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

Spencer G. Lucas, Steven C. Semken, Andrew B. Heckert, William R. Berglof, Gretchen Hoffman, Barry S. Kues, Larry S. Crumpler, and Jayne C. Aubele

2003, pp. 1-34. https://doi.org/10.56577/FFC-54.1

in:

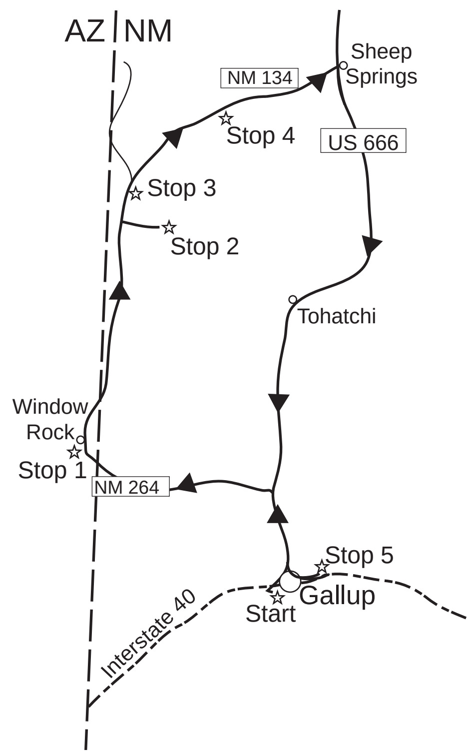
Geology of the Zuni Plateau, Lucas, Spencer G.; Semken, Steven C.; Berglof, William; Ulmer-Scholle, Dana; [eds.], New Mexico Geological Society 54th Annual Fall Field Conference Guidebook, 425 p. https://doi.org/10.56577/FFC-54

This page is intentionally left blank to maintain order of facing pages.

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

SPENCER G. LUCAS, STEVEN C. SEMKEN, ANDREW B. HECKERT, WILLIAM R. BERGLOF, GRETCHEN HOFFMAN, BARRY S. KUES, LARRY S. CRUMPLER AND JAYNE C. AUBELE

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).

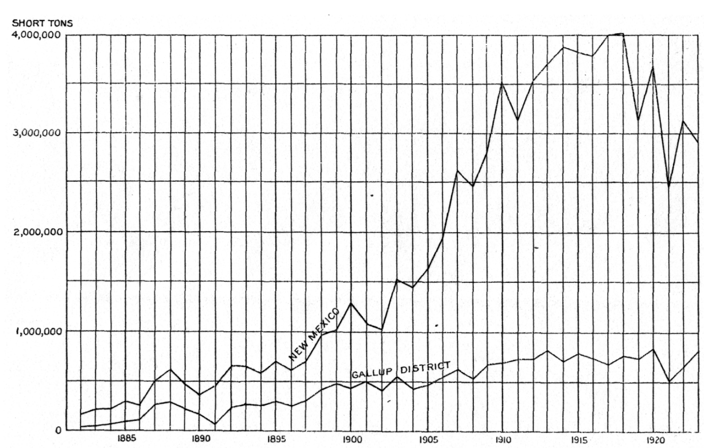


FIGURE 1.1. Annual coal production in the Gallup area and in New Mexico, 1882-1923 (from Sears, 1925).

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**

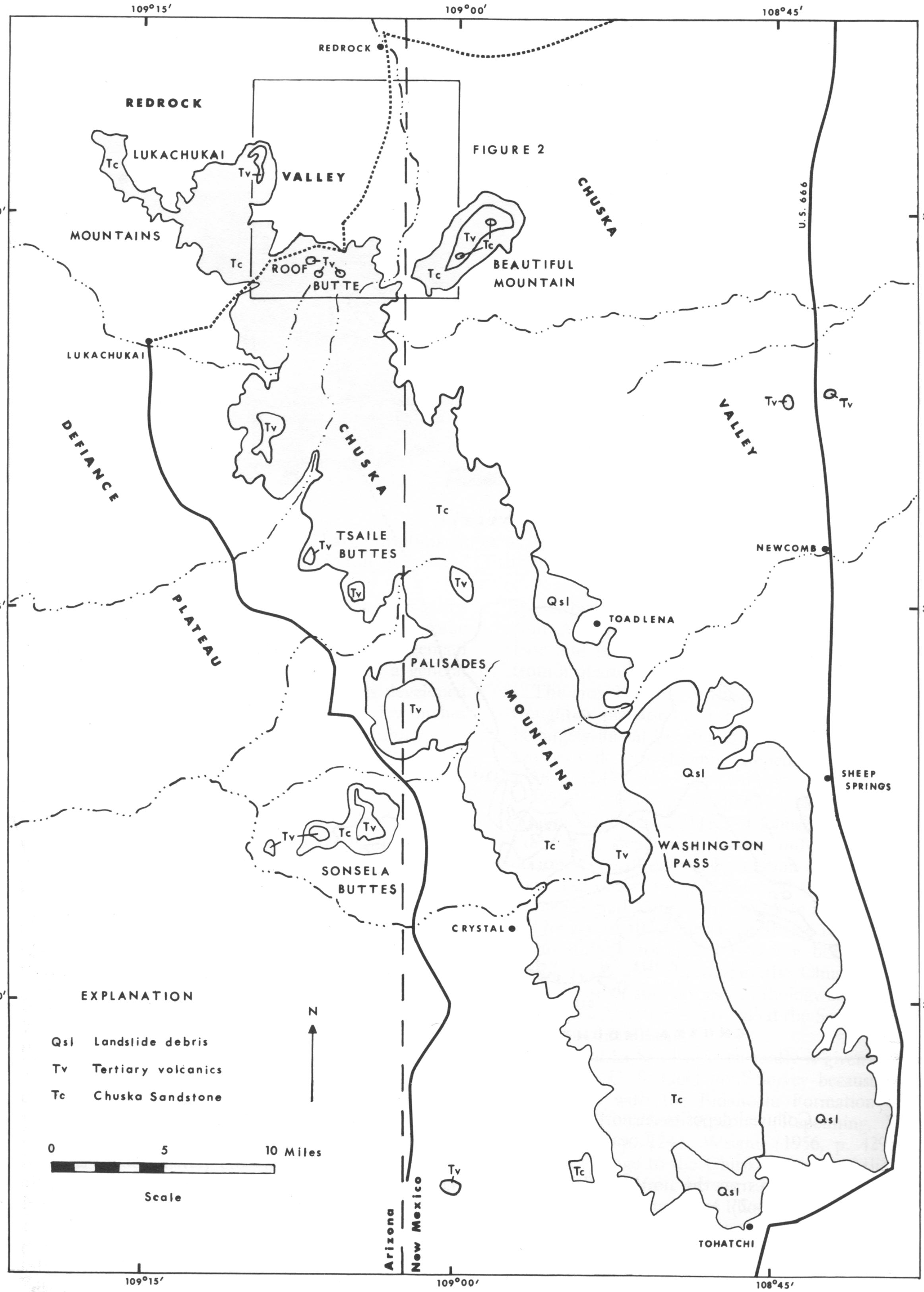


FIGURE 1.2. Generalized geologic map of the Chuska (Ch'óshgai) Mountains (from Blagbrough, 1967). Qsl = Quaternary landslide depositss, Tc = Chuska Sandstone and, Tv = Navajo volcanics.

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 Tséghádhoodzání, "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

S. M. Cather
New Mexico Bureau of Geology and Mineral Resources,
New Mexico Tech, Socorro, NM 87801

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

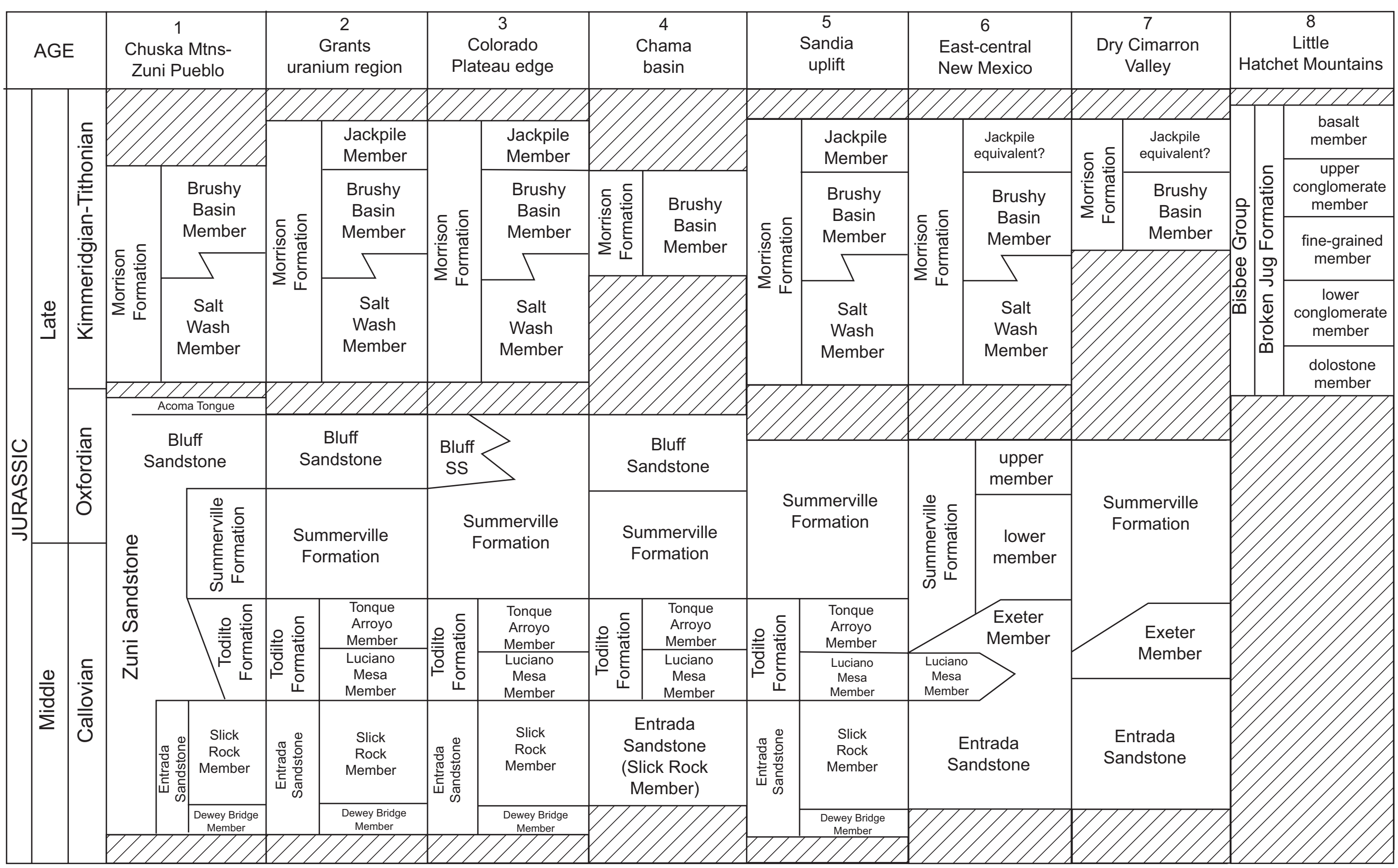


FIGURE 1.5. Correlation of Jurassic strata in New Mexico (from Lucas and Anderson, 1998).

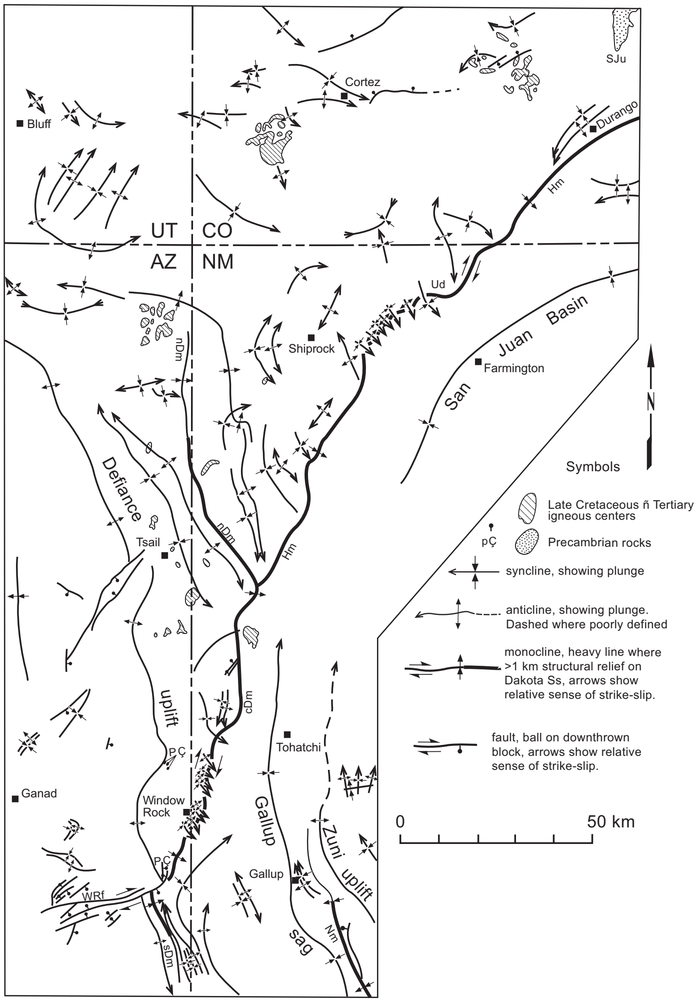


FIGURE 1.6. Map of structures in the Four Corners–Gallup region. Hm, Hogback monocline; SJu, San Juan Uplift; Ud, Ute dome; nDm, north Defiance monocline; cDm, central Defiance monocline; sDm, South Defiance monocline; WRf, Wide Ruins fault; Nm, Nutria monocline. Modified from Kelley (1967) and Woodward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

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

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

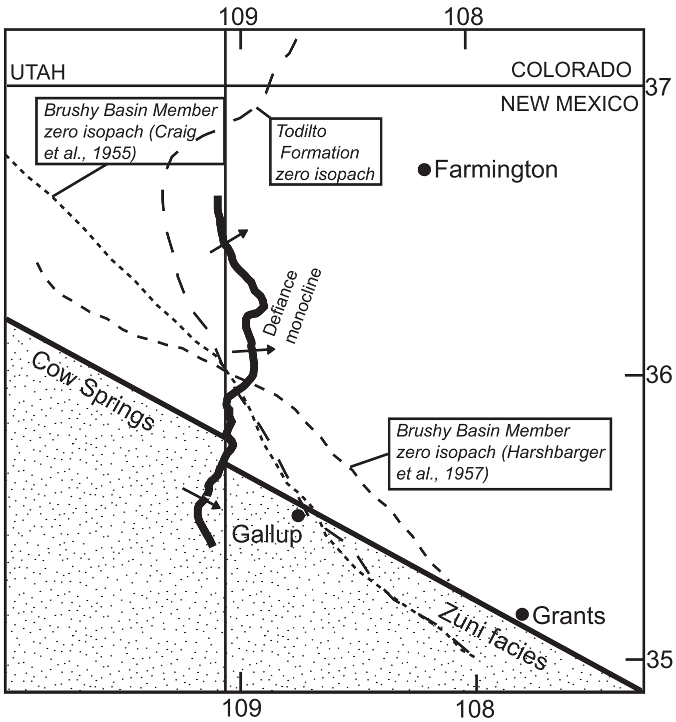


FIGURE 1.7. Map of part of northwestern New Mexico and northeastern Arizona showing dextral offset across the Defiance monocline (after Kelley, 1967) and zero isopach contours of the Todilto Formation (from Kirkland et al., 1995) and Brushy Basin Member of the Morrison Formation.

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**

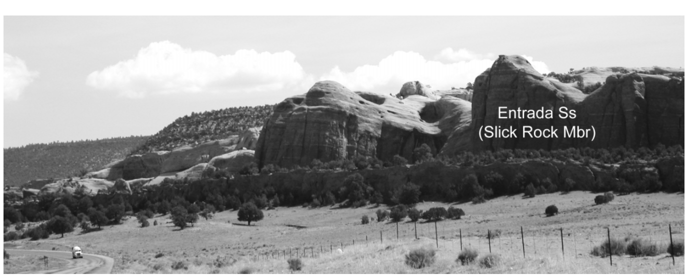


FIGURE 1.8. Panoramic view of Mesozoic section from mile 37.2.

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 Irrigation 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**

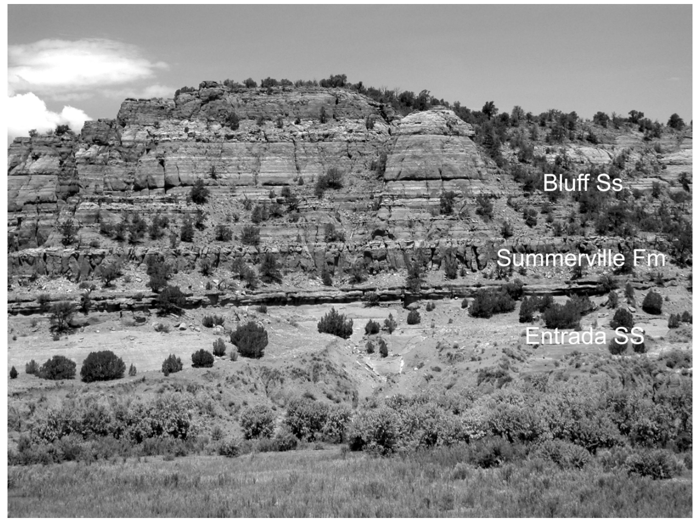


FIGURE 1.12. Entrada-Summerville-Bluff section north of the road at mile 49.5.

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.

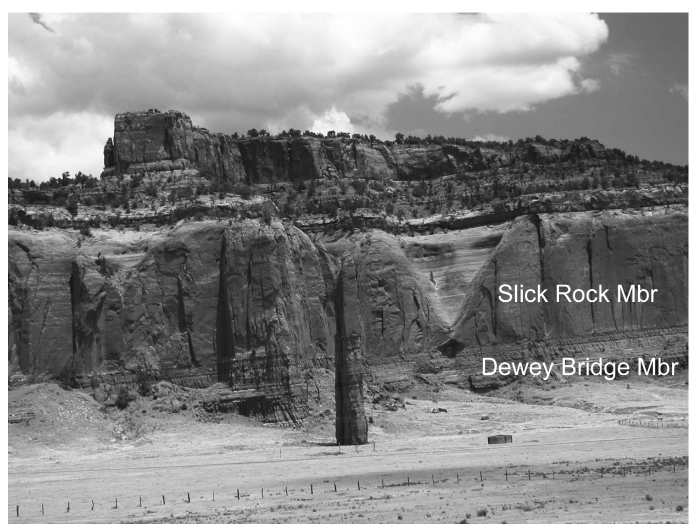


FIGURE 1.13. Venus Needle, an erosional outlier of the cliffs of Entrada Sandstone.

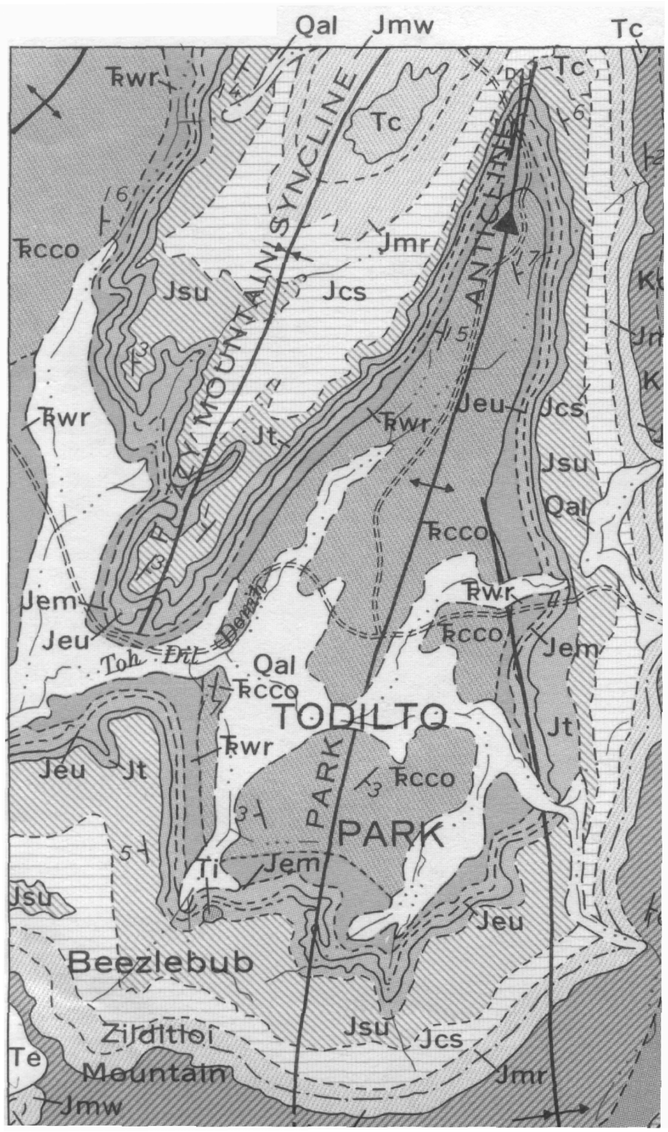


FIGURE 1.14. Geologic map of Todilto Park (from Cooley et al., 1969). Units are: Trcco = Owl Rock Formation, Trwr = Wingate Sandstone, Jem = Dewey Bridge Member of Entrada Sandstone, Jeu = Slick Rock Member of Entrada Sandstone, Jt = Todilto Formation, Jsu = Summerville Formation, Jcs = Bluff Sandstone (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

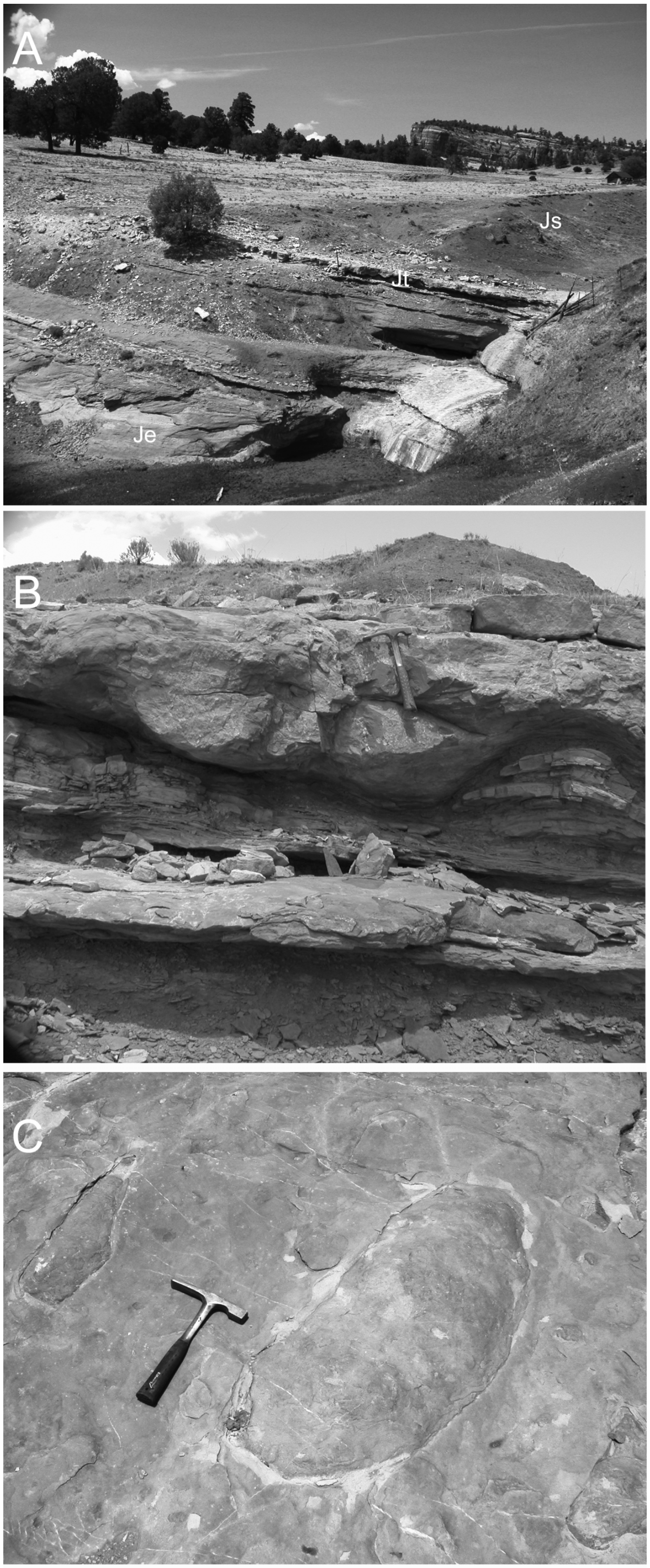


FIGURE 1.15. Outcrop of the Todilto Formation at Stop 2. A, Overview Je = Entrada, Jt = Todilto, Js = Summerville). B-C, Cross section (B) and outcrop (C) views of so-called Todilto stromatolites.

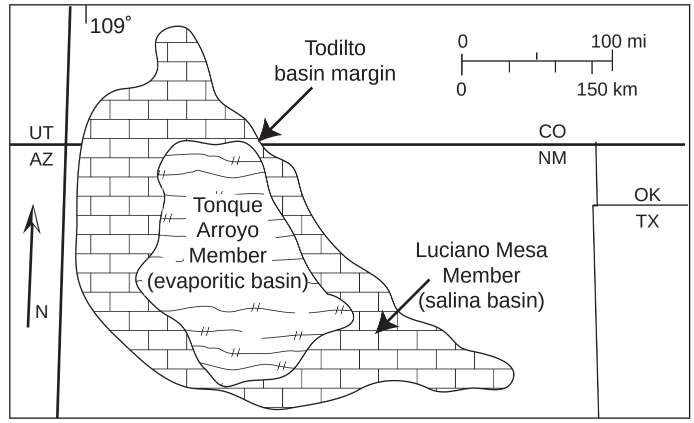


FIGURE 1.16. Distribution of the two members of the Todilto Formation in northern New Mexico and southwestern Colorado (after Lucas and Anderson, 1997).

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

Spencer G. Lucas[1], Andrew B. Heckert[1] and William R. Berglof[2]
[1]New Mexico Museum of Natural History,
1801 Mountain Rd. NW, Albuquerque, NM 87104;
[2]University of Maryland University College-Asia, Unit 5060,
Box 0100, APO AP 96328-0100

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.

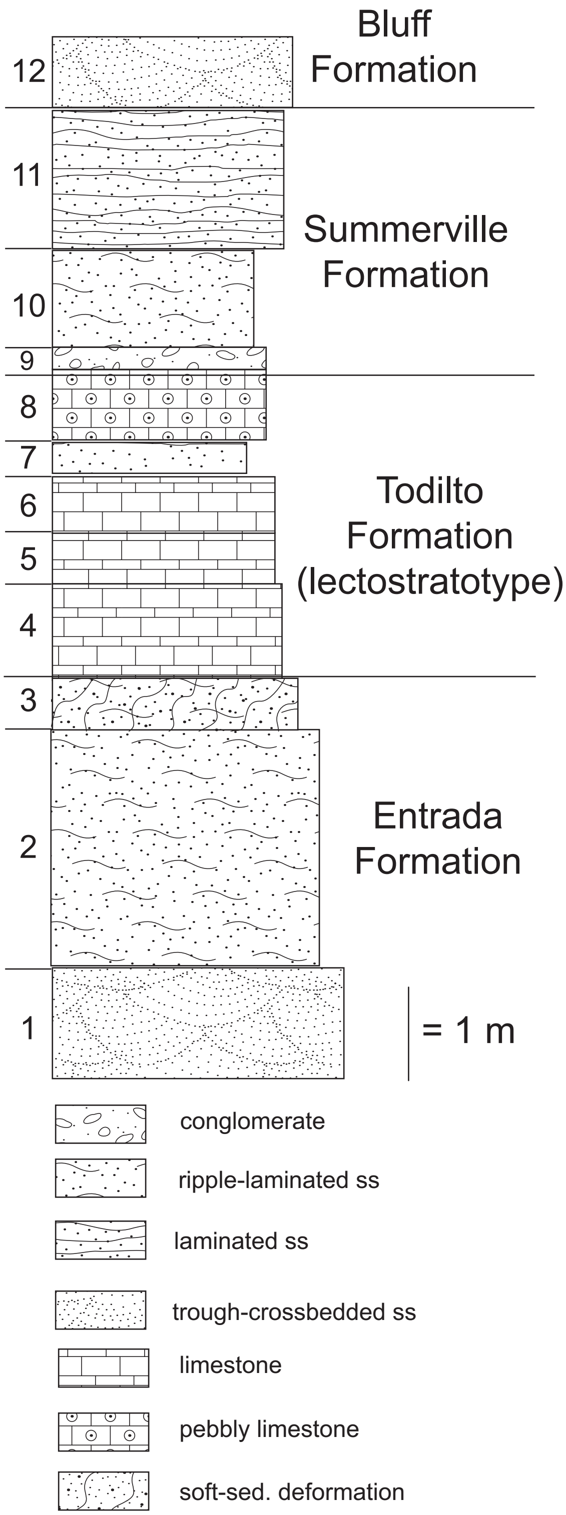


FIGURE 1.17. Lectostratotype section of the Jurassic Todilto Formation.

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

Fraser Goff
EES-6, Los Alamos National Laboratory, Los Alamos, NM 87545

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

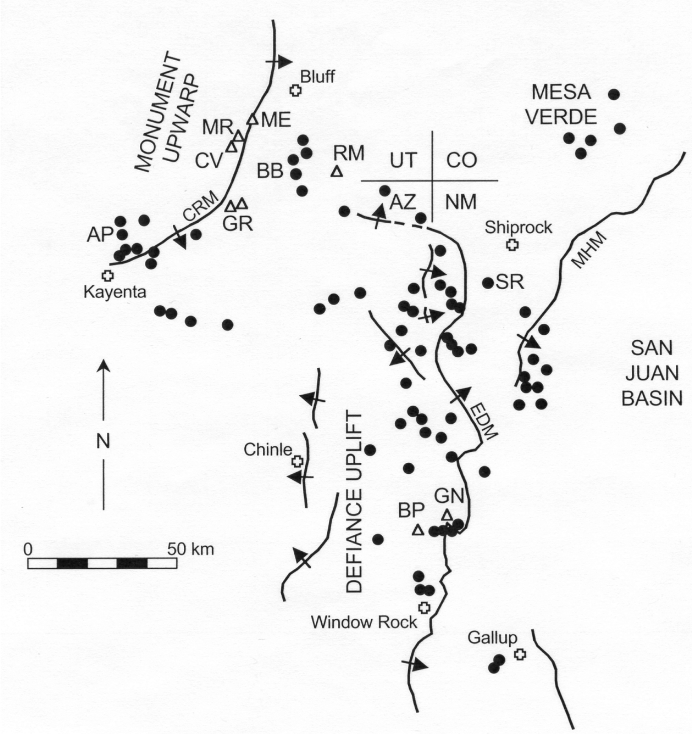


FIGURE 1.20. Map of the central Navajo volcanic field, after Smith and Levy (1976) and McGetchin et al. (1977). Dark circles indicate minettes; open triangles represent SMUs. Monoclines are indicated by heavy lines. Abbreviations: AP = Agathla Peak, AZ = Arizona, BB = Boundary Butte, BP = Buell Park, 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 nіłts’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

Spencer G. Lucas
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

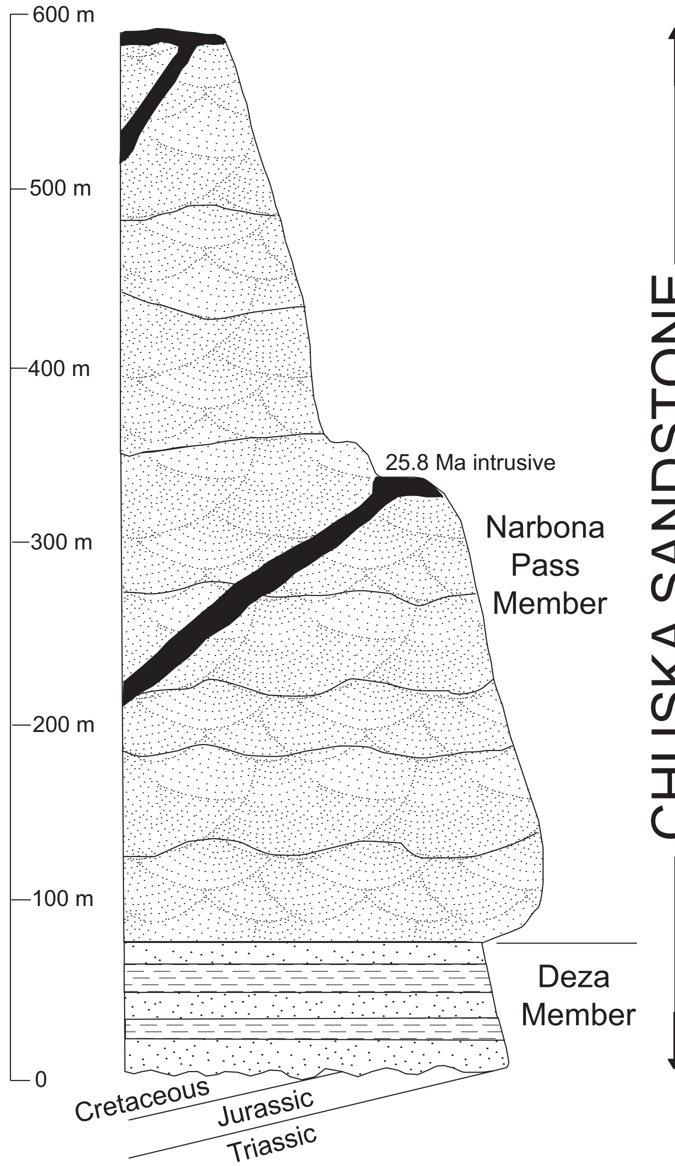


FIGURE 1.21. Generalized stratigraphy of the Chuska Sandstone (modified from Trevena, 1979).

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 intrusives 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$\pm$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 líchíí'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.

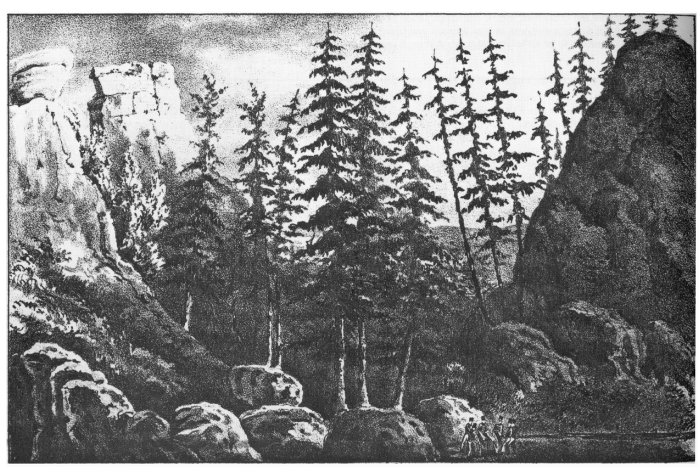


FIGURE 1.23. Simpson's (1850) drawing of Narbona (Washington) Pass.

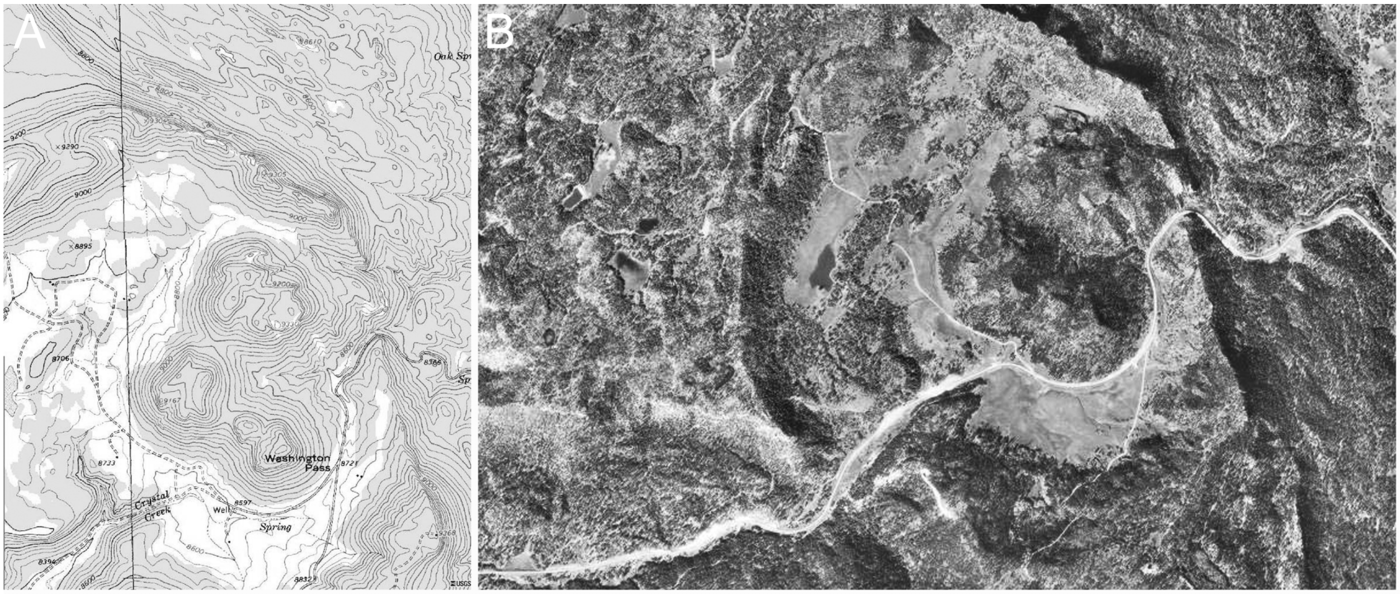


FIGURE 1.24. Topographic map (A) and aerial photograph (B) of Narbona Pass maar.

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

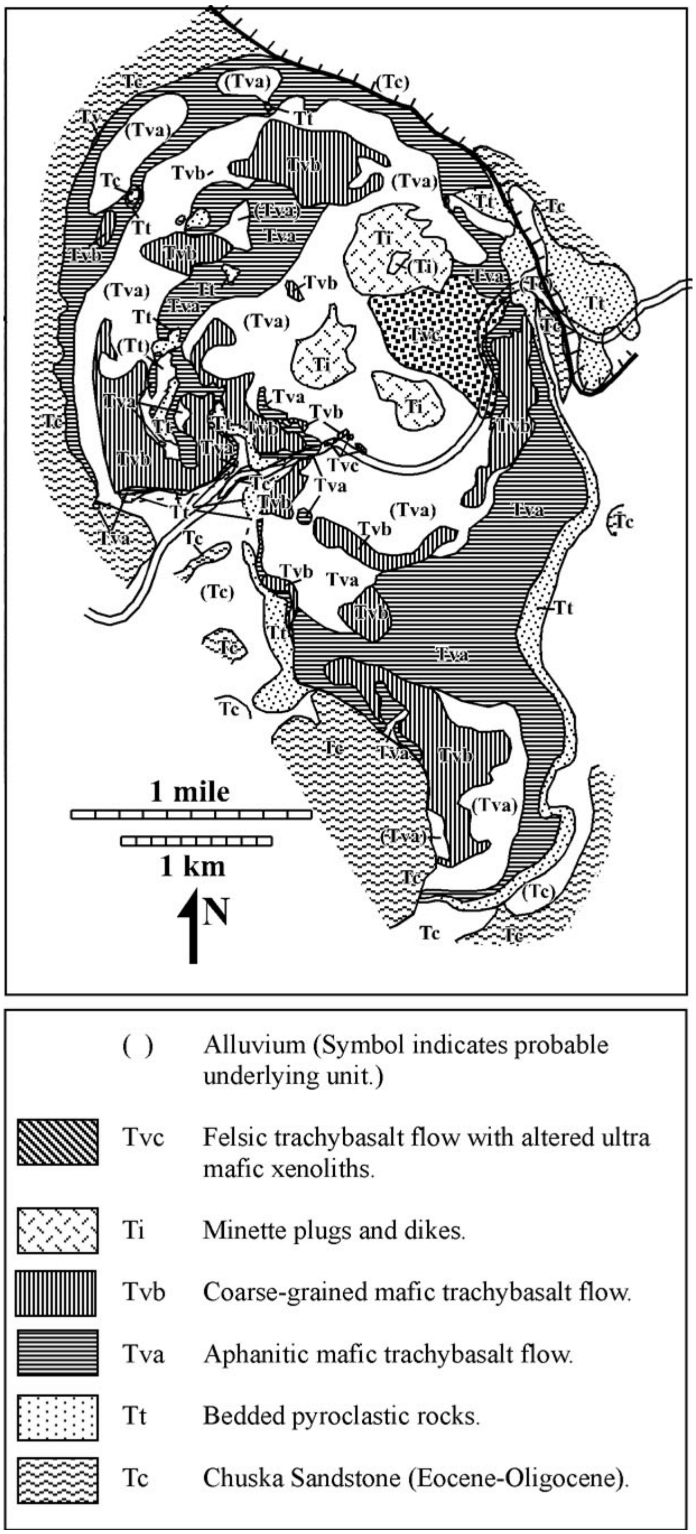


FIGURE 1.25. Geologic map of Narbona Pass maar (after Ehrenberg, 1978).

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 líchíí'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**

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**

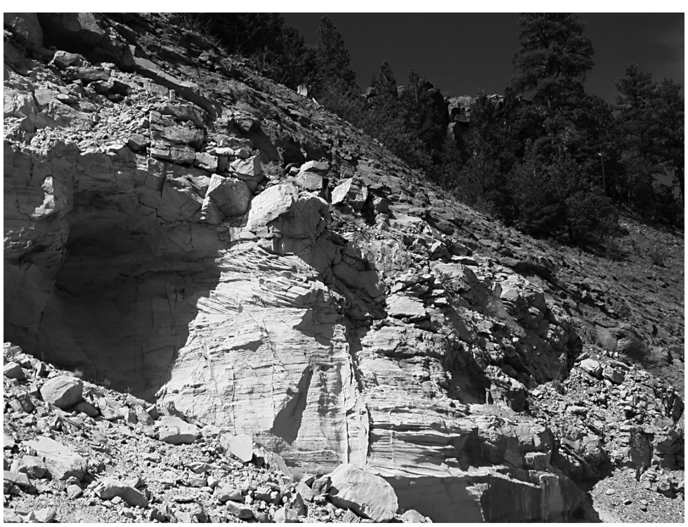


FIGURE 1.27. Narbona Pass Member of Chuska Sandstone and overlying pyroclastic beds at mile 79.15.

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**

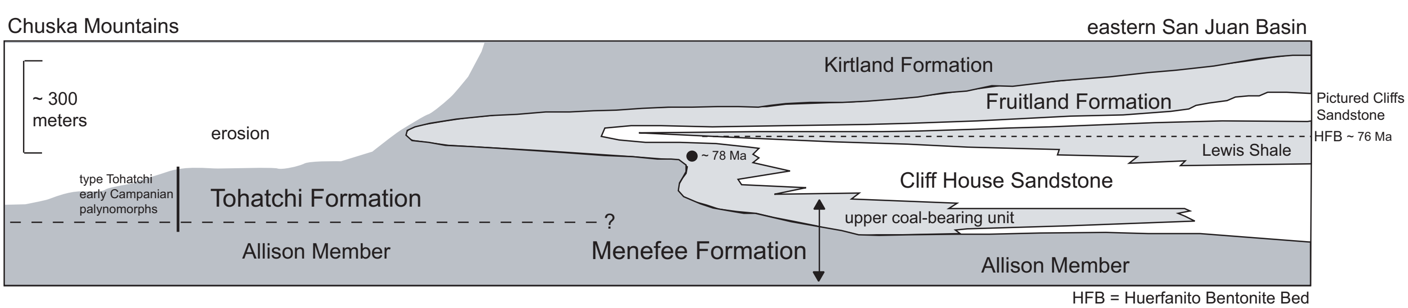


FIGURE 1.29. Restored cross section (based in part on O'Sullivan et al., 1972, fig. 8) showing correlation of Tohatchi Formation in Chuska Mountains to units in the eastern San Juan Basin. Ar/Ar age of upper Menefee Formation from Amarante et al. (2002) and of Huerfanito Bentonite Bed from Fassett et

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,

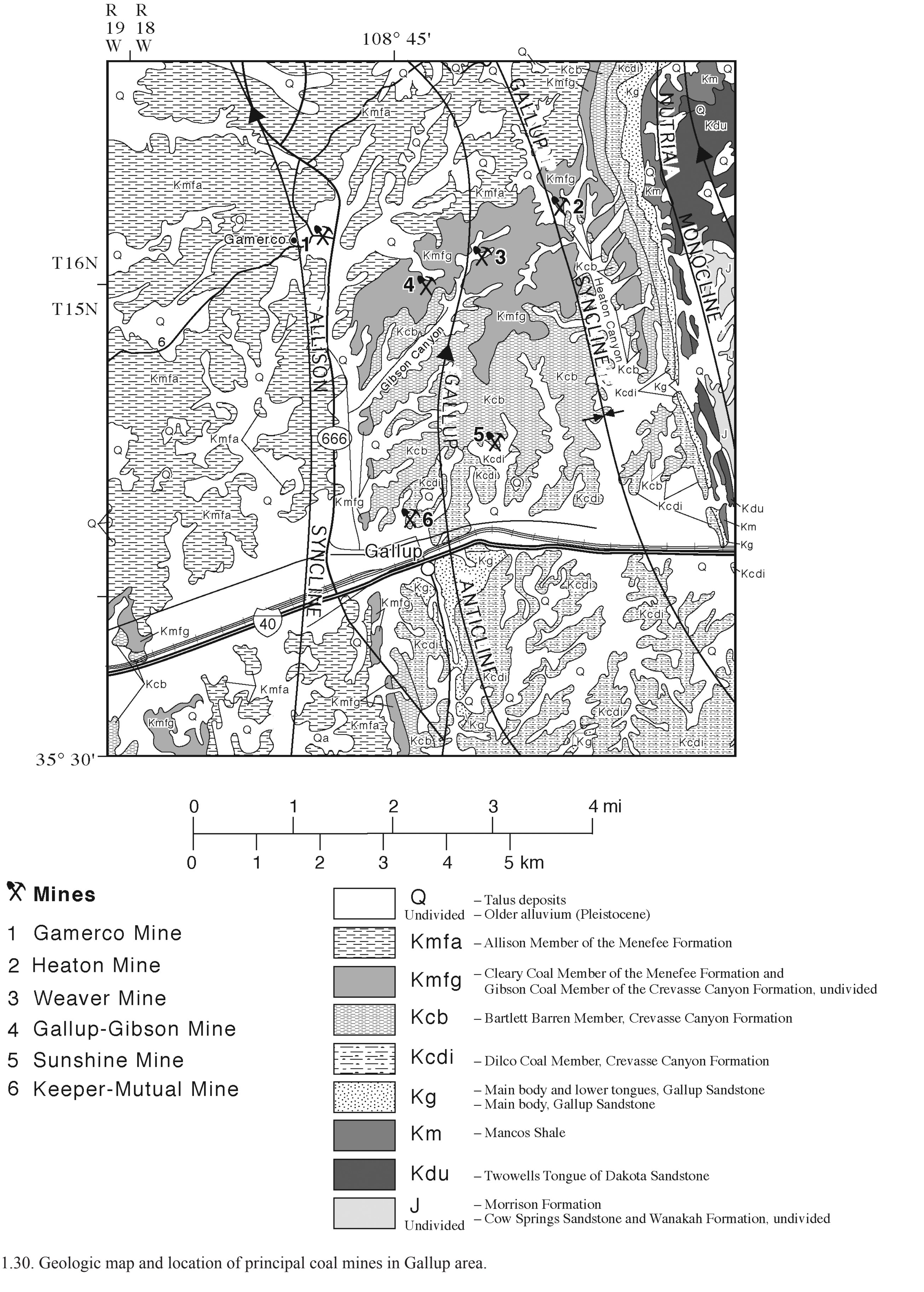


FIGURE 1.30. Geologic map and location of principal coal mines in Gallup area.

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

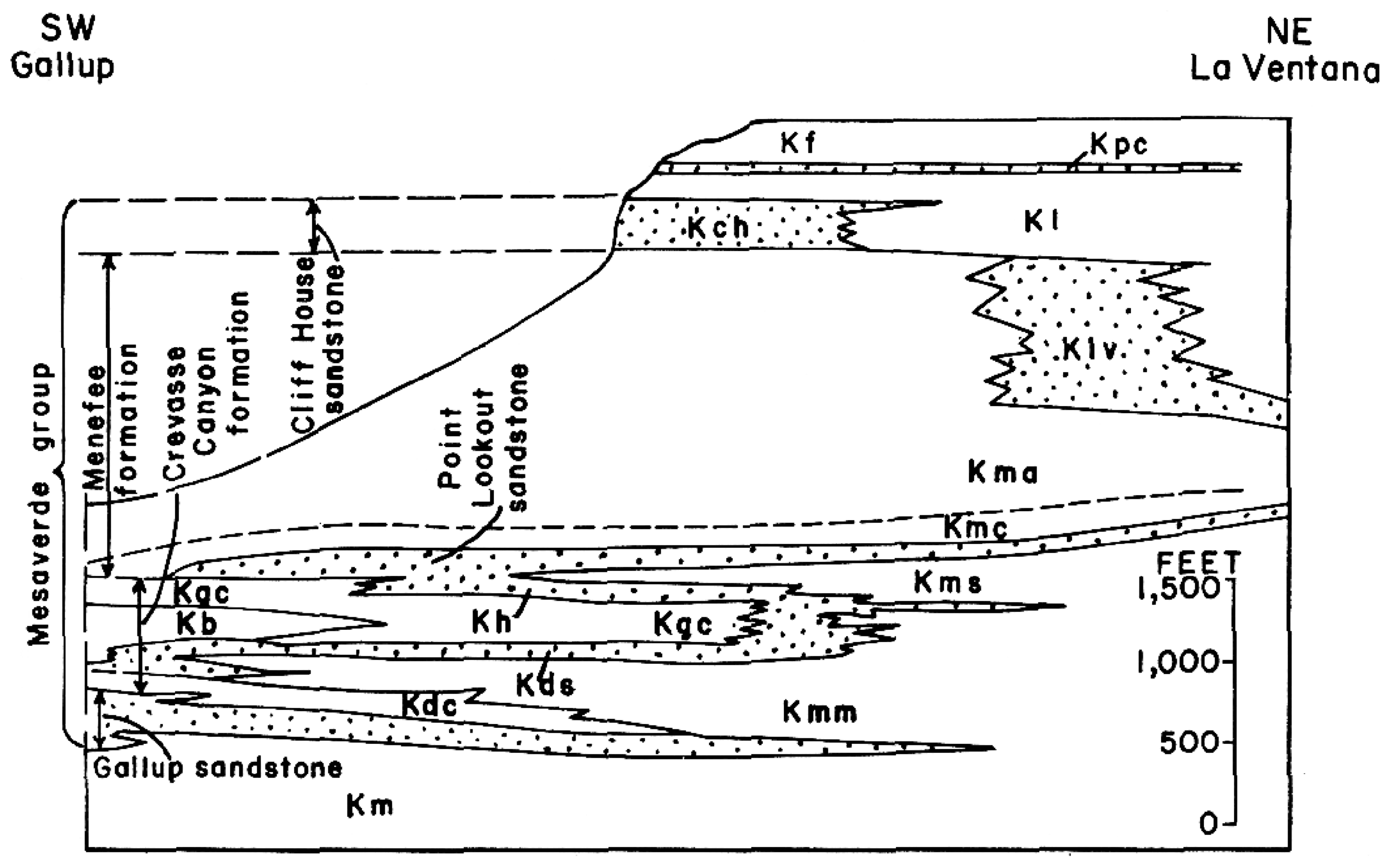


FIGURE 1.31. Cross section of intertongued marine, shoreline and coal-bearing Cretaceous strata in the Gallup area and across the San Juan Basin (from Baltz et al., 1967). Stratigraphic units are: Kf = Frutiland Formation and younger strata, Kpc = Pictured Cliffs Sandstone, Kl = Lewis Shale, Kch = Cliff 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

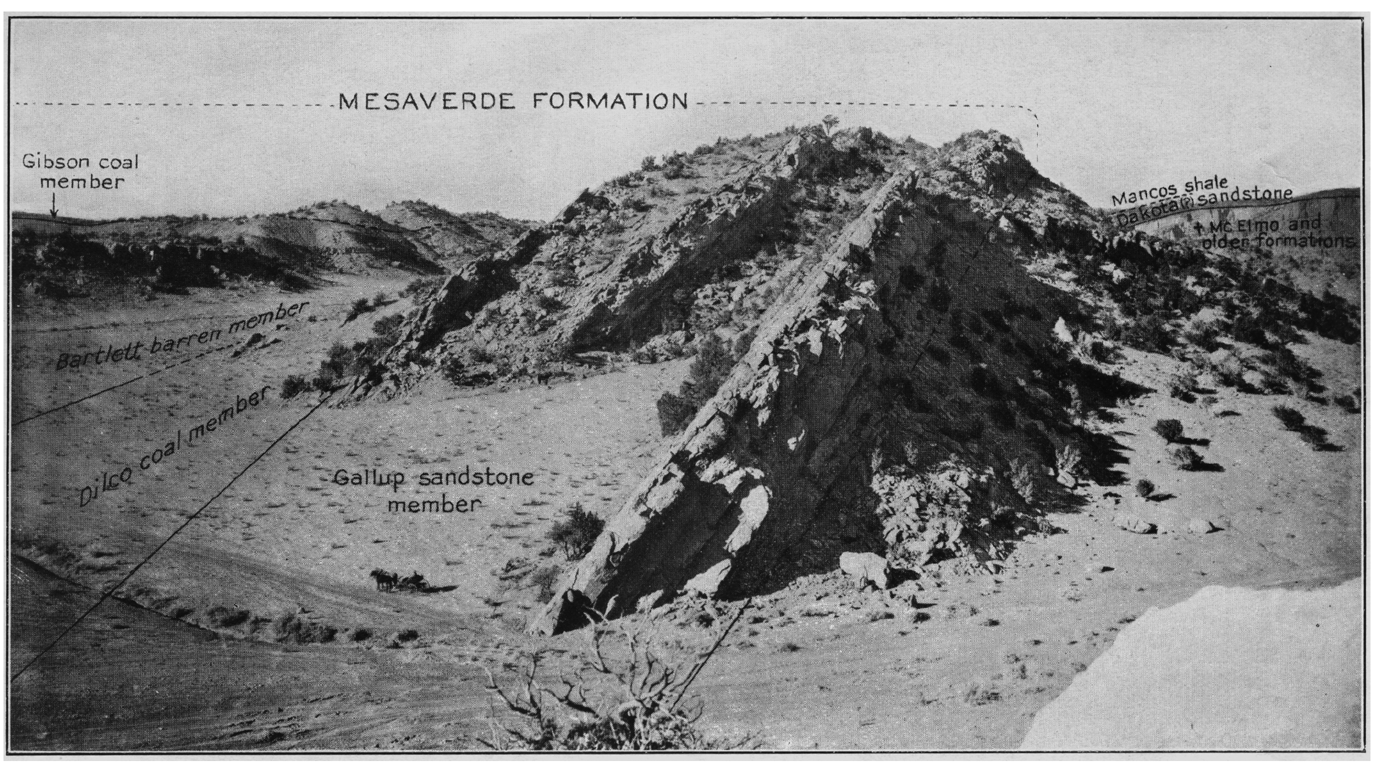


FIGURE 1.33. Sears' (1934, pl. 7) photograph of the type section of the Gallup Sandstone.

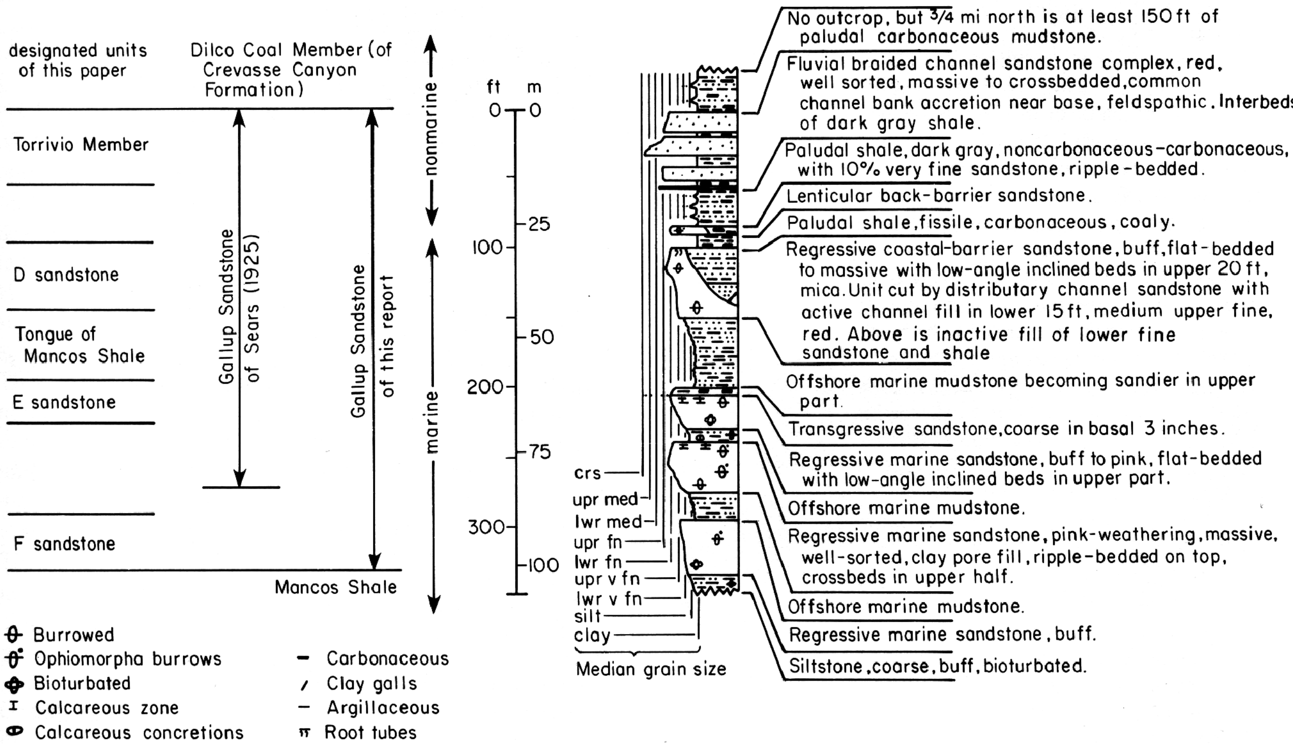


FIGURE 1.34. Molenaar's (1983) columnar principal reference section of the Gallup Sandstone.

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

Spencer G. Lucas
New Mexico Museum of Natural History,
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

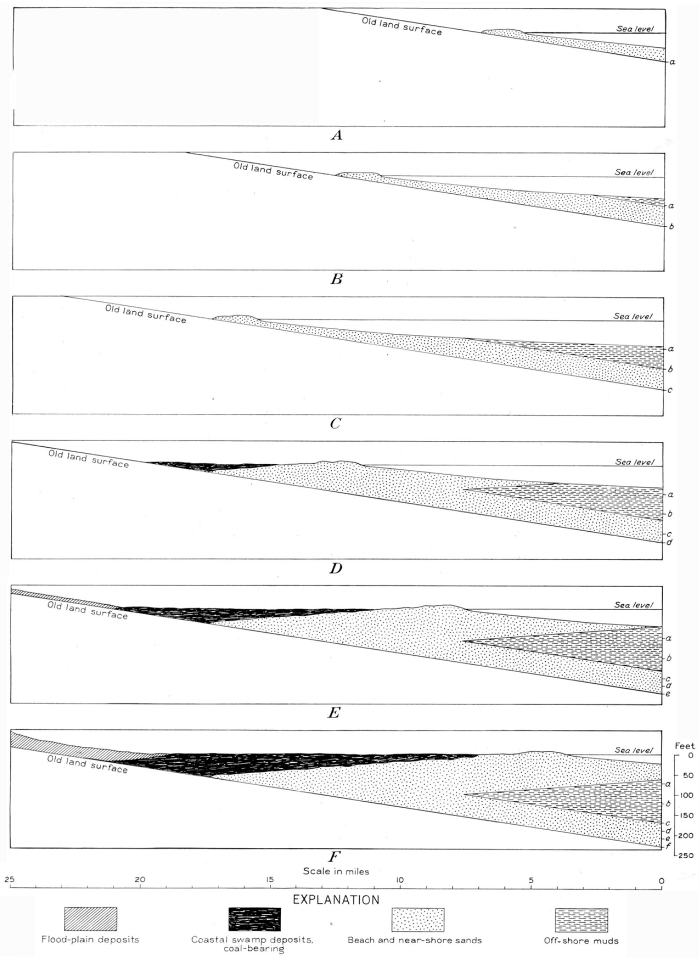


FIGURE 1.35. Plate 25 of Sears et al. (1941) had a brief caption: "Diagram showing change from transgressive to regressive deposition through decrease in rate of trough subsidence."

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.