First-day road log, trip 1, from Washington Ranch to Dark Canyon, Mosley Canyon, and Queen Highway, through Indian Basin and Rocky Arroyo, to Azotea Mesa and the McKittrick Hill Caves, and return to Washington Ranch by way of Happy Valley

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CAPITAN REEF, BACKREEF, AND McKITTRICK HILL CAVES

FIRST-DAY ROAD LOG, TRIP 1, FROM WASHINGTON RANCH TO DARK CANYON, MOSLEY CANYON, AND QUEEN HIGHWAY, THROUGH INDIAN BASIN AND ROCKY ARROYO, TO AZOTEA MESA AND THE MCKITTRICK HILL CAVES, AND RETURN TO WASHINGTON RANCH BY WAY OF HAPPY VALLEY

LEWIS LAND, DAVID LOVE, AND VICTOR POLYAK

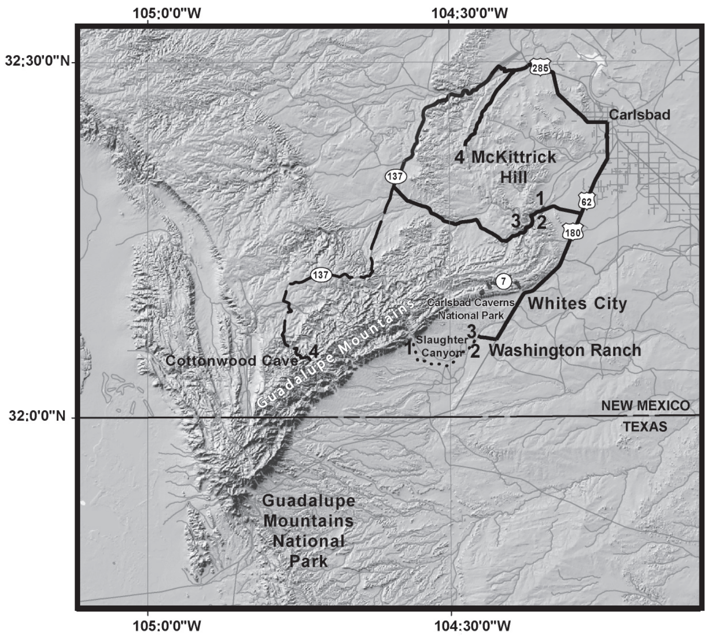
Assembly Point: Washington Ranch Road near tufa dam.

Departure Time: 7.15 AM, in conjunction with

the Cottonwood Cave trip.

Distance: 118.3 miles

Four stops (and three optional stops)



SUMMARY

Trip 1 of the first day of the conference focuses on world-class exposures of the Capitan Reef along the eastern edge of the Guadalupe Mountains and on carbonate and evaporite facies of the adjacent backreef, on the way to and from the McKittrick Hill Caves. ***The road log for trip 1 serves as the trunk log for the other three field trips of the first day of the conference, each of which has a separate road log that begins where they diverge from Trip 1.*** **Trip 2** diverges at the entrance to Washington Ranch, turning right onto Rattlesnake Springs Road to visit spectacular exposures of the Capitan Reef, fore-reef talus, and near backreef units in Slaughter Canyon, on the way to the mouth of Slaughter Canyon Cave. **Trip 3** diverges at the entrance to Whites City, off Highway 62-180, and will proceed up Walnut Canyon to visit exposures of the Capitan Reef and backreef units, and culminates in a tour of Carlsbad Cavern, one of the largest and most geologically significant caves in North America. Conference attendees on **trip 4** travel the farthest with trip 1, driving up Dark Canyon road to visit reef exposures at the mouth of the Canyon, and backreef facies farther up the canyon. Trip 4 diverges at the Queen Highway, turning left and driving into the high Guadalupe Mountains to visit Cottonwood Cave, which contains some of the largest and most spectacular cave formations outside Carlsbad Cavern itself.

The route for trip 1 follows National Parks Highway (62-180) and parallels the Guadalupe Escarpment for several miles before turning west toward Dark Canyon. The first stop examines the famous exposures of the Capitan Reef at the mouth of the canyon. Stop 2 focuses on the pisolite facies belt and teepee structures near the Yates-Tansill contact in the near backreef section. Stop 3 provides excellent exposures of grapestone-grain-Seven Rivers Embayment and drives through an extensive section of the far backreef environment, consisting of redbeds and gypsum of the Seven Rivers evaporite facies. The final stop of the day will be the caves of McKittrick Hill, which are formed in the pisolite facies belt of the Seven Rivers Formation, a carbonate fabric almost unique to the Guadalupe Mountains region.

0.0 Assemble along the main Washington Ranch road near the tufa dam across the Black River (Figure 1.1.1).

The headwaters of the Black River are in the Guadalupe Mountains 29 km southwest of here. East of the dormitories and cafeteria is an inset terrace between the Holocene former floodplain and the higher terrace ahead.

See minipaper by Land & Love for a geological walking tour of Washington Ranch, p. 15.

After crossing Black River, set odometers to zero at intersection of main road and paved road to right. Proceed south, up the terrace riser. *0.1*

0.1 Crossing intermediate terrace of the Black River. In quarried pits west of the road, exposures of the strath (base)

FIGURE 1.1.1. Tufa dam across Black River at Washington Ranch.

of this deposit are 16-18 m above the Black River, and the top surface of gravel is ~3 m higher. In the quarry and in exposures further west along the Black River, this terrace is underlain by dipping sandstone and claystone units of karst fill. The surface of the terrace is probably mid-Pleistocene in age. Along the road ahead are low areas of fine-grained alluvium and aeolian deposits that fill solution depressions developed along the contact between Pleistocene terraces and the underlying Castile gypsum. *0.3*

0.4 Yield sign and gate to Washington Ranch. **Turn left** onto Washington Ranch Road and proceed toward US 62-180. Note a higher terrace of the Black River to the east. The terrace pinches out against the Gypsum Plain and Yeso Hills of the Castile Formation to the south. The contact is blurred by an EW trending line of solution depressions. *0.1*

Slaughter Canyon field trip turns right at this intersection. (Road log on page 15)

0.5 Rise onto higher terrace of the Black River with well-cemented limestone cobble conglomerate exposed in road cuts. This conglomerate continues east to the junction with US 62-180. *0.3*

0.8 Headquarters complex of Carlsbad Caverns National Park visible on skyline at 9:00, atop the frontal scarp of the Guadalupe Mountains. The scarp consists of the Capitan Reef facies capped by backreef Tansill limestone. *1.1*

1.9 Junction of Washington Ranch road with US 62-180. Note official historic marker: "The Civilian Conservation Corps provided employment for more than 50,000 young men in New Mexico during the Great Depression of the 1930's. At the National Park Service CCC Camp, they developed nearby Rattlesnake Springs into a permanent water source for Carlsbad Caverns, built roads, parking areas, and trails, which made the

FIGURE 1.1.2. Civilian Conservation Corps Historic Marker at Washington Ranch turnoff.

park more accessible to the public." (Figure 1.1.2) **Watch for traffic. Turn left** (northeast) on US 62-180. *0.5*

2.5 Descend into valley of the Black River, passing exposures of conglomeratic well-cemented terrace gravels unconformably overlying Castile Gypsum below level of roadcuts. *0.1*

2.6 MP (Milepost) 11. *0.6*

3.2 Roadcuts expose well-cemented conglomerate and mudstone terrace deposits of the Black River. *0.6*

3.8 Crossing Black River. *3.3*

7.1 Exposures of terrace and piedmont gravels beyond mouth of Walnut Canyon. *0.1*

7.2 Crossing channel of drainage from Walnut Canyon. Entering outskirts of Whites City, the gateway to Carlsbad Caverns National Park. *0.1*

7.3 Junction to left with NM 7 to "downtown" Whites City. **Stay straight**, and continue northeast on US 62-180. *0.3*

Carlsbad Cavern field trip turns left at this intersection. (Road log on page 21)

7.6 MP 16. The very flat skyline to the south is punctuated by isolated low hills. These are castiles – erosional knolls of biogenic limestone imbedded in the Castile Gypsum, one of which will be visited on Day 2. *0.5*

8.1 Apache Canyon Trading post to left (Figure 1.1.3). As we continue northeast, the Guadalupe Mountains decrease in

FIGURE 1.1.3. Apache Canyon Trading Post near Whites City, National Parks Highway.

stature to low-relief hills as the reef complex dips into the subsurface. The escarpment to the left is formed by Tansill Formation grainstones deposited behind the reef. The age-equivalent Capitan reef is lower on the slope and is mostly buried at this location. *1.8*

9.9 Two sinkholes in Tansill dolomite to left (west). *1.9*

11.8 Route rounds bend to avoid hills capped by Tansill dolomite to northwest. *0.6*

12.4 Junction with NM 396/CR 720 to right leads to Black River Village and Malaga. **Continue straight.** Tansill Formation dolomite exposed to left on northwest side of 62-180. The Capitan Reef is now in the shallow subsurface. A well drilled north of the road junction in 2003 intersected a cave in the "Capitan Massive" at 25 m below ground level, as indicated by a 3.5 m bit drop followed by persistent lost circulation problems, and eventual formation of a 5 m diameter sinkhole next to the rig. The operator never recovered circulation and was forced to dry-drill to the intermediate casing point at 127 m.

From this point southwest to the state line, Kelley (1971a) noted on aerial photographs a sharp linear change in vegetation patterns near the base of the escarpment to the left (Figure 1.1.4), and mapped a surface fault separating the Delaware Basin from the reef escarpment. Hayes and Bachman (1979) revisited localities where Kelley had reported surface faults and concluded that the steep dip observed along the Guadalupe Escarpment was unfaulted original sedimentary dip. Adams et al. (1993) suggest that the linear pattern marked by a vegetation change at the base of the slope probably reflects processes of reef front exhumation that have been occurring episodically since early Triassic time. *1.3*

13.8 MP 22. Route cuts east-dipping cuestas of the Culebra dolomite member of the Rustler Formation (upper Ochoan), overlying less resistant Salado siltstone and residual gypsum. *1.0*

14.8 MP 23. Culebra dolomite exposed in roadcuts (Figure 1.1.5) exhibiting characteristic anhydrite molds caused by leaching of evaporites (Figure 1.1.6). Small-scale folding in the roadcut is probably not of tectonic origin but more likely due to subsurface dissolution of underlying evaporite beds. *2.2*

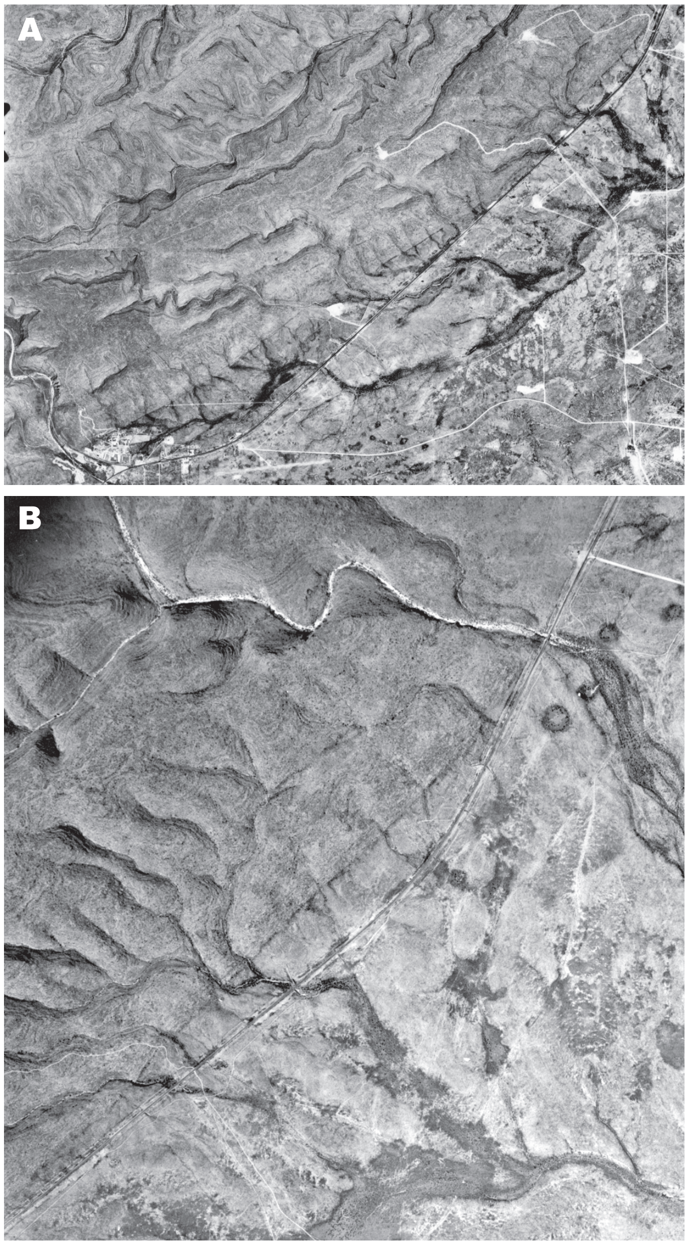


FIGURE 1.1.4. A. Aerial view of Barrera Fault or lineament (Kelley, 1971). B. Closer aerial view of the Barrera Fault ca 1943.

17.0 Brown sign on right shoulder: Dog Canyon Campground, 60 miles west. **Prepare to turn left.** *0.1*

17.1 **Watch for oncoming traffic. Turn left** (west) onto CR 408, Dark Canyon Road. *0.4*

17.5 Route crosses geomorphic surface correlated with the Orchard Park plain (Horberg, 1949). *1.1*

18.6 Crossing cattleguard. Frontier Hills at 10:00. Kelley's (1971a) maps indicate the hills are cuestas formed by east-

FIGURE 1.1.5. Small-scale folding in Culebra dolomite. See Plate 11A for a color image of this outcrop

dipping beds of the Culebra Dolomite member of the Rustler Formation capping less resistant Salado. In this area the Rustler overlaps the underlying Salado and Castile and comes very close to resting directly on the Capitan Reef. *0.8*

19.4 Crest of hill; quarry to right exploits gravels in terrace of Dark Canyon arroyo. *0.3*

19.7 Descend onto low terrace of Dark Canyon arroyo. Note significant change in vegetation. *0.6*

20.3 Guadalupe Escarpment ahead. Much of the relief observed along the escarpment is exhumed Permian topography. *0.2*

20.5 Ranch complex at 10:00 is on a terrace of Dark Canyon arroyo. *0.3*

20.8 Cattleguard. Tansill Formation is exposed in bluffs on both sides of the mouth of Dark Canyon. **Prepare to turn right.** *0.3*

21.1 **Turn right** (northeast) onto CR 672 and cross Dark Canyon Arroyo. 1941 floods reached a crest of 6 to 10 m at this point and emplaced a large boulder erratic on adjacent terrace. Park on right side of road but not in channel. *0.2*

21.3 Stop 1. Capitan Reef outcrop at mouth of Dark Canyon.

Please do not take rock hammers. Bring water to wet fossils to make them more visible. This is the northernmost exposure of the Capitan Reef where it briefly re-emerges in outcrop before plunging again into the subsurface and bending to the east beneath Carlsbad. This is also one of two outcrops of the reef readily accessible by paved road, and for that reason it is visited by almost all industry and academic field trips. These outcrops on Bureau of Land Management acreage were vandalized by a graduate student using a diamond saw who removed the most spectacular fossils, particularly crinoids with intact calyxes attached, the former locations of which are now indicated by square, saw-cut holes (Figure 1.1.7). Please do not disturb or remove the remaining fossils.

Walk up dip slope to study biota of sponge-algal reef facies in the upper part of the Capitan Reef-Tansill equivalent (Figure 1.1.8). Some workers in this area (e.g., Noe and Mazzullo, 1994; Toomey and Cys, 1977; Babcock, 1977) have interpreted outcrops on the north and south sides of the mouth of Dark Canyon as patch reefs formed in the upper Tansill (designated respectively the "Toomey Reef" and the "Babcock Reef") rather than as exposures of the Capitan Reef proper. For simplicity we shall leave such controversy to the experts and refer to this exposure as the Capitan Reef.

Lithology of the Capitan at this outcrop is predominantly limestone. Large algal heads and *Archaeolithoporella*, a problematic algae, are present in growth position. The largest algal head is ~55 cm in diameter. Clusters of *Tubiphytes*, another problematic

FIGURE 1.1.6. Close-up photo of Culebra dolomite showing characteristic vuggy porosity. See Plate 11B for a color image of this outcrop.

FIGURE 1.1.7. Geo-vandalism of Capitan Reef outcrop, mouth of Dark Canyon.

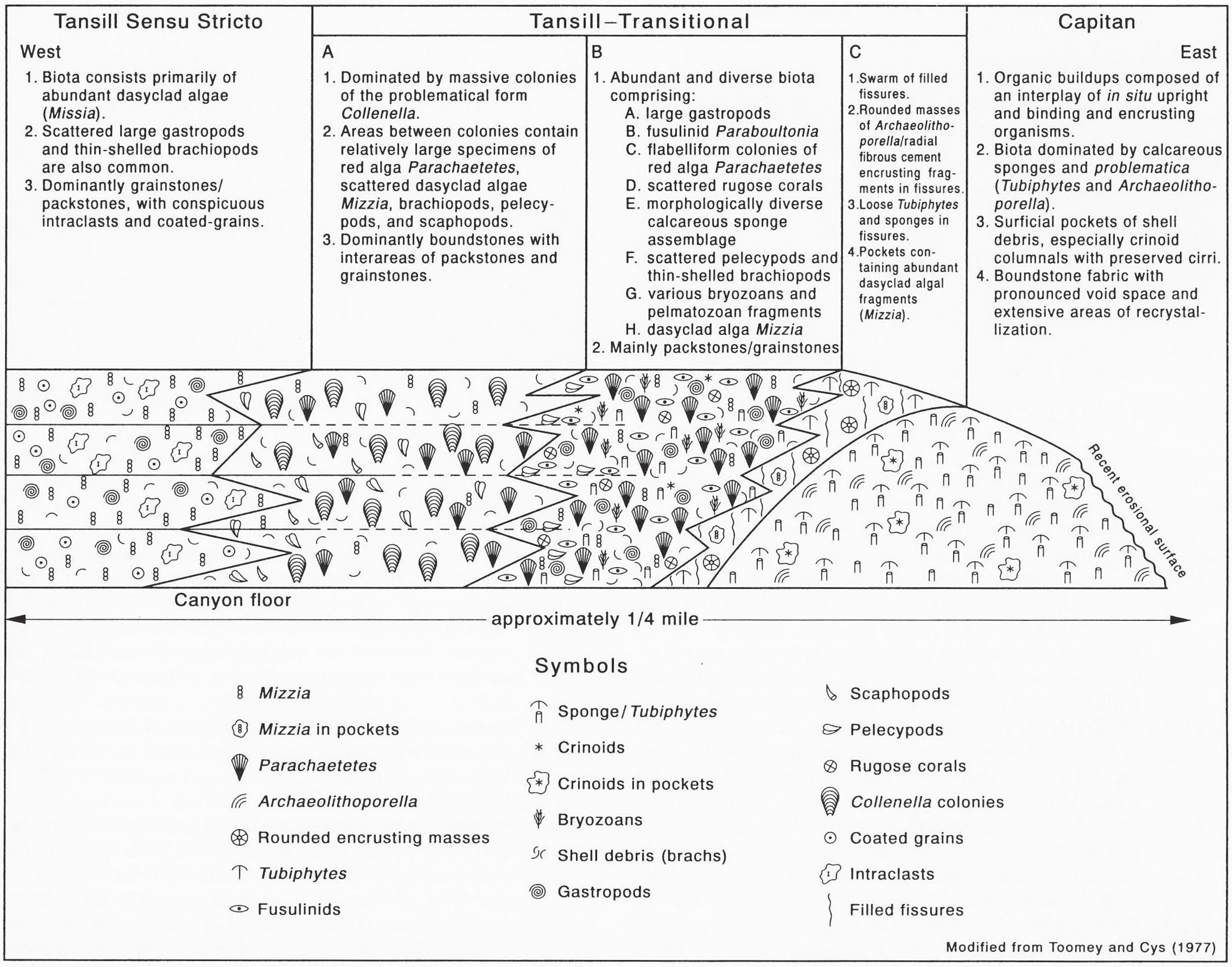


FIGURE 1.1.8. Schematic diagram of biotic relationships in shelf to shelf margin transition, mouth of Dark Canyon.

fossil, can be found filling swales and channels between buildups of *Archaeolithoporella*. Pockets of *Mizzia*, a dasyclad alga with hollow stems, can be found, as well as calcareous sponges, aragonitic-shelled gastropods, bivalves, cephalopods, bellerophontids, brachiopods, and *Collenella*, a problematic hydrocoral or stromatoporoid which grew in massive, bush-like colonies up to 1 m high.

All aragonitic mollusc fossils have been dissolved and the resulting voids filled by calcite cement. In addition to abundant fossils, the Capitan Reef and near-backreef units also contain large volumes of early marine cement (up to 80% of outcrop at some locations) that originally consisted of isopachous crusts and thick, botryoidal, fan-ray druses. Precipitation of such large volumes of marine cement may have been promoted by active seawater pumping through sediments deposited on a wide and shallow shelf (Mazzullo, 1999).

One striking feature of this exposure are beds containing delicate crinoid stems up to 12 cm long (Figure 1.1.9). The crinoid stems appear to be bent over and preserved in place in a north-south alignment by currents flowing parallel to the ancient reef front (Figure 1.1.10). As you walk up-canyon (shelfward), from reef to near-backreef facies, note the change in bedding character from massive, unstratified reef rock to outcrop with a more layered character formed in Tansill dolomite. The abruptness of the facies change seen here is similar to modern facies transitions that occur on the margins of carbonate platforms in Florida and the Bahamas.

Also present at this outcrop are rock middens and Indian grinding holes (mortars) worn into the bedrock. The holes and middens are thought to be associated with processing of mesquite beans by Mescalero Apaches and possibly earlier groups of Native Americans. **After stop, turn around and return to stop sign at CR 408.** *0.2*

21.5 Stop sign. **Turn right** onto CR 408 and drive up Dark Canyon past steep bluffs and cliff walls formed in Tansill dolomite, the uppermost unit of the Guadalupian series in the

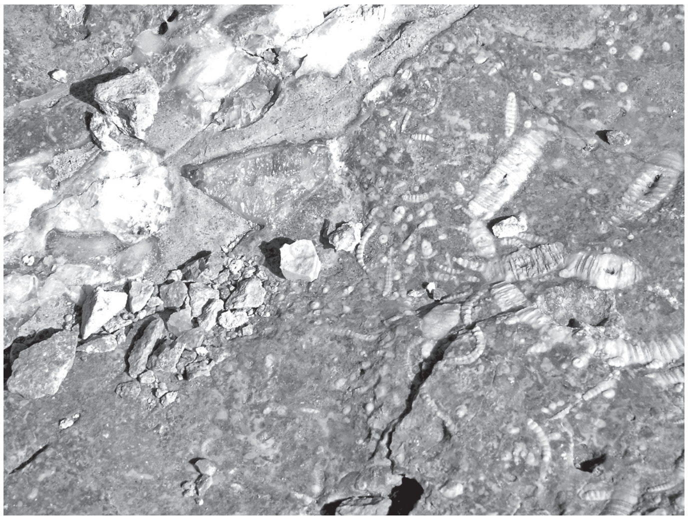


FIGURE 1.1.9. Close-up of crinoid fossils exposed in Capitan Reef outcrop, mouth of Dark Canyon.

backreef section (Artesia Group). The formation was named by DeFord (1941) from exposures in the Ocotillo Hills north of Carlsbad. In the shelf area 8-10 km behind the reef the Tansill consists of ~38 m of evaporites, fine sand and mudstone, with thin dolomite beds. Near the transition to reef facies the Tansill changes to dolomite and dolomitic limestone and thickens to more than 90 m. The Ocotillo Silt, a unit of fine sand, silt, and shale, occurs in the upper part of the Tansill section, and forms the green line in the cliffs on either side of Dark Canyon near this location.

FIGURE 1.1.10. Current alignment of crinoid stems, Capitan Reef outcrop, mouth of Dark Canyon.

The route west traverses through east-dipping strata of the backreef Artesia Group, and cuts progressively downward in the section, into the underlying Yates, Seven Rivers, Queen and Grayburg Formations. *0.2*

21.7 USGS stream gaging station to right. Dark Canyon is dry most of the year, but sometimes floods during summer monsoons. Flood events in Dark Canyon and other bedrock streams in the Guadalupe Mountains are considered to be an important source of groundwater recharge to the Capitan Reef aquifer (Hendrickson and Jones, 1952). Note small cave near gaging station. Well-bedded strata on both sides of Canyon are Tansill backreef facies. *0.2*

21.9 Crossing Dark Canyon arroyo. *0.2*

22.1 Hippy Hole cave at 9:00, a small cave in the Yates formation. NSS Pecos Valley Grotto practices rappelling and cave rescue in Hippy Hole. *0.6*

22.7 Crossing Dark Canyon Arroyo. Yates Formation to right. *0.2*

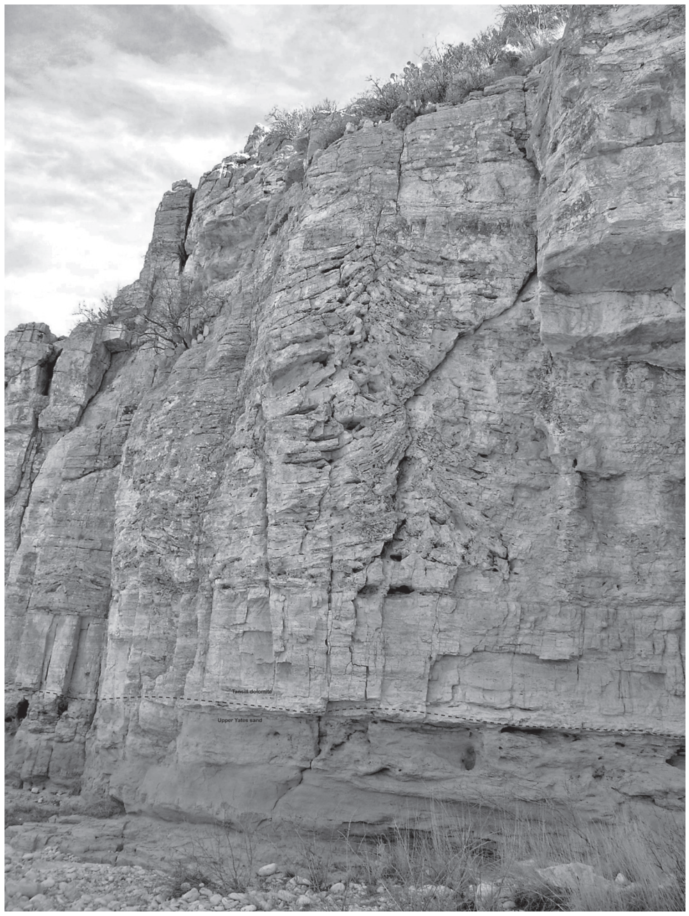


FIGURE 1.1.11. Cliff exposure of well-developed teepee structure in Tansill dolomite over upper Yates sand in lower Dark Canyon. Note lateral continuity of the Yates sand just above the stream bed.

FIGURE 1.1.12. Yates-Tansill contact at top of laterally continuous orange siltstone. Note large square holes cut in outcrop. Someone was clearly very interested in this exposure. See Plate 10A for a color image.

FIGURE 1.1.13. Pisolitic dolomite, lower Dark Canyon. See Plate 10B for a color image.

22.9 Stop 2: Yates-Tansill contact. Park on shoulder.

Note teepees in wall of canyon at 9:00 (Figure 1.1.11), and large square holes in outcrop cut by unknown, overenthusiastic geologists. The contact between the Tansill and Yates Formations is exposed here, where basal Tansill dolomite overlies an orange, very fine-grained sandstone bed in the uppermost Yates (Figure 1.1.12) [Alton Brown (2006, personal communication) reports that some workers believe the contact is higher in the section, and that this exposure may represent the base of the Hairpin dolomite]. The upper Yates sand is a very widespread stratigraphic marker on the Northwest Shelf and on the Central Basin Platform in West Texas. The abrupt lithologic change can be readily identified on well logs and used to map shallow structure. The following discussion is modified from Scholle (2000).

Teepee structures are well-exposed in the cliff face in pisolitic dolomites of the lower Tansill Formation, just above the upper Yates sand. These are polygonal expansion structures, marked by buckled and deformed sediments, cement crusts, and pockets of pisolitic sediment beneath and between teepees. Note the upward propagation of teepees through a thick stack of carbonate layers, and truncation of some of the teepees by a laminated siltstone unit. The origin of these teepees is controversial. They have been interpreted variously as giant mud-cracks in a periodically-exposed tidal flat environment, and as disrupted strata deformed by upwelling groundwater discharging from submerged springs in a shallow lagoon (e.g., Kendall and Warren, 1987; Warren, 1983; Kendall, 1969). Teepees are always found in association with pisolitic sediments.

The pisolitic dolomites (Figure 1.1.13) represent probably the most controversial facies in the Permian of the Guadalupe Mountains. The pisolitic facies tract, only a kilometer or so wide, persists through the entire Grayburg to Tansill section – almost a kilometer of sedimentary buildup. Individual pisoids range in size from a few millimeters to >5 cm. Pisolite beds commonly display coarsening-upward sequences (Dunham, 1969), although cross-bedded and unsorted pisolite deposits also occur. Pisolite nuclei include some marine fossils but are dominantly fragments of older pisoids. In their later stages, pisoids grow "in place", displaying fitted fabrics, common or shared coatings, and passing into botryoidal crusts of former aragonite marine cements (Loucks and Folk, 1976; Scholle and Kinsman, 1974).

The pisolite facies belt occurs as a transition zone between fossiliferous marine grainstones, packstones, and wackestones on the seaward side of the shelf, and largely barren, evaporitic dolomicrites on the landward side, and thus may have formed a barrier to water movement between open shelf and more restricted lagoonal settings. Detailed interpretation of the depositional environment of this unit has been the subject of much speculation over the years. Pisolite formation was originally attributed to marine growth of algal nodules (oncolites), but has been variously reinterpreted as the product of marine inorganic precipitation in a subtidal setting (Esteban and Pray, 1977); caliche formation in continental or coastal spray zones (Dunham, 1969; Scholle and Kinsman, 1974); and back-barrier, marine or groundwater spring seepage (Handford et al., 1984).

Indian mesquite bean grinding holes can be found at the base of the cliff. After stop, continue west up Dark Canyon. Outcrops on both sides of road for the next several miles are Yates Formation, with the highest hills capped by thin Tansill dolomites.
0.1

23.0 Quarry to left in Pleistocene terrace, up-canyon at 2:00. *0.8*

23.8 Crossing Mosley Canyon arroyo. *0.2*

24.0 Cliff exposure of ooid-pisolite facies grainstone belt in Yates dolomite to left, located about 2.5 km shelfward from the Capitan Reef.

The term "Yates" has been used by subsurface geologists in the Permian Basin since the 1920's. Gester and Hanley (1929) originally designated a type section from subsurface data in the Yates Field in Pecos Co., Texas. The formation is continuous from its type locality in the subsurface to outcrops in the Guadalupe Mountains, where it consists of interbedded sandstone, dolomite and gypsum sandwiched between non-sandy dolomites of the Tansill and Seven Rivers Formations. The dolomite facies near the Capitan Reef grades into evaporite facies in the shelf area 8 to 11 km from the reef escarpment. *0.7*

24.7 Cross drainage. Windmill on right. City of Carlsbad monitoring well on hill to left, inside chain-link fence. The well is completed in the Capitan Reef aquifer, and is used for monitoring water levels and water quality in the aquifer. Massive dolomite beds at arroyo level are uppermost Seven Rivers Formation, overlain by Yates. *0.2*

24.9 Note dolomite cliffs to left. Two distinctive ledges represent the Hairpin dolomite of the Yates Formation, widely traceable in backreef facies. *0.3*

25.2 Stop 3. Mosley Canyon. Cross canyon and park cars on shoulder.

Walk upstream ~30 m to low ledges of Yates dolomite. These outcrops are in the grapestone-grainstone facies belt, which is about 6 km wide and ~5 km shelfward from the Capitan reef (Figure 1.1.14). By analogy with similar grapestone facies deposited on the Bahamas Platform today, these sediments were probably deposited in a low-energy, subtidal lagoon ~3 m deep. Grapestones are clusters of peloids and ooids bound together by blue-green algae, and represent a lower-energy environment further from the reef and behind (landward of) the pisolite facies belt.After stop, continue west on CR 408. *0.9*

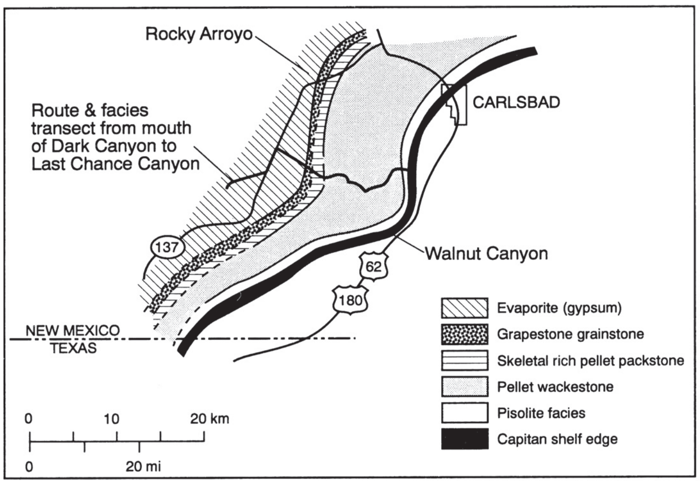


FIGURE 1.1.14. Facies distribution in the lower Seven Rivers Formation (modified from Dunham, 1972).

FIGURE 1.1.15. Non-tectonic folding in Seven Rivers Formation.

26.1 Undulations in strata at 3:00 represent the south end of the Carlsbad fold belt (Figure 1.1.15), which extends in an arcuate trend north, northwest, northeast and east around the northern margin of the Delaware Basin. The Carlsbad folds are probably not tectonic folds. Motts (1972) interpreted these structures as biohermal mounds that do not extend below the Artesia Group. Individual folds within the fold belt have axes oriented perpendicular to the reef front, probably resulting from currents flowing across the reef into the basin. *0.7*

26.8 Junction with White Ranch Road to left. Conical hill ahead is Sweatergirl Mountain, formed by thin-bedded Yates dolomites making a facies transition into siltstones and gypsum (Figure 1.1.16). Evaporites and mudstones progressively increase in the section as we drive west, accounting for the generally more subdued topography. *0.2*

27.0 Crossing scoured bedrock of Mosley Canyon. Basal Yates dolomites to southwest, part of the pelgrapestone-wackestone-packstone facies 5 – 7 km from the Capitan Reef. *1.7*

28.7 Drainage divide between Mosley Canyon and Dark Canyon drainage basins. Also crossing the Yates-Seven Rivers

FIGURE 1.1.16. Sweatergirl Mountain, formed by thin-bedded Yates dolomite capping redbeds and gypsum of far backreef facies.

contact. Hills to NW are Yates overlying thin-bedded Seven Rivers dolomites. *0.8*

29.5 Crossing cattle guard, still driving on Yates Formation. *0.3*

29.8 Turnoff to left leads to Big Manhole Cave, regarded by some cavers as a possible second entrance into Lechuguilla Cave, based on strong airflow. **Continue straight.** Digging at Big Manhole has been ongoing for several years in an attempt to break through into larger passage. *0.5*

30.3 Pass junction with CR 408A to right. **Continue straight.** *1.1*

31.4 Note folds in valley wall exposed at 3:00. These are non-tectonic folds in the Seven Rivers Formation probably caused by subsurface dissolution of evaporites. *1.2*

32.6 Large gypsum solution fold in bluffs of Seven Rivers Formation to right. *0.1*

32.7 Note prominent cliff exposure of gypsum solution folds in SevenRivers to left. *1.1*

33.8 Redbeds in Seven Rivers Formation at 3:00. Meinzer et al. (1926) first used the term Seven Rivers to describe a gypsiferous member of the Chupadera Formation cropping out in the Seven Rivers Hills northwest of Carlsbad. *0.7*

34.5 Terraces of Last Chance Draw at 9:00. *0.8*

35.3 High terrace gravels to right. *1.0*

36.3 Crossing cattle guard. *2.1*

38.4 High gravel terrace to right. At this point the road crosses the Seven Rivers-Queen contact and passes onto thin alluvial veneer covering Queen bedrock. *0.2*

38.6 Seven Rivers redbeds exposed at 2:00 in Bandana Point, formed by Seven Rivers gypsum and mudstone capped by a more resistant dolomite – the Azotea Tongue of the Seven Rivers Formation. On horizon to west, Queen and Grayburg strata are folded on the Huapache monocline. We are now leaving the northeastern prong of the Guadalupe Mountains and entering the Seven Rivers Embayment. This is a topographic erosional basin, caused by differential erosion of less-resistant evaporites and redbeds in the far-backreef facies. *0.6*

40.2 Junction with Queen highway (NM 137). The Queen Highway is one of the earliest roads built by the Civilian Conservation Corps (CCC) in New Mexico. It connects US 285 with the Queen, El Paso Gap, and Dog Canyon areas of the western Guadalupe Mountains. Queen Formation beneath road, poorly exposed. *0*

Cottonwood Cave field trip turns left here.

40.2 **Turn right** (NNE) onto NM 137 to go to McKittrick Hill caves. *1.2*

41.4 Bandana Point at 3:00. *1.4*

42.8 Curve to right at H Bar Y Ranch Road (CR 405). **Continue straight.** *0.2*

43.0 Lookout Point at 11:00 is capped by dolomites of Azotea Tongue. *0.5*

43.5 MP 38. Note how the Seven Rivers Formation has changed facies to red beds and gypsum, which are preserved from erosion by Azotea Tongue dolomite at the top of Lookout Point. *0.8*

44.3 Passing Lookout Point; we are at the approximate contact between the Queen Formation (west of the highway) and the Seven Rivers Formation in the slope to the right (east). The route stays near this contact for the next few miles *0.5*

44.8 Entering Indian Basin Gas Field. *0.7*

45.5 MP 40. Cone Butte to right (Figure 1.1.17) is formed in Seven Rivers gypsum and red beds capped by Azotea Tongue dolomite. Erosional knolls of gypsum and redbeds capped by more resistant dolomite are one of the most distinctive features of the carbonate-to-evaporite transitional facies in the Seven Rivers Embayment. Queen Formation crops out in draw to west. *0.4*

FIGURE 1.1.17. Cone Butte, formed in gypsum and redbeds of the Seven Rivers Formation capped by dolomites of the Azotea Tongue of the Seven Rivers. See Plate 8A for a color image.

FIGURE 1.1.18. Overview of Indian Basin gas field, with workover rig in foreground.

45.9 Cattleguard. Old Ranch Knoll 3 km to the northeast (12:00). *1.6*

47.5 MP 42. Old Ranch Knoll at 1:00. *1.0*

48.5 MP 43. Multiple gas wells of Indian Basin Field on wellpad to left. *1.0*

49.5 MP 44. (Note: This milepost may be missing from signpost). Guadalupe National Backcountry Byway scenic overlook. Overview of Indian Basin gas field (Figure 1.1.18), discovered in 1963, which produces from Morrow sands at 2700-3000 m depth, and fractured upper Pennsylvanian dolomites of the Cisco and Canyon Formations at 2100-2400 m. The upper Pennsylvannian dolomites, which appear to have been hydrothermally altered, are the main producing zone and have an averate porosity of 6%. Cumulative production in Indian Basin is 2.7 TCF of gas and 100 million barrels of oil (Craig Corbett, 2006, personal communication). The trapping mechanism in this gas field is composite: Structural, stratigraphic and hydrodynamic in nature. Regional dip of the Pennsylvanian carbonates is ~2.5° to the NE, and northeast flow of water through the porous dolomite pay zones tilts the gas-water contact from ~950 m below sea level on the west side of the field to 1150 m BSL on the east side, for a total gas column of 193 m (Frenzel, 1988). Now leaving Seven Rivers Embayment. Park ahead on right to view the famous Teepee butte. *0.5*

50.0 Optional Stop. The Teepee.

Park on shoulder.

The Teepee (Figure 1.1.19) is a conical hill of redbeds and gypsum of the Seven Rivers Formation capped by Seven Rivers dolomite. Sediments exposed in the slopes here have been interpreted by Jacka (1988) as showing an upward transition from a shallow lagoonal carbonate deposit to a deflation flat and inland sabkha. Sarg (1988), on the other hand, interpreted both dolomite and evaporite-mudstone facies as being deposited in a broad, shallow lagoon. The Teepee, with its classic symmetry, is one of the best-known examples of the erosional hills and ridges formed in gypsum and redbeds and capped by dolomite that are ubiquitous landforms in the transitional facies of the Artesia Group. *0.5*

FIGURE 1.1.19. The Teepee, a conical outlier of Seven Rivers redbeds and gypsum capped by Seven Rivers dolomite.

50.5 MP 45. Descending into valley of Rocky Arroyo *1.0*

51.5 MP 46. Junction with CR 401/Marathon Road to Indian Basin field. **Bear right** and stay on NM 137.

This portion of the route begins a traverse through the famous transition from far-backreef evaporites and mudstones into near-backreef dolomites within the Seven Rivers Formation. A spectacular facies change, as documented in Sarg's (1976) doctoral dissertation, occurs over the course of just one mile as the route continues east. This transition from evaporites to carbonate facies also occurs within the Grayburg, Queen, Yates, and Tansill Formations.

The prominent ledge at the level of Rocky Arroyo is formed by dolomites in the Queen Formation, overlain by the Shattuck Sandstone. A nearly complete section of the Seven Rivers overlying the Shattuck Member of the Queen is exposed in the north slope of Rocky Arroyo. Here, 60 m of Seven Rivers gypsum with red siltstone stringers grade laterally into bedded dolomite. One mile further down the arroyo the Seven Rivers section is almost completely dolomite.

An alternate interpretation of these well-known roadcuts exposed over the next 1.5 miles is provided by Brown (2006, written communication). The abrupt gypsum-dolomite transition may be viewed as dissolution modification of a more gradual transition from carbonates to interbedded gypsum and siltstone. Individual gypsum beds within the Seven Rivers Formation abruptly change laterally to much thinner, reddish, high porosity limestones associated with brecciation in the overlying dolomites (Bates 1942). The red limestones are probably gypsum dissolution and calcitization residues. Bates' (1942) measured sections show that the interval between the top of the Queen and a shale marker bed within the Seven Rivers is a 75 m gypsum-clastic section at the west end of the outcrop and a 27 m red limestone, shale, and dolomite section at the east end of the outcrop. Thinning must be the result of bed-by-bed gypsum dissolution, because this type of depositional relief is unlikely in a shelf setting near sea level. The overlying Azotea tongue dolomite drops down to the east to form an east-dipping monocline, in response to dissolution of underlying gypsum. The Azotea Tongue thickens at the monocline because strata preserved east of the monoclinal axis are truncated by erosion on the hilltop to the west. According to this interpretation, most of the dolomite east of the transition is thus younger than the sequence of gypsum and redbeds exposed further west, and is not a simple lateral facies replacement. *0.4*

51.9 Road crosses complex of higher terrace and fan surfaces flanking inner valley of Rocky Arroyo. *0.6*

52.5 MP 47. Roadcut ahead in Seven Rivers dolomite. Note lenticular sandstone and brecciated nature of the dolomite in the roadcut. Note also two prominent Pleistocene terrace levels above arroyo-valley floor to north. *0.6*

53.1 Optional stop. Seven Rivers/Queen Contact. Park on shoulder to left.

Seven Rivers/Queen contact in roadcut (Figure 1.1.20). Below the highway, at creek level, the Shattuck sandstone member of the Queen consists of discontinuous beds formed by channels, bars, and horizontally-layered sheet flood deposits formed in a braided stream environment. Thinner, more continuous beds higher in the section contain adhesion ripples and other features suggestive of aeolian transport. At the base of the roadcut section, the sandstones include burrows and gypsum crystal molds, and represent pond and salina deposits with a thin wadi interval near the top. Top of the Shattuck sandstone is ~3.5 m above the base of the outcrop, and is characterized by pseudomorphs after gypsum rosettes, some of which are truncated on bedding planes. Overlying dolomites are predominantly pond/salina deposits with thin sabkha intervals. Breccia zones are interpreted as dissolved evaporite beds, possibly correlative with the gypsum beds near the base of the Seven Rivers section seen on the north wall of Rocky Arroyo a mile earlier. *0.1*

FIGURE 1.1.20. Queen-Seven Rivers contact, Rocky Arroyo. See Plate 8B for a color image.

FIGURE 1.1.21. Shelter cave formed in Quaternary tufa deposits, Rocky Arroyo.

53.2 Carbonate-cemented Pleistocene colluvium in cut to right. *0.3*

53.5 Curve to right at MP 48. Note cliffs of solid dolomite of the Seven Rivers Formation beyond ranch at 12:00. *0.5*

54.0 Cattle guard on low (Holocene?) terrace of Rocky Arroyo *0.1*

54.1 Crossing Rocky Arroyo. Note shelter caves formed in late Quaternary tufa deposits in banks to left (Figure 1.1.21). The tufa deposits visible here and sporadically for the next few miles along Rocky Arroyo are Pleistocene spring deposits

FIGURE 1.1.22. Cyanobacterial stromatolites (crinkle beds) in Seven Rivers dolomite, Rocky Arroyo.

formed during a pluvial climate interval. Tubular structures in the tufa were formed by green algae. *0.2*

54.3 Ranch entrance to right. **Continue straight.** Highway crosses the Queen-Seven Rivers contact (Seven Rivers Formation to the east and in the massive cliff across Rocky Arroyo). *0.2*

54.5 MP 49. Rocky Arroyo cemetery ahead on right. *0.7*

55.2 Optional stop. Seven Rivers Dolomite.

Park on shoulder.

Roadcut exposures to left of "crinkle beds" in Seven Rivers dolomite (Figure 1.1.22). These features have been interpreted as cyanobacterial stromatolites by Jacka (1988). The thickness of the stromatolite interval, 60 cm, is approximately the same as the paleotidal range. Vuggy porosity in the outcrop, some of which contains dead oil, was formed by leaching of anhydrite. Note also massive tufa deposits in stream bed to right (south side of road). Indian grinding holes are present in the bedrock stream bed. *0.7*

55.9 Site of Rocky Arroyo School. Southeast edge of Seven Rivers Hills to left and northeast prong of Azotea Mesa to right. Yates/Seven Rivers contact in slopes to right and left. Alluvial cover thickens to east. *0.5*

56.4 Ranch house on right. East of here, the route crosses the Seven Rivers/Yates contact in the shallow subsurface. *0.1*

56.5 MP 51. Leaving valley of Rocky Arroyo. Route to east is along the western margin of the Pecos Valley. Bedrock in this area is Yates Formation, overlain by a thin veneer of alluvium. This part of the Pecos Valley is separated from the Roswell Artesian Basin to the north by the Seven Rivers Hills. The geology of the Pecos Valley has been described by Cox (1967) with emphasis on geohydrologic conditions between the former site of Lake McMillan and Carlsbad Springs. *0.5*

57.0 Crossing Deadman Arroyo, with good exposure of upper terrace gravels. Pedogenic calcrete cap exhibits early stage IV morphology. *0.5*

57.5 MP 52. High-level gravels, with locally well developed pedogenic calcretes (stages IV-V) cover a broad and irregular erosion surface cut on the Yates Formation. The surface here is about 23 m above Rocky Arroyo. Meinzer et al. (1926) were the first to describe the major valley-fill units in this area, which they thought were of post-Ogallala, Quaternary age. They described three terrace levels above the Pecos channel between former Lake McMillan and Lake Avalon, and also subdivided an older conglomeratic part of the valley fill into two informal units, the "quartzose" and "limestone conglomerates" that are collectively up to 23 m thick. These conglomeratic units form pronounced bluffs and armored stream beds along the Pecos River above and in the vicinity of Carlsbad, and may be as old as late Miocene. **Slow and prepare to turn right.** *0.5*

58.0 Junction with CR 406/Waterhole Road. **Turn right.** Continue south on Quaternary gravel terrace *0.3*

58.3 Descend onto lower terrace of Rocky Arroyo. *0.2*

58.5 Road forks. **Bear left.** *0.1*

58.6 Cross Rocky Arroyo and ascend terrace to south. *0.8*

59.4 Junction of Waterhole Road with unnamed dirt road. **Turn right** on route to McKittrick Hill, and proceed SW across dissected surface of Azotea Mesa. For the next several miles we will be driving across Yates dolomite occasionally covered by a thin veneer of Quaternary terrace gravels. *0.3*

59.7 Thin-bedded Yates dolomite in hills to left and right. *1.0*

60.7 Yates dolomite in hillslope to right, dipping ~20°. *1.9*

62.6 Cattle guard and cattle guard bypass. Yates dolomite in hill to left. *1.8*

64.4 Dry petroleum exploration hole to right, plugged in 1985. Surface location: 21S.25E.31. *0.1*

64.5 Road forks. *Bear right.* *0.2*

64.7 Cattle guard. **Continue straight.** *0.5*

65.2 Road forks. **Bear left.** *1.3*

66.5 Cattle guard. Immediately after crossing, road forks. **Bear left.** There has been a significant increase in oil and gas drilling in the area around McKittrick Hill in recent years, as indicated by the presence of oil field equipment, infrastructure (Figure 1.1.23), and traffic on the back roads as well as the pres-

FIGURE 1.1.23. Oil field infrastructure on road to McKittrick Hill.

ence of numerous drilling rigs. Most of the wells in this area are producing from upper Pennsylvaninan dolomites in the oil-water transition zone on the east flank of the Indian Basin field. Perforations to ~1,280 m below sea level produce oil and water from the transition zone. Perforations above -1,140 m produce gas. Some of the wells in the field produce 400-500 barrels of oil and 5-6000 barrels of water per day. Oxy USA along produces ~10,000 BOE/D and ~80,000 BWPD from its Indian Basin leases. The water is pumped off with a high-volume submersible pump and disposed of in deeper Devonian carbonates. Production from the Indian Basin transition zone is relatively new. These wells were originally non-commercial until it was discovered that the pay zones could be de-watered with a high volume pump. Individual wells in this area cost ~2-3 million dollars to drill and complete. Almost all of the wells are directionally drilled from well pads approved by the Bureau of Land Management (Craig Corbett, 2006, written communication. *0.5*

67.0 Road to right leads to tank battery. **Continue straight.** *0.3*

67.3 T-junction at Oxy USA well pad. **Turn right,** passing well pad to left, and continue up hill. Road becomes rougher, due to Yates dolomite cropping out in roadbed. *0.4*

67.7 Cross cattle guard. Immediately after crossing, pass turn-off to well pad to right [surface location: 22S.24E.14]. **Continue straight.** *0.8*

68.5 Ascending McKittrick Hill anticline. NE-dipping Yates dolomite in arroyo to left. The McKittrick Hill dome is one of the Carlsbad Folds, interpreted by Motts (1972) as biohermal mounds, not true tectonic folds. *0.1*

68.6 Parking area to left. **Stay on road** and continue up hill. *0.2*

68.8 Stop 4. McKittrick Hill caves. Crest of McKittrick Hill.

Basal Yates sandstone visible in wall of arroyo to east. Park vans on old well pad, eat lunch, and divide into groups to enter caves.

The five principal caves of McKittrick Hill – Dry, Endless, McKittrick, Sand, and Little Sand caves – are formed along the south and east flanks of the McKittrick Hill anticline. The caves are located within the pisolite facies belt of the upper Seven Rivers dolomite, just below the contact with the basal Yates sand, a stratigraphic setting similar to the one occupied by Cottonwood Cave in the high Guadalupes. The caves are primarily horizontal, with less than 30 m of vertical relief (with the exception of Dry Cave, with a maximum depth of 63 m), and lower levels that often terminate in flat, sandy floors. Many of the passages are maze-like with two or more distinct levels, and frequently trend parallel to the strike of bedding along the flanks of the McKittrick Hill structure. Gypsum is common in all of the caves, with thickness exceeding 2 m in places (Smith, 1978b; Hill, 1987). Endless Cave has some of the most spectacular speleogenetic gypsum occurrences in the Guadalupe Mountains. A summary of an extensive study of this gypsum is offered by Hill (1987). Important paleontological discoveries have been made in Dry Cave, including late Pleistocene sloths, armadillos, extinct horses, camels, llamas, and dire wolves, which were studied and documented by Harris (1970; 1985), and Harris and Porter (1980).

All of the caves were originally heavily decorated with carbonate and gypsum flowstone and speleothems. However, extensive vandalism and formation mining throughout the early 20th century have resulted in loss of some of the most spectacular cave formations.

Primary features to look for in the Seven Rivers Formation host rock include exposures of pisolitic dolomite, stromatolite heads, algal mats, and teepees (Figure 1.1.24). Secondary features to note include drill holes in gypsum blocks formed by dripping water, gypsum overgrowth crusts, streamlined surfaces, and unusual structures known as commode holes. These features resemble drill holes in gypsum in that they include round to ellipsoidal holes when viewed from above. However, they are significantly larger than drill holes (15 – 100 cm diam.), with overhanging upper lips or a rounded crown of gypsum partially rimming the hole. Unlike drill holes, commode holes may not be vertical and do not correspond to overhead limestone pendants, joints or stalactites. Some of the best examples of commode holes are found in Endless Cave, where many of these features have been modified by gypsum-rim speleothemic material along their upper edges (Hill, 1987).

Alunite from Endless Cave was dated by $^{40}Ar/^{39}Ar$ at the New Mexico Geochronology Research Laboratory at New Mexico Tech. The alunite, a byproduct of the sulfuric acid speleogenesis of Endless Cave, is 6 million years old, indicating that speleogenesis at McKittrick Hill took place at that time. These caves are at the same elevation as Glacier Bay in Lechuguilla Cave, where

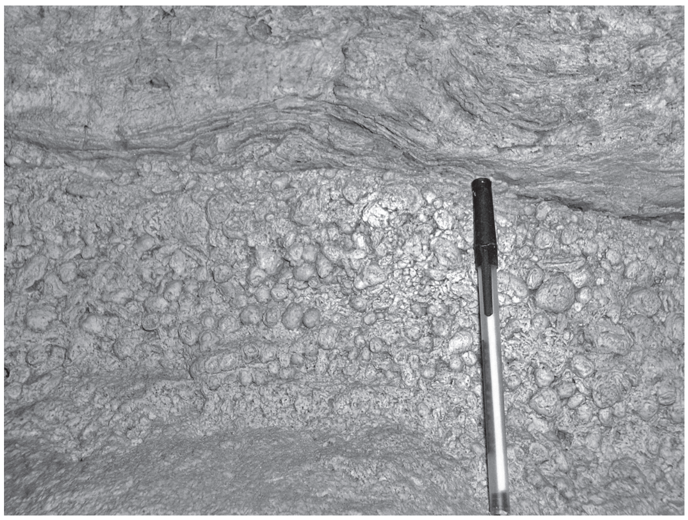


FIGURE 1.1.24. Pisolitic dolomite, algal mats and stromatolites exposed in walls of one of the McKittrick Hill caves.

alunite ages are identical (Polyak et al., 1998). Quartz, gypsum and hydrated halloysite are other speleogenetic minerals occurring in these McKittrick Hill caves (Hill, 1987).

In 1943, Standard of Texas drilled an exploratory well on the crest of McKittrick Hill anticline, reaching a depth of 1,189 m before plugging as a dry hole the following year. In 1957 Northern Natural Gas drilled another dry hole to a depth of 3,625 m, just 23 m away from the surface location of the Standard hole. At least four water well drill holes penetrate Endless Cave.

After visiting caves return to vehicles and proceed back to Waterhole Road. *9.4*

78.2 Junction with CR 406/Waterhole Road. **Turn right.** From here to the junction with US 285 we will be driving on a thin and discontinuous veneer of Quaternary terrace gravels overlying Yates bedrock. Yates dolomite visible in hills to left and right, and sometimes in roadbed. *0.2*

78.4 Borrow pit to right. *1.8*

80.2 Junction with US 285. **Watch traffic! Turn right** (ESE) onto US 285. *0.5*

80.7 Crossing Spencer Draw. *0.9*

81.6 Adobe Flat at 3:00. *1.0*

82.6 **Turn right** onto CR 524/Happy Valley Road toward Carlsbad. *0.6*

83.2 Roadcut/borrow-pit exposure of thin-bedded dolomite of Yates Formation west of road (to right). Small folds in outcrop are cored with gypsum. Low hills are thinly bedded dolomite of the Tansill Formation. *1.4*

84.6 MP 2. Approaching crest of hill and drainage divide. *0.4*

85.0 Cross pipeline. Route descends into southeast-trending synclinal valley of Hackberry Draw. Ridge to right (12:30 to 3:00) is the Hackberry Hills anticlinal structure with a fold axis oriented normal to the Capitan Reef trend. The hills are surmounted by the McGruder Hill dome. According to Motts (1962), the cores of the anticlinal structures appear to be biohermal mounds in the Seven Rivers Formation with Yates and Tansill draped over them. *1.3*

86.3 Ocotillo Hills dome at 9:00 to 11:00. Route ahead crosses poorly exposed beds of Castile Formation preserved in the trough between the Hackberry and Ocotillo Hills. *1.0*

87.3 Living Desert State Park to left on West Church Street. **Continue straight.** Entering community of Happy Valley. *1.1*

88.6 MP 6. Pedogenic calcrete (stages IV to V) exposed in caliche pit ahead on left. *0.3*

88.9 Highway curves to left (east) and merges with West Lea Street. *0.7*

89.6 Four-way stop; **turn right** (south) onto Standpipe Road (CR 658). For the remainder of the trip the route is on alluvial fill of the Carlsbad segment of the lower Pecos Valley. *2.0*

91.6 Route curves to right, skirting inner channel of Dark Canyon Draw to left. *1.2*

92.8 Stop sign at junction of Standpipe and Hidalgo Roads. **Turn left** (east) on Hidalgo Road (CR 672). *0.2*

93.0 Cross channel of Dark Canyon Draw; Rustler-Culebra Dolomite in low hill to right. *1.3*

94.3 Stop sign ahead at cross-road (Boyd Drive); **continue east** on Hidalgo. *0.3*

94.6 Stop sign at junction of Hidalgo Road with US 62-180/National Parks Highway. Skeen-Whitlock Building on left, where DOE maintains offices for administration of the Waste Isolation Pilot Plant (WIPP). **Turn right** onto 62-180 and proceed southwest. *21.8*

116.4 Junction with Washington Ranch Road. **Turn right** and return to Washington Ranch. *1.5*

117.9 Gate to Washington Ranch. **Turn right** and enter ranch. *0.4*

118.3 Crossing tufa dam at WR.

End of Day 1 - Trip 1 road log.

GEOLOGICAL WALKING TOUR OF WASHINGTON RANCH

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Surficial geology at Washington Ranch consists of Holocene and late-to-middle Pleistocene alluvium and calcareous tufa deposits overlying upper Permian gypsum of the Castile Formation. Although the Castile is the Permian bedrock underlying this reach of the Black River, it is nowhere exposed on the grounds of the ranch headquarters. In the immediate vicinity of Washington Ranch, the Castile is mantled by very poorly sorted Quaternary gravels, locally cemented by calcium carbonate (caliche and travertine), to form a hard limestone cobble conglomerate that breaks along clasts (Sares, 1984). Conglomerates are exposed in prominent bluffs along the southeast bank of the Black River, in the stream banks, and in places armor the streambed. The Quaternary gravels consist of pebbles and cobbles of limestone derived from the Capitan Reef and near backreef units, eroded from the Guadalupe Escarpment located a few km to the north. Some of the gravels contain resistant siliceous pebbles, probably reworked from Cretaceous conglomerates into Miocene equivalents of the Ogallala Formation, and reworked again into Quaternary deposits. Thickness of the gravel/conglomerate deposits is highly variable, ranging from 4 – 104 m (Love and Land, 2006; Hayes, 1957; 1964).

The most visually striking surface features at Washington Ranch are the extensive tufa deposits that line the Black River and form tufa dams at five different locations. The most accessible tufa dam is formed just west of the Black River crossing, where the field trip will assemble each day of the conference (Figure 1.1.25-A). Casts of reeds and other aquatic plants are some of the more common features seen in the tufa deposits. Multiple episodes of tufafication are indicated along this reach of the Black River. The most prominent tufa dams predate fine-grained marsh-floodplain sediments, presumed to be late Holocene in age, because the marsh sediments overlie the upper level of the tufa dams in several locations. Later episodes of tufa formation are indicated by tufaceous material cementing fine-grained fossiliferous Holocene sediments (Love and Land, 2006).

Guide

This geological walking tour of Washington Ranch leads the user around the headquarters area to examine outcrops of Quaternary gravels and tufa deposits along the banks of the Black River. UTM coordinates are provided for most stops (NAD 83 datum), and locations are indicated on the accompanying air photo (Figure 1.1.25). Although bedrock geology and some Quaternary deposits have been mapped in general (King, 1949; Horberg, 1949; Hayes, 1957; Kelley, 1971; Sares, 1984), the features seen along these local trails have not been previously documented or studied in detail.

A. Main tufa dam, at Black river crossing, is the most accessible of the five tufa dams found on Ranch property [13S-551605, 3553414]. Another dam occurs just downstream. Examine casts of aquatic vegetation incorporated in the tufa. Note dark-gray fine-grained alluvium containing snail shells in berm downstream from the dam. Upstream, the channel of the Black River has been excavated into a deep, artificial slot to store water when available. Much Holocene alluvium has been removed to form artificial terraces on both sides of the river. The path on the east side of Black River follows the top of fine-grained Holocene alluvium and artificial fill related to building construction.

B. Exposure of Quaternary cross-bedded terrace gravels behind dining hall [551509, 3553273]. The top of this exposure is 7-10 m above the tufa dam, and the unit is inset against a higher terrace. Note finer-grained beds within this outcrop. Across the Black River, artificial terraces and water storage ponds are formed by regrading alluvium. The highest point beyond the headquarters building to the west, however, is one of the older, well-cemented piedmont levels from Rattlesnake Canyon. From here, a trail continues southwest following the east bank of the river, past bluffs formed from cemented gravels.

C. Cemented Quaternary conglomerate of the intermediate Black River terrace (21 m above tufa dam) forms steep bluffs behind the Ranch ropes course, in places cutting down into underlying tilted, finer-grained, thin-bedded sediment that may be older sinkhole fill [551343, 3552947]. Unpaved trail leads to the top of the bluffs for an overview of Washington Ranch and the Black River Valley. **Please do not climb on ropes course equip-**

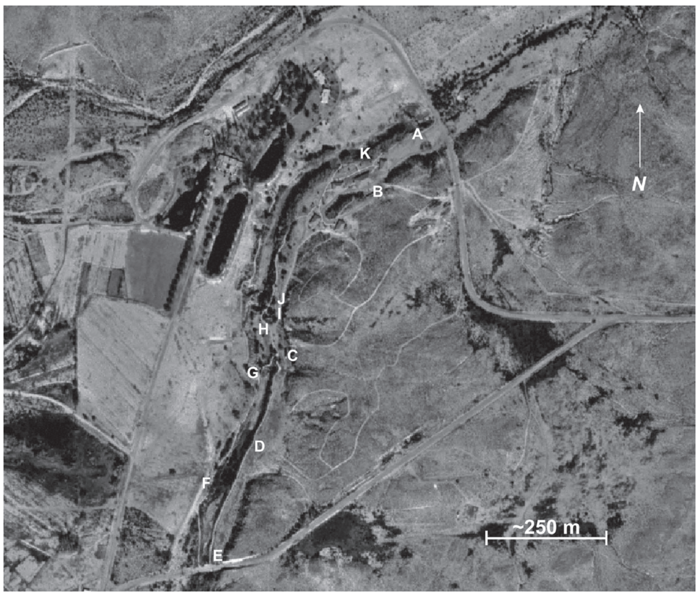

FIGURE 1.1.25. Areal view of Washington Ranch with geological walking tour locations represented by letters.

ment. At this station the trail forks. The right fork crosses the Black River on a foot bridge over a large tufa dam (Station G). Take the left fork and continue following paved trail for a slightly longer hike. Note the large overhang on the upstream (south) side of the tufa dam.

D. Route continues on a Holocene fine-grained alluvial terrace. Across the river to the west, note 4 m high tufa bluffs with vertical depositional lineations. A coarse gravel bar in the river channel is a product of the most recent flood event.

E. At the low water crossing, turn left and walk a few meters up the paved road, where boulder to cobble conglomerates are exposed in the adjacent roadcuts [551226, 3552499]. The upper conglomerate beds are rotated ~20°, probably due to solution subsidence in the underlying Castile gypsum. The conglomerate overlies finer-grained, more steeply-tilted sediments and soils that may be older sinkhole fill. On the west side of the river, the paved road ascends two conglomeratic terrace levels (piedmont levels 6 and 5; Love and Land, 2006) to the Washington Ranch fire station. Large trees to west beyond the fire station are part of the Rattlesnake Spring Picnic Area of Carlsbad Caverns National Park. Return to low water crossing, cross Black River, and continue hike on paved trail on the west bank. Note large boulders in the streambed composed of limestone conglomerate ripped from channel walls, an indicator of the flashy nature of discharge in the Black River drainage. Gully bed cementation in this reach of the river is currently forming new conglomerate bedrock.

F. Path ascends to level 6 (4-5 m above channel). On the west side of the path, well-cemented limestone-clast conglomerate is exposed. Below the path, horizontal and vertical tufa deposits line the river bank.

G. At the footbridge across the Black River, a large, compound tufa dam can be observed that has been anthropogenically modified to facilitate streamflow, water storage, and diversion [551275, 3552903]. Limestone conglomerate overlies the tufa dam material in places, supporting the model that the tufa dams are older, exhumed features (Love and Land, 2006). Visitors may speculate about the origin of the large overhang on the upstream side of the tufa dam. The trail forks again here. The right fork crosses the bridge and returns to the opposite (east) bank. Take the left fork and continue following pavement along west bank. Note the large rimstone dams formed from tufa in the streambed to right. Relief on the rimstone dams may have been enhanced by plunge pool formation.

H. Another large tufa dam can be found just off the trail to the right [551275, 3553028], with a well-developed plunge pool and secondary dam a few meters downstream. Tufa around the margins of the plunge pool contains casts of large reeds and other aquatic plant material.

I. Enter streambed at level of secondary dam. Exotic tufa formations are exposed in several locations along the east bank of the Black River. Just below the secondary dam, a continuous layer of tufa along the bank changes abruptly from horizontal to near-vertical stratification, following original water flow patterns – a “paleo-waterfall” deposit.

J. A few meters farther downstream, a shelter cave is formed in tufa deposits on the east bank of the river [551290, 3553083]. Bulbous pendants (tufa stalactites?) are suspended from the ceiling of the cave. Origin of the pendants is unclear. They may be typical stalactites later coated with tufa, in which case their bulbous morphology may be caused by an old pool level where downward-stalactite growth ceased; or they may be tufa-coated erosional pendants. Coralloid (popcorn) texture is well-developed on the walls of the cave. More shelter caves can be found farther downstream. After examining those caves, exit streambed, return to paved trail, and walk back to Ranch facilities. Path to left leads to fountains and ponds near the headquarters building. Water for these features comes from Rattlesnake Spring to the southwest by way of an irrigation canal.

K. In the excavated channel near the bridge between headquarters and the dining hall, visitors may examine the well-cemented conglomerate exposed beneath gray, fine-grained snail-bearing Holocene alluvium.

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