount St. Helens-like) lateral collapse are debated.

The original height of the volcano is a question frequently asked by laymen. Estimates of the original height are fraught with all sorts of potential error, largely resulting from the extreme individuality of most volcanoes. Long-lived volcanoes similar to Mount Taylor experience erosion in many cases that continually worries away the steep and loosely consolidated summits even while the volcano is active. As a result, not all the material erupted succeeds in adding to the summit before limited erosion removes it prior to the next eruption. If the summit pyroclastic cone was well developed, an original cone topping out at 13,000 to 14,000 ft is within reason. Many cones evolve through several stages of growth and collapse, as well as multiple summits, rather than a single conical mass, resulting in a more rounded and "lumpy" summit. If the near-terminal morphology attained this form, then 12,000 to 13,000 ft may be a better estimate of the original height.

The San Francisco Peaks near Flagstaff Arizona, some 0.5 million years younger, are probably a good analogue for the appearance of Mount Taylor as late as 0.5 to 1 Ma. It is notable that there is good evidence that late collapse of the east flank occurred at San Francisco Mountain. A similar event could well have been involved at Mount Taylor volcano.

Mount Taylor is a part of a much larger field of volcanism (Crumpler, 1980, 1982, 1990). Mesa Chivato extends for 60 km north and east of Mount Taylor. Volcanism in the northern volcanic field consists mostly of individual scoria cones, numerous maar craters, alkali basalt lava flows, and exotic viscous lava flows of alkali compositions (hawaiite, mugearite, benmoreite, and aphyric trachyte) typically seen in oceanic islands and in the major rifts and hot spots of Earth. These include domes of silvery white trachyte, benmorite, and mugearite. Faulting was concurrent with much of the volcanism, and several long fault scarps are parallel to fissures and cut across individual cones. Fissure eruptions are better developed in the northern Mount Taylor field than in many other fields, perhaps because of the contemporaneous strong extensional environment during eruptions. Several cones are distinctly elongated along the general northeast-southwest trend of faulting and fissures. Maar craters and collapse crater overlapping along this same trend are common.

11.7 **Stop sign; turn left**. Mount Taylor at 12:00. **0.9**

12.6 Mile marker 6. At 9:30-11:00 note Jurassic section dipping northeast with lower red rock cliffs of Entrada Sandstone and cuesta beyond capped by Dakota Sandstone. The Todilto Formation forms a white cap on top of the Entrada. **0.3**

12.9 Low cuesta at 1:00 to 3:00 between the highway and La Jara Mesa is developed along the Grants monocline. The Grants monocline dips NNE and may be traced through the low gap in East Grants Ridge (southwest of the grassy scoria cone flanks) across Lobo Canyon, and across the base of Horace Mesa near the northeastern edge of Grants where it merges gently with the generally north and eastward-dipping sedimentary units sloping away from the Zuni Mountains. **0.4**

13.3 Road curves left. **0.3**

13.6 Mile marker 7. **1.0**

14.6 Mile marker 8. On low mesas to right, Entrada Sandstone is capped by limestone in the Todilto, and uranium ore was produced from numerous open pit and shallow underground mines in the Todilto Formation. El Tintero at 9:30. Haystack Mountain at 10:00 was the site of the famous discovery of uranium in the Todilto Limestone by Paddy Martinez in 1950. **0.7**

15.3 View of El Tintero at 9:30. From a distance El Tintero has the appearance of a small knob on top of a broad swell. The odd box shape of the small scoria cone, which is perched near the summit of a much broader shield volcano, is the result of quarrying for cinders that has disturbed the otherwise well-preserved flanks of a typical cone. This will be the site of the last stop of the day. **0.6**

15.9 McKinley County line. Note cuesta to left

(Fig. 3.6) at 10:00 to 11:00 with Jurassic Entrada Sandstone capped by the Todilto. **1.0**

16.9 Highway intersects the Entrada-Todilto cuesta and outcrop. **Slow down and prepare to turn left** ahead. **0.3**

17.2 **Turn left** and cross cattleguard. View is directed toward cliffs of Entrada Sandstone capped by Todilto Formation. Road proceeds on Todilto dip slope. **0.2**

17.4 Mine rubble visible on left for approximately next 2 mi is from numerous open pit and shallow underground uranium mines in the Todilto Formation. The area has been extensively reclaimed, and the open pit mines are no longer accessible. After reclamation in the early 1990s, signs in English, Navajo, and Spanish were placed in the area warning of potential radiological hazard (Fig. 3.7). Not long afterward, the signs disappeared, presumably vandalized. Additional Todilto mines, mostly underground at depths up to 500 ft, were operated to the right (north) of the road.

Uranium was also produced from deposits in sandstone at several surface and underground mines in the Poison Canyon Tongue (of economic usage) within the Brushy Basin Member of the Morrison Formation. Access to these mines was from below or just above (north) of the Dakota rims above the Morrison Formation to the north and east of this point.

FIGURE 3.6. Crossbedded eolian sandstone of the Jurassic Entrada Sandstone overlain by a thin interval of limestone of the Todilto Formation at mile 15.9.

FIGURE 3.7. Warning sign in three languages, long since removed.

Monolith at 2:00 is the eroded remnant of a large sandstone pipe in the Bluff Sandstone. **0.9**

18.3 Road curves right. Mesa ahead exposes the Jurassic-Cretaceous section at Stop 2. **0.1**

18.4 Site (to right) of Barbara J #2 underground uranium mine in the Todilto (Fig. 3.8). Production began in the 200-ft-deep mine in 1959 and continued through 1968, producing 46,495 tons of ore that yielded 191,199 pounds of U_3O_8. **0.4**

18.8 Limestone quarry in Todilto Formation on left. **0.2**

19.0 Road forks, continue left. **0.4**

19.4 Crest of hill in Quaternary dune sands. **0.3**

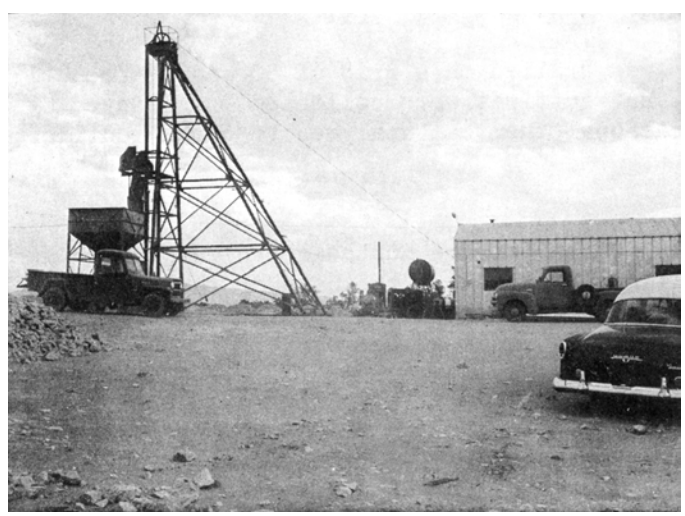

FIGURE 3.8. The headframe of the Barbara J # 2 Mine as seen in 1959 (source: Atomic Energy Commission, 1959).

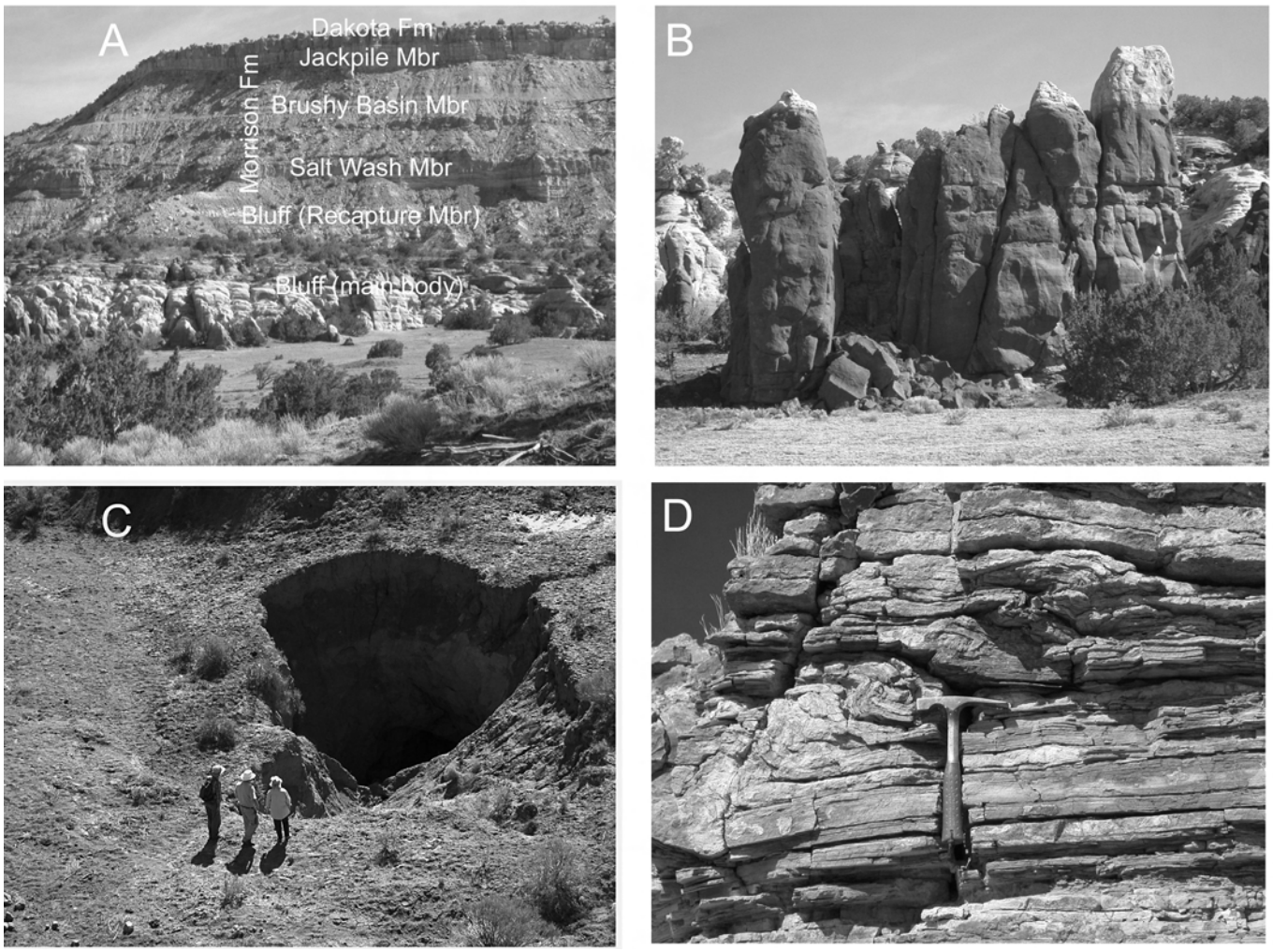

FIGURE 3.9. Four views of the Jurassic rocks at Stop 2. A. View of mesa with Bluff Sandstone (main body and Recapture members), overlain by Salt Wash, Brushy Basin, and Jackpile members of Morrison Formation capped by Cretaceous Dakota Formation. B. Closeup of main body of Bluff Sandstone. C. Post-mining collapse in Todilto Formation. D. Small scale folding in limestone of Todilto Formation.

19.7 **Stop 2**. **Pull off to right** at curve before culvert. Here, we examine large sandstone pipes in the Bluff Sandstone, and we discuss Todilto uranium deposits and mining and the intraformational folds that were the locus of uranium mineralization in the limestone (Fig. 3.9).

Numerous large and small uranium deposits in the Todilto Formation were mined from within an area of some three square miles beginning near this stop and extending back to Highway 605. This was one of the most important mining areas in the Todilto. Some of the workings of one underground mine, the Section 25 shaft, are probably directly beneath us here.

The Todilto dips up to five degrees toward the northeast in this general area. Southwest of the road (to the right, if we look back) we have been driving on the Todilto was at shallow depth and there was extensive mining from open pits and shallow underground mines. Downdip, to the northeast of the road, the mines were mostly underground at depths sometimes exceeding 400 ft.

The primary uranium deposits consist mainly of uraninite and subsidiary coffinite, with small quantities of blue-black vanadium minerals, replacing limestone along intraformational folds and at times filling fractures. Where the deposits are

extensively oxidized, as in those found close to the surface, brightly colored, yellow tyuyamunite and uranophane are important ore minerals. Tyuyamunite is the calcium analogue of carnotite, containing both uranium and vanadium.

Intraformational folds in the Todilto (Fig. 3.9D) have a wide range of sizes and geometries. Some folds that were not obviously mineralized are exposed on Todilto outcrops, especially near the former mining areas. None of the larger folds are close to this stop, but smaller examples are accessible in the Todilto outcrops south of the road.

The origin of the intraformational folds has been controversial and remains unclear. Many folds show characteristics of soft-sediment deformation of the limestone not long after its deposition. This is consistent with estimated lead-uranium ages of 150-155 Ma for the uranium deposits that are localized by the folds (Berglof and McLemore, this volume), an age close to that of the Todilto itself. One hypothesis for the formation of the folds involves slumping of limestone mud on gentle slopes in response to earthquake shaking. Such shaking might also be a factor in the formation of sandstone pipes in the Summerville and Bluff above the Todilto; pipes are most prominent in areas where the intraformational folds are best developed and the limestone is mineralized with uranium. However, analysis of the trends of intraformational fold axes does not uniquely support this concept or other alternative hypotheses, and the origin of the folds remains uncertain.

Numerous sandstone pipes occur here and in Jurassic rocks in northwestern New Mexico, especially in the Grants, Laguna, and Gallup areas. The pipes are cylindrical or sub-cylindrical and range in diameter from less than a meter to tens of meters. They commonly contain material derived from overlying rock units, sometimes retaining recognizable original stratification, or they may be composed mostly of breccia. Many are bounded by ring faults, where the material within the pipes has moved downward with respect to the country rock outside the faults. Pipes are likely to be recognized where the enclosing strata are well exposed on cliffs or slopes on the sides of mesas. Some are more resistant to erosion than the surrounding rocks and appear as distinctive erosional remnants.

Most known pipes are in the Bluff Sandstone and the Summerville Formation, and were first recognized and described in the early 1950s when the Jurassic rocks received intensive study following uranium discoveries near Grants and Laguna. Attention was also drawn at the same time to the smaller number of pipes occurring in the Morrison Formation, as some of these are mineralized with uranium, most notably the Woodrow deposit near Laguna (Wylie, 1963), along with a few additional ones in the Laguna and Grants districts. None of the many pipes in the Bluff and Summerville are known to be mineralized. Exposed pipes in these formations in the Grants district are clustered near the area of most intense uranium mineralization in the Todilto Formation, and not far from the larger deposits in the Morrison, but there is no known connection between the Bluff/Summerville pipes and the uranium deposits.

The origin of the pipes has been the subject of considerable debate and remains unclear. The most likely origin seems to be related to foundering of sand into underlying water-saturated mud not long after the sediments were deposited (Schlee, 1963; Moench and Schlee, 1967). Several authors have suggested that solution of the underlying Todilto limestone and gypsum may have been a contributing factor, but have not cited direct evidence in support of this hypothesis. However,

no outcropping pipes are known to extend downward into the Todilto, nor is the formation known for extensive karst or cave development. Extensive underground mining of Todilto uranium deposits in the Grants district similarly did not encounter sandstone pipes penetrating the limestone host rocks. One intriguing hypothesis, first hinted at in one of the earliest studies (Rapaport et al., 1952) and mentioned more specifically by Schlee (1963), is that earthquakes could have contributed to the formation of sandstone pipes. A voluminous literature now exists on "seismites" (seismogenically produced or altered structures) in numerous geological environments (e.g., Ettensohn et al., 2002). Under this hypothesis sandstone pipes could have affinities with sand boils and other water-escape structures observed to form during modern earthquakes.

After stop, continue west on unpaved road. 0.4

20.1 **Cattleguard. 0.4**

20.5 Crest of hill; after rounding a curve, the view at 12:00 is of the crest of the Zuni Mountains along the skyline and the mesa-like shape of Mount Sedgwick (9256 ft elevation); cross and descend through the Todilto Formation. Good view of the Jurassic section on Dos Lomas on the right. **0.3**

20.8 **Cattleguard;** Black Mesa (West Grants Ridge) is on the skyline at 11:00. Note Todilto exposures on left. **0.4**

21.2 Cross **one-lane metal bridge** (weight limit 10 tons). **Cross carefully!** On right are unusual mounds in the Todilto Formation (Fig. 3.10). These enigmatic, vaguely fold-like features, not known with this geometry elsewhere in the Todilto, may have formed in soft lime mud as a result of sediment loading from encroaching overlying dune sands (Green, 1982). **0.1**

21.3 Crest of hill; cross and descend through the Todilto Formation. Good view of the Zuni Mountains ahead. **0.2**

21.5 **Cattleguard. 0.2**

FIGURE 3.10. Mound in Todilto Formation limestone at mile 21.2.

21.7 Note Entrada Sandstone to right; Wingate Sandstone ("Iyanbito Member") visible at base of exposure is at one of its westernmost outcrops. **0.6**

22.3 Pass under power lines. **0.5**

22.8 Crest of hill; road to left. At 10:00, note the dip slope of the Permian San Andres Limestone over Yeso red beds on the north flank of the Zuni Mountains. El Tintero volcanic cone is at 11:00, an exposure of Todilto Formation above the Entrada Sandstone at 12:00, and Haystack Mountain at 1:00 with a section above the Todilto including Summerville, Bluff, and Morrison formations, with a Dakota Formation cap. **0.5**

23.3 Summit of El Tintero volcano at 10:30. Haystack Mountain (Fig. 3.11) at 12:30**. 0.8**

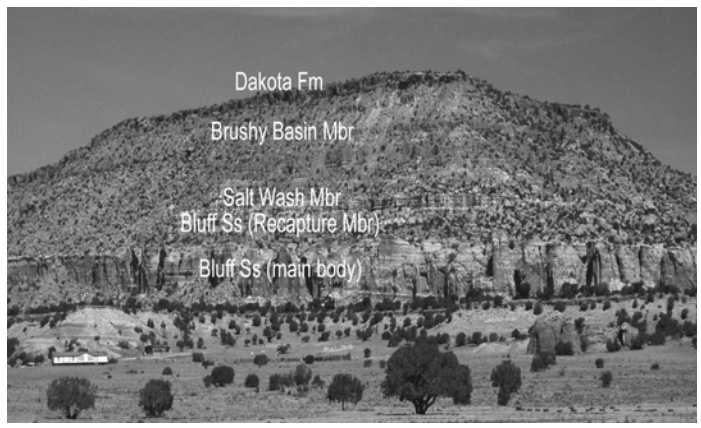

FIGURE 3.11. Photograph of Haystack Mountain (Butte).

24.1 Culvert. View of El Tintero. **0.6**

24.7 Cattleguard. Todilto caps Entrada mesa ahead. **0.6**

25.3 Road enters at an angle from right; bluff to right is Entrada capped by Todilto. Good view to left of El Tintero and cinder quarry on it (Fig. 3.12); continue straight ahead. **0.2**

25.5 **Stop 3** at crest of hill. Road crest crosses basalt of El Tintero. Lunch stop. Examine El Tintero volcanic cone and review local mining history. El Tintero ("the inkwell") is a small shield volcano (elevation, 7222 ft) at the northwest end of the Bluewater basalt flow (Fig. 3.12). The Bluewater flow from El Tintero is isolated from the other relatively young flows of the Grants area, and extends more than 10 mi along and to the north of I-40, from a little south of Prewitt, past Bluewater, to NM Highway 605, a short distance northwest of Milan. The flow is tholeiitic in composition and preserves many primary flow structures (Crumpler, 1982).

The vent area (Fig. 3.12) is characterized by a summit scoria cone that contains a small bowl-shaped crater. Although much damaged now from cinder quarrying operations, the flanks of the cone are relatively undissected. An unusual lobe-shaped feature at the southwest base of the cone has the characteristics typical of perched lava ponds. Similar, but much larger examples of this feature occur at the source area of the Jornada del Muerto volcano in southern New Mexico.

Laughlin et al. (1993) and Laughlin and WoldeGabriel (1997) summarized the ages obtained for the Bluewater flow from three different dating methods: ^{3}He yielded 57 $\pm$ 6 ka; ^{36}Cl gave 35.6 $\pm$ 3.4 ka (probably too young), and uranium series work produced an age of 79 $\pm$ 40 ka.

The volcanic flows of the Mount Taylor area were of special interest to Captain Clarence E. Dutton, who surveyed the geology of the Zuni Plateau and Mount Taylor region, and produced one of the classic works in the history of American geology (Dutton, 1885). Dutton recognized for the first time that these flows were of different ages, and that the younger flows had nothing to do with the eruptions of Mount Taylor. Dutton's (1885, p. 180-181) comments on El Tintero (Fig. 3.13) convey well his exceptional powers of observation and interpretation:

"The lavas from the north of Bluewater [flowed from] the Tintero (inkstand), a low lava cone so inconspicuous that no geologist or other traveler who has written of this country appears to have noticed it hitherto.

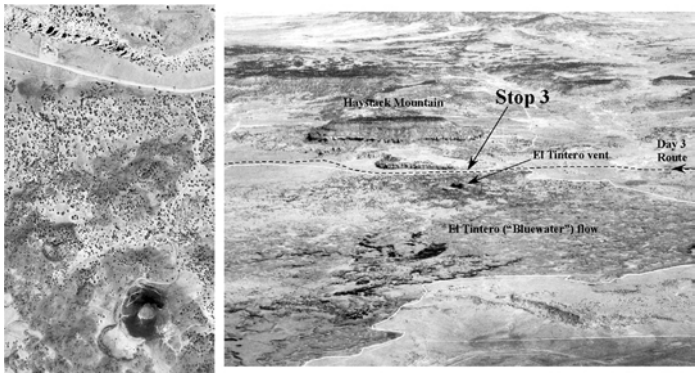

FIGURE 3.12. Vertical air photo (left) of the vent area for El Tintero volcano and surrounding lava flows (also known as the Bluewater flow). Note the lobe-shaped lava pond surface at the southwest base of the cone. Oblique air photo (right) of El Tintero, Haystack Mountain, and most of the area encompased in the Day 3 road log.

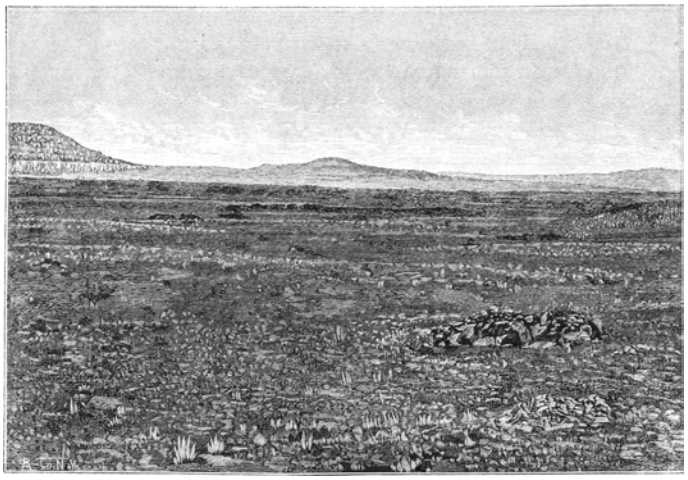

FIGURE 3.13. Dutton's (1885, fig. 25) woodcut illustration of El Tintero.

It has always been supposed that these fields of "malpais" emanated from Mount Taylor, and the supposition is a most natural one. Any one who crosses them or skirts along their edges without taking the pains to follow them to their sources would jump at once to that conclusion. From every point on the surface of the malpais Mount Taylor rises grandly as the most commanding object of the landscape; its volcanic nature is betrayed in every line and feature, and there is nothing else in sight to suggest a volcanic vent. But it is quite certain that they did not come from Mount Taylor, nor from any of its appendages; and the origin which I have stated has been verified with absolute certainty.

The Tintero vent is a low mound, rising by feeble slopes to a height which is difficult to state for want of any definite plane to refer it to. It may be represented rather as the maximum point of thickness in the sheets of lava, which are piled one on another or which spread out from it in every direction except the north. A well developed crater is found at the summit. It is not composed of fragmental ejecta but of massive lavas….It is evident that many streams have flowed from it, spreading out east and west to a width of five miles and flowing southerly into the trough of the [Rio] San Jose. Midway between Bluewater and Grant [sic] the streams narrow to the width of a mile or less. In many places the sheets are very fresh, but the older ones have been drifted over with blown sand and soil, through which the rough clinkers still project. Some of these streams may be many hundreds of years old, but others betoken such recency that we are tempted to attach some credence to the traditions of the Mexicans that when their Spanish ancestors first came to these regions they were still hot and steaming."

One of the largest uranium deposits in the Todilto, and one of the first to be developed and mined, was immediately behind the Todilto rims above this point, mainly in sec. 19, T13N, R10W. It has been reclaimed. The legendary discovery (or rediscovery) in 1950 of uranium in the Todilto by Paddy Martinez, a Navajo sheepherder, which initiated the uranium boom in the Grants district, was at Haystack Mountain (also referred to frequently as Haystack Butte.) There were additional uranium mines in the Todilto to the right (north) of the road west of Stop 3. **To return to I-40 continue straight west. 1.9**

27.4 Paved road begins. Crest of Zuni Mountains between 9:00-12:00. **2.1**

29.5 Pass under railroad tracks, dirt road. **0.1**

29.6 Stop sign. **Turn left** on old Highway 66 to return to Grants. **0.2**

29.8 View of El Tintero and Mount Taylor at 10:00. **2.6**

32.4 Edge of lava flows from El Tintero. **0.3**

32.7 Road cut in El Tintero lava flows revealing the upper vesicular zone of the flows. **0.7**

33.4 Road descends margin of lava flows that continue to the left of the road. Numerous topographic rises here are relief features typical of lava flows variously referred to as "pressure ridges." **1.2**

34.6 The road crosses another toe of the lava flow. **1.1**

35.7 **Turn right** onto NM Highway 606. **0.4**

36.1 **Turn left** (east) onto I-40 on ramp. Mount Taylor is at 10:00.

End of Third-day Road Log.