Third-day road log, from Living Desert State Park turnoff at US 285, north to Brantley Dam and Lake McMillan, through Artesia, Lake Arthur, Hagerman, Dexter and ending at Bottomless Lakes State Park

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GYPSUM KARST PROCESSES IN THE SEVEN RIVERS FORMATION

THIRD-DAY ROAD LOG, FROM LIVING DESERT STATE PARK TURNOFF AT US 285, NORTH TO BRANTLEY DAM AND LAKE MCMILLAN, THROUGH ARTESIA, LAKE AUTHUR, HAGERMAN, DEXTER AND ENDING AT BOTTOMLESS LAKES STATE PARK

LEWIS LAND AND DAVID LOVE

Assembly Point: Intersection of Miehls Drive and US 285. Refer to Happy Valley supplemental road log for directions from Washington Ranch to assembly point

Departure Time: 8:15 AM

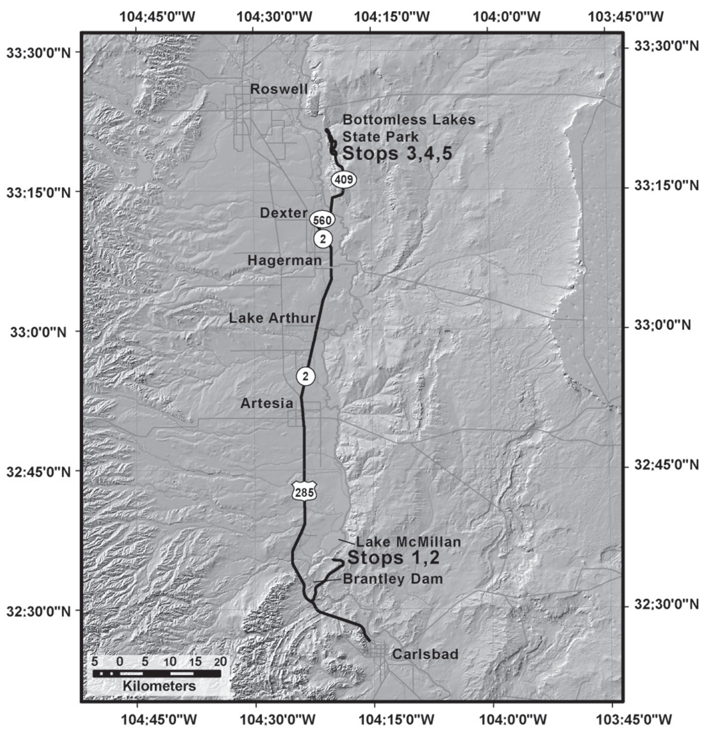
Distance: 92.7 miles

Five stops and one optional stop

SUMMARY

The third day of the conference focuses on engineering hazards and hydrologic issues associated with gypsum karst processes in the Seven Rivers Formation. The trip begins with an excursion through Happy Valley west of Carlsbad, to the intersection with US 285 (see supplemental log for directions), and proceeds north to the dam site of old Lake McMillan. This reservoir, the predecessor to Brantley Lake, was constructed in 1893, and was plagued with leakage problems caused by sinkhole formation in the lake bed almost from its inception, since it was built on the evaporite facies of the Seven Rivers Formation. Stop 1 provides a view of the old reservoir and dam, which was breached in 1991 and the water allowed to flow into the new Brantley Reservoir. A visit to stop 2 requires the use of high-clearance vehicles, which will ascend the back side of the McMillan Escarpment for an overview of the reservoir and impressive exposures of mass wasting and gypsum fissures along the steep eastern margin of the Lake. From here, the trip proceeds back to US 285 and north across the Roswell Artesian Basin, the primary source of irrigation and drinking water for farming communities in the lower Pecos Valley. The Seven Rivers gypsum serves as a leaky confining unit for the karstic San Andres limestone, the principal source of groundwater in the Artesian Aquifer. The final three stops of the Field Conference will examine spectacular examples of gypsum cenotes at Bottomless Lakes State Park, east of Roswell, where they occupy the discharge end of the regional hydrologic system in the Artesian Basin.

0.0 Stop sign. Intersection of Miehls Dr and US 285. Living Desert State Park sign to right.



Set odometers to zero as your vehicle passes stop sign and turn left (west) onto US 285. *0.2*

0.2 Roadcut to left is an exposure of the shallow marine, outer shelf facies of the Tansill Formation on the northeast flank of Tracy Dome, dipping ~10° east toward the Pecos River. Dolomites of the grapestone-grainstone facies belt indicate deposition in the subtidal environment of a backreef lagoon. The Tansill lagoon was about 22 km wide and at this point was about halfway between the reef and the shoreline. In the lower portion of the roadcut, the Ocotillo Silt member of the Tansill is exposed as a blue-gray siltstone, and probably represents aeolian coastal plain sediments (Jacka, 1988). *0.1*

0.3 Pecos River to right. Between Brantley Dam and Carlsbad Springs the Pecos is a losing stream, in the process recharging near-backreef units of the Capitan Reef aquifer (Cox, 1967). *0.8*

1.1 MP 38. Irrigated farmland to east on Lakewood Terrace of the Pecos Valley. *1.0*

2.1 US 285 relief route at MP 39. **Continue straight.** This route was built to accomodate transport vehicles carrying transuranic radioactive waste to the Waste Isolation Pilot Plant (WIPP) site east of Carlsbad. Tansill dolomite in roadcut to left. The type section of the Tansill has been described by DeFord (1941) in the Ocotillo Hills to the southwest. *2.2*

4.3 Brecciated dolomite, gypsum, and siliciclastics of the Tansill Formation in roadcut to left. *0.4*

4.7 NM 524 to left leads to Happy Valley (see day 1 for log). **Continue northwest on US 285.** The hill on the left is a ridge surrounding a circular depression ~1.5 km in diameter, interpreted by Motts (1962) as a young solution-collapse feature. Tansill dolomites on the flanks dip steeply toward the center of this crater-like structure, which is floored by gypsum of the Yates and Tansill Formations. Non-tectonic folds caused by subsurface dissolution and subsidence are widespread in this portion of the Pecos Valley. A well drilled to a depth of 336 m in the center of the depression bottomed in Seven Rivers dolomites (Kelley, 1971b). *1.5*

6.2 The feature superficially resembling a cinder cone on the skyline at 9:00 is Round Mountain, the largest of the so-called Three Twins, residual knolls formed in evaporites and redbeds of the Yates Formation capped by more resistant Tansill dolomite. Such residual hills and ridges are common features in the carbonate-to-evaporite transitional facies belt of the Artesia Group. *0.1*

6.3 Roadcuts over the next mile expose interbedded gypsum, dolomite and redbeds of the Yates Formation, representing the carbonate-to-evaporite and redbed facies change within the Yates. Note small folds in the roadcuts, part of an arcuate fold belt called the Waterhole Anticlinorium (Kelley, 1971a) that wraps around the west and north sides of the Carlsbad area. *1.7*

8.0 Cross Rocky Arroyo. Yates dolomite at 3:00 forms ridge in middle distance. *0.4*

8.4 Ascending terrace of Rocky Arroyo. *0.4*

8.8 **Turn right** onto CR 30/Capitan Reef Road to Brantley Lake State Park. *0.2*

9.0 Brantley Dam at 12:00. Driving over partially cemented terrace gravels of Pecos River. *0.4*

9.4 Large borrow pit for dam construction on right. At 10:00 is the back side of the Seven Rivers Hills. *0.4*

9.8 Wing wall of Brantley Dam to left. *0.2*

10.0 Descend off conglomeratic terrace deposits to lower river level below Brantley Dam. Now driving on intermediate terrace of Pecos River floodplain. *1.1*

11.1 Spillway of Brantley Dam at 9:00. Well-developed Holocene coppice dunes on both sides of road. Prominent bluffs on opposite bank of Pecos at 2:00 are formed in Quaternary cemented terrace gravels, rotated as much as 40° due to solution-subsidence in underlying evaporites, redbeds and dolomites of Yates transitional facies. *0.1*

11.2 Cross Pecos River on bridge south of Brantley Dam. *0.1*

11.3 Return to low terrace level, passing coppice dunes and fine-grained floodplain sediments in roadcut to right. *0.2*

11.5 Route ascends valley border to higher terraces. *0.5*

12.0 Monitoring wells to left. *0.3*

12.3 Poorly-exposed Yates dolomite and redbeds in low roadcuts to left. *0.3*

12.6 Flat-topped crest of hill; wingwall of Brantley Dam at 10:00. *0.5*

13.1 Road to left leads to Brantley Lake State Park and Visitors Center. **Continue straight.** *0.2*

13.3 Cuesta to right is formed in redbeds and gypsum capped by dolomite of the Yates Formation. *0.1*

13.4 Yates gypsum exposed in bar ditch. *0.9*

14.3 Cross railroad. Yates gypsum exposed in railroad bed on both sides of road. McMillan Escarpment at 10:00. Dolomitic facies of Yates is exposed in railroad cuts ~800 m to southeast. *0.5*

14.8 T-junction with Lake Road (CR 34). **Turn left** onto Lake Road. *0.3*

15.1 Stop sign at intersection with Netherlin Road. **Continue straight.** *0.3*

15.4 Seven Rivers dolomite capping cuesta at 3:00. *0.3*

15.7 McMillan Dam at 12:00. Brantley Lake at 9:30. Seven Rivers Hills on horizon (Seven Rivers dolomite capping redbeds and gypsum). *0.2*

15.9 Stop 1: McMillan Dam and old Lake McMillan lake bed. Park on shoulder.

Breached dam straight ahead. Note man-made dike along east margin of lake, at base of McMillan Escarpment (Figure 3.1).

FIGURE 3.1. Dry lake bed of old Lake McMillan. McMillan Escarpment on horizon to right, formed in Seven Rivers evaporites and redbeds capped by dolomite on the ridge crest. The dike at the base of the escarpment was constructed in the early 20th century in an attempt to prevent loss of water into sinkholes along the eastern margin of the lake. Note gypsum fissures in face of escarpment.

The following discussion is based largely on Cox (1967), who investigated geohydrologic conditions beneath McMillan Dam and downstream as far as Carlsbad Springs.

Lake McMillan is located within the evaporite facies belt of the Seven Rivers Formation. McMillan Dam was constructed in 1893, and the reservoir almost immediately began experiencing leakage problems through sinkholes formed in the lake bed, particularly along the eastern margin of the lake. Water flowed through karst conduits in the Seven Rivers gypsum and returned to the Pecos River through discharge from Major Johnson Springs, ~5.6 km downstream at the present site of Brantley Reservoir. East and southeast of the facies change, the less soluble dolomite facies of the Seven Rivers retards any significant formation of solution channels. In 1908-09 a dike was constructed along the southeast shore of the lake, near the base of the McMillan Escarpment, in an attempt to isolate the areas of worst sinkhole formation. The dike was extended in 1953-54 along most of the eastern shore to prevent water from reaching exposed sinkholes during periods of high lake level. Occassionally breaks would occur in the dikes causing lake water to inundate the sinkholes. At these times whirlpools were reported in the lake, indicating that sediment cover over sinkholes in the lake bed had been disturbed. High rates of leakage would occur for short periods of time until the dikes were repaired and sediment cover on the floor of the lake restored.

Storage capacity of Lake McMillan steadily decreased after the dam was constructed because of deposition of suspended sediment, particularly during flood events, and by the early 1940's less than half of its original storage capacity remained. The possibility of dredging was considered but soon discarded when it was realized that removal of the accumulated sediment would considerably increase leakage through karst fissures in the gypsum bedrock underlying the lake. Fortunately, loss of storage capacity decreased by the mid-40's because a stand of salt cedar became established in bottom lands upstream from Lake McMillan, acting as a baffle for much of the suspended sediment carried by the Pecos River.

Consideration for construction of a new dam began as early as 1905. The U.S. Bureau of Reclamation began construction of Brantley Dam in 1984, and in 1991 McMillan Dam was breached and Lake McMillan allowed to drain into Brantley Lake. Based on recommendations by Cox (1967), the new reservoir is located mostly within the dolomitic facies belt of the Seven Rivers Formation.

Features to note near the old damsite include small-scale nontectonic folds, expressed as undulations in the Seven Rivers dolomite, almost certainly the result of subsurface dissolution of evaporites. Larger-scale folds exposed in the walls of the Pecos River channel on the other side of the dam probably have a similar origin. *0.1*

16.0 Turn around and return to Netherlin Road intersection. *0.7*

16.7 Intersection with Netherlin Road (CR 236). **Turn left. High-clearance vehicles only from this point on.** Other vehicles park on shoulder. *0.5*

17.2 **Slow. Turn left** on two-track just before cattle guard. All remaining vehicles should have high clearance from here on to Stop 2. Follow fence line. *0.4*

17.6 **Turn left** away from fence line. Watch for deep ruts in two-track. *0.5*

18.1 Two-track reaches ridge crest. Lake bed of old Lake McMillan below. Northeast end of Brantley Dam at 7:00. *0.1*

18.2 Small sinkhole to right. Vehicles should be careful of footing. *0.2*

18.4 Stop 2: Crest of McMillan Escarpment. Watch for parking directions from flaggers.

The McMillan Escarpment is a cuesta formed in gypsum and redbeds of the Seven Rivers Formation, capped by more resistant Seven Rivers dolomites. The carbonate-to-evaporite and redbeds facies change can be readily observed in a vertical sense during a partial descent down the face of the escarpment. Also present are large gypsum fissures and slump blocks, indicating continued mass wasting and evolution of the eastern margin of the lower Pecos valley by undercutting of the gypsum escarpment (Figure 3.2). Small gypsum caves and sinkholes occur at the base of the cliff. These karst features began causing serious leakage shortly after construction of the reservoir. Attempts to isolate the worst areas of sinkhole formation by construction

FIGURE 3.2. Continued mass-wasting processes indicated by large gypsum fissures formed in the face of the McMillan Escarpment.

of a dike along the eastern shore of the lake were only partially successful.

Watch your footing on unstable slopes. After stop, return to Netherlin Road. *1.2*

19.6 **Turn right** onto Netherlin Road. *0.5*

20.1 Junction of Netherlin and Lake Roads. **Turn left** onto Lake Road. *0.3*

20.4 Junction with CR 30. **Turn right** and return to US 285. *6.0*

26.4 Junction of CR 30 with US 285. CR 30 is known as the Capitan Reef Road on the east side of the highway. The road continues across the highway toward the village of Queen in the high Guadalupes and is known as the Queen Highway. 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. **Prepare to turn right onto Highway 285. Re-zero odometers as you turn onto highway.**

0.0 **Turn right** and proceed north on US 285. *0.3*

0.3 MP 46. *0.7*

1.0 Seven Rivers Hills at 10:00. Brantley Dam at 3:00. *1.5*

2.5 Yates dolomite at top of roadcut on left probably overlies siltstone and gypsum covered by dolomite riprap. *0.1*

2.6 Seven Rivers dolomite in roadcuts to left and right. *0.3*

2.9 Brantley Lake road and boat ramp to right. *0.9*

3.8 Crest of Seven Rivers Hills. Brecciated redbeds and gypsum of the Seven Rivers evaporite facies are exposed in roadcuts to left and right. The McMillan Escarpment can be seen as a low cuesta east of the Pecos River at roughly 3:00. The north-south-trending Seven Rivers gypsum and dolomite outcrop belt, which forms the McMillan Escarpment, swings southwest at this point and crosses the Pecos River, due to a northeast-trending, southeast-dipping monocline. The same outcrop belt forms the cuesta of the Seven Rivers Hills, which are capped by more resistant dolomites of the Azotea Tongue of the Seven Rivers Formation (Kelley, 1971b). The Seven Rivers Hills are (somewhat arbitrarily) regarded as the southern boundary of the Roswell Artesian Basin. *0.1*

3.9 Descending into alluvial lowlands formed by a confluence of the Seven Rivers tributaries of the Pecos River. For the past several million years, the Pecos has been migrating progressively eastward due to uplift of the Sacramento Mountains to the west combined with dissolution of gypsum bedrock to the east. Floodplain deposits of the Pecos River form a shallow water-table aquifer in the Roswell Artesian Basin. *1.4*

5.3 MP 51. About 1 km to the west the New Mexico Interstate Stream Commission has drilled several augmentation wells to pump water from the deep Artesian Aquifer and pipe it directly into the Pecos River. These augmentation wells form part of a consensus plan between the Carlsbad Irrigation District (CID) and the Pecos Valley Artesian Conservancy District (PVACD) to help meet our interstate compact obligation to share water resources in the Pecos with the state of Texas. *0.5*

5.8 Crossing South Seven Rivers Arroyo. Pecan orchard to right. Pecans are an important cash crop in the largely agricultural economy of the Artesian Basin. *0.7*

6.5 Gravels capped with soil in roadcuts are Seven Rivers terrace deposits. *2.8*

9.3 MP 55. Junction with CR 31 to Lakewood to right. **Continue straight.** *0.8*

10.1 Crossing North Seven Rivers Arroyo. Route continues north on broad, east-sloping plain. *1.8*

11.9 Partially-cemented Quaternary gravel terrace deposits in roadcut to right. *0.4*

12.3 MP 58. Crossing Fourmile Draw. *1.4*

13.7 BP pipeline crosses under road. Three years ago several shallow fissures were discovered by a BP aerial survey in the vicinity of the pipeline (Figure 3.3). The fissures are probably associated with subsurface dissolution and subsidence in the Seven Rivers gypsum, which underlies the alluvial valley fill in this area. Depth of some of the fissures exceeds 1 m (Figure 3.4). *2.2*

FIGURE 3.3. Fissure crossing pipeline access road south of Artesia, developed in alluvium overlying Seven Rivers evaporites.

15.9 Extensive oil field infrastructure can be observed to the right of the highway in the Empire Field, which produces oil and gas from the Abo reef. The reef manifests itself in the subsurface as the Artesia-Vacuum Arch, an EW trending structural nose that extends for ~120 km into Lea Co. (Kelley, 1971a). The first oil discovery in southeastern New Mexico was made in this area in 1924. *0.8*

16.7 Crossing the Rio Peñasco. The Peñasco is a perennial stream in the Sacramento Mountains to the west, but becomes a losing stream when it flows across the Pecos Slope west of Artesia, in the process recharging the underlying San Andres Artesian Aquifer. *1.0*

FIGURE 3.4. Close-up of earth fissure near pipeline south of Artesia. Consultant for scale (consultant is ~2 m in length).

17.7 Junction with CR 65 to left. **Continue straight.** Sprinkler irrigation systems become increasingly common from this point north, as we drive farther into the Artesian Basin. Note the repeating image of three transformers on a utility pole and a mound of earth, indicating the presence of a nearby water well and pump and a pond for surface storage. *1.6*

19.3 Atoka Grocery on left. *1.2*

20.5 "Village of Atoka welcomes you". This town grew along ATSF railroad and is host to the Eddy County Arena. Note new pecan orchards along both sides of the road. *0.8*

21.3 MP 67. Historic marker, showing the route of Castaño de Sosa's 1590-91 expedition up the Pecos River. *0.2*

21.5 Halliburton service company yard to right. *0.5*

22.0 Entering southern Artesia. The town acquired its name in 1903 because of the abundant resources of artesian water that were discovered in the area around the turn of the 20th century, making the region an agricultural oasis. In recent years dairy farming has become increasingly important to the agricultural economy of the lower Pecos valley (Figure 3.5).

Artesia lies near the southern end of the Roswell Artesian Basin, from which groundwater is withdrawn from the karstic San Andres limestone aquifer to support irrigated agriculture. The Seven Rivers Formation in its redbed-evaporite facies serves as a leaky confinging unit for the San Andres aquifer. Although water levels in the Artesian Aquifer have declined substantially since development began in the early 1900's, some wells northwest of Artesia still display strong artesian flow. *1.5*

23.5 Main Street Artesia, and junction with highway 82. **Continue straight.** Navajo Refinery to right. In addition to

FIGURE 3.5. Dairy farming has become an increasingly important part of the local economy in recent years.

FIGURE 3.6. "The Derrick Floor", a monument to the petroleum industry in downtown Artesia.

irrigated agriculture, Artesia is also a local center for oil and gas activity. Yates Petroleum corporate headquarters is located 3 blocks to the west. A monument to the southeastern New Mexico petroleum industry, "The Derrick Floor", was recently installed a few blocks farther west (Figure 3.6). The Wellhead Brewpub, owned by one of the Yates family and the only brewpub in the lower Pecos valley, is across the street from Yates' offices. *0.3*

23.8 Crossing Eagle Draw in north Artesia, another losing stream and tributary to the Pecos River. *2.3*

26.1 Artesia adult video store to left (the only adult entertainment facility in the lower Pecos valley). **Veer right** onto NM 2 to Lake Arthur and Hagerman. Route follows ATSF railroad line northeastward. *0.7*

26.8 Artesia cemetery to left. Just beyond cemetery, terrace gravels are exposed in low roadcuts to left and right. *2.3*

29.1 MP 3. Low hills at 2:30 on east side of valley are formed in redbeds of Seven Rivers Formation. *2.3*

31.4 Bridge over Cottonwood Creek. This drainage is controlled by large levees on both sides of the channel for several km. *0.7*

32.1 Chavez County line. At this point the route crosses the NNE-trending subsurface KM fault. The KM fault parallels the Pecos Buckles, a series of surface faults that extend across the Pecos Slope to the west. Like the Buckles, the KM fault is thought to combine right-lateral motion with normal vertical displacement, and may be of Laramide age (Kelley, 1971a). The hydraulic gradient in the Artesian Aquifer increases abruptly just west of the KM fault, indicating that it acts as a partial barrier to down-gradient groundwater flow. Water levels are several tens of meters deeper in the Artesian Aquifer on the southeast side of the fault. *1.2*

33.3 Crossing Walnut Creek. *0.9*

34.2 Entering outskirts of Lake Arthur, one of several small agricultural communities of the lower Pecos Valley between Roswell and Artesia. In 1977, a Lake Arthur resident discovered an image of Jesus Christ on a flour tortilla she was preparing for her husband. By 1979, the Shrine of the Holy Tortilla had been visited by over 35,000 of the faithful. Images of Christ on a tortilla were later reported in Phoenix, AZ and Hidalgo, TX, but the Lake Arthur holy tortilla may be the first documented sighting in recent history. *1.0*

35.2 Lake Arthur cemetery to left. Sierra Blanca on western horizon at 9:00. Capitan Mountains batholith at 10:00. *3.5*

38.7 El Gomez bar on left. *3.6*

42.3 Entering Hagerman, home of the Hagerman Bobcats. Unlike most communities in the Artesian Basin, Hagerman farmers derive most of their irrigation water from the Hagerman Canal west of town, rather than from the Artesian Aquifer, and secondarily from wells in the shallow alluvial aquifer. The Hagerman canal originally transported water south from the Rio Hondo east of Roswell. Because of intensive pumping from the Artesian Aquifer, all of the tributaries of the Pecos River, including the Rio Hondo, have been dry for many decades, except during brief flood events. For this reason, most of the "surface water" in the Hagerman canal is actually groundwater pumped into the canal from wells. *0.4*

42.7 Intersection with NM 249. **Continue straight.** *1.2*

43.9 Historic bridge over the Rio Felix, another of the now dry tributaries of the Pecos River. *0.3*

44.2 Red bluffs east of Pecos River at 2:30 are formed in Seven Rivers redbeds and gypsum. *4.2*

48.4 Entering village of Dexter, home of the Dexter Demons. As the Pecos Slope descends to the east toward the river, the potentiometric surface rises toward ground level. Water levels in wells near the river are only a meter or two deep, and many wells near Dexter still display strong artesian flow during winter months when irrigation is minimal. *0.6*

49.0 **Turn right** across railroad tracks onto Shawnee Road East (NM 190). *0.7*

49.7 Lake Van, an artificially flooded sinkhole, is visible between houses to the right, south of Shawnee Road. Lake Van is one of at least nine lakes or seasonal lakes here. *0.6*

50.3 Dexter Fish Hatchery entrance to right. Established in 1931, the Dexter National Fish Hatchery and Technology Center is the only federal facility in the nation dedicated to holding, culturing and studying fishes facing extinction. *0.2*

50.5 Route descends low terrace of Pecos River. Agricultural activity quickly diminishes east of Dexter because of deteriorating water quality east of the freshwater-saltwater interface in the Artesian Aquifer. Groundwater near the Pecos River has a TDS content in some areas as high as 7,000 ppm. *0.6*

51.1 Sharp bend to left onto Wichita Road. *0.3*

51.4 Zuber Lake Farm and artesian well to right. Rock-walled mound in front of house is an intermittently-flowing spring. *0.5*

51.9 Crossing Pecos River. Note banks 3 – 4 m high with natural levee sloping to the east. Water in this reach of the Pecos River is quite brackish, with TDS >2,000 ppm. Lakes along the river are a combination of oxbows and sinkholes. *0.3*

52.2 **Sharp left turn** to north. *1.4*

53.6 Road curves to right to northeast and ascends escarpment of Seven Rivers Formation redbeds and gypsum. *1.3*

54.9 Route continues north on top of escarpment. Outcrops of Seven Rivers redbeds and gypsum are west of road. *0.2*

55.1 Sierra Blanca on skyline at 8:30. Capitan Mountains at 9:30. City of Roswell across valley at 9:00. Reddish-brown ridge on far horizon to east is part of the outcrop belt of Triassic Santa Rosa Sandstone. *1.7*

56.8 Sinkhole valley to left. *2.8*

59.6 Road veers left and descends into valley. Dimmitt Lake to right, a large sinkhole lake on private land. Lea Lake, the largest of the cenotes of Bottomless Lakes State Park, at 11:30. *0.2*

59.8 Stop sign. Turn left toward Bottomless Lakes State Park (Figure 3.7). *0.2*

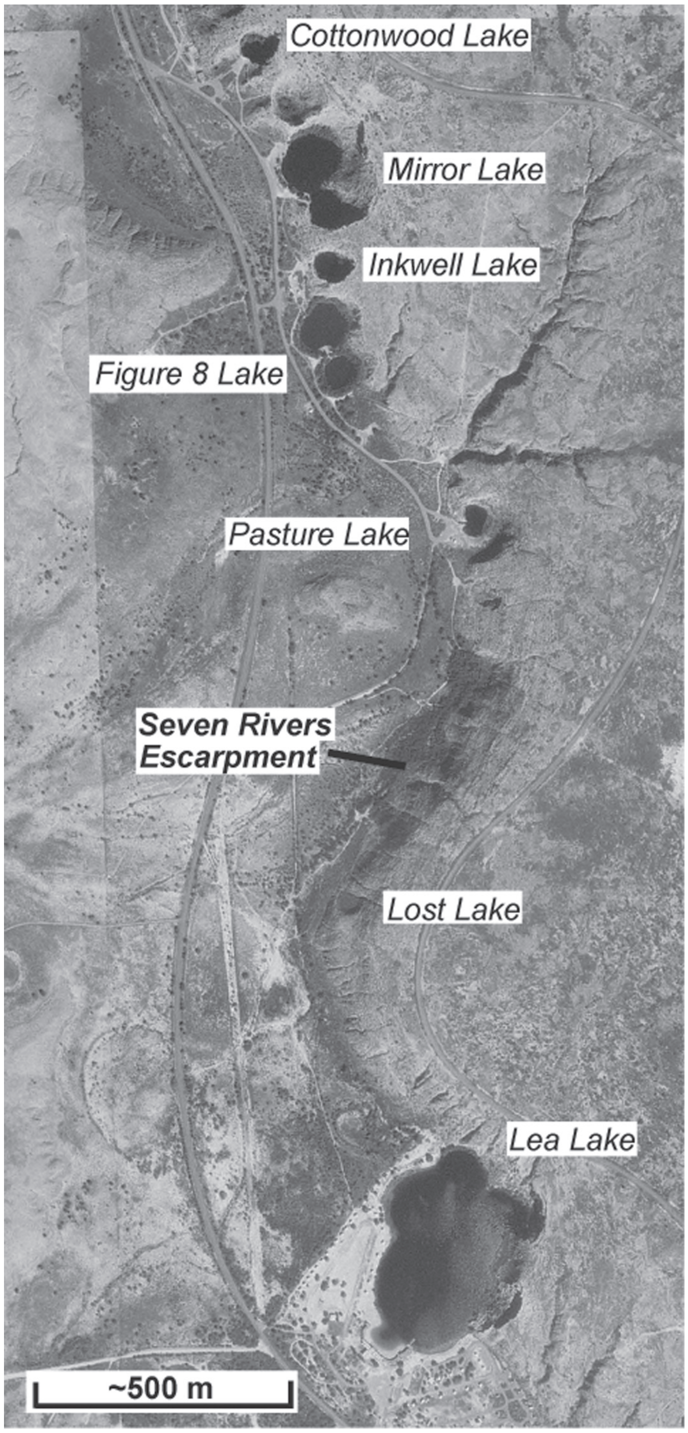


FIGURE 3.7. Digital orthophoto image of Bottomless Lakes State Park, showing flooded cenotes. Lazy Lagoon, the northernmost of the lakes, is off the map to the north. All the lakes visible in this image are formed in gypsum and redbeds within the Seven Rivers Escarpment, a geologic setting similar to that observed at Lake McMillan.

60.0 Stop 3: Lea Lake sinkhole. Turn right into Lea Lake Recreation Area, park and eat lunch.

Lea Lake is the only lake in Bottomless Lake State Park where swimming is permitted. Because of the clarity of the water, the

FIGURE 3.8. Rockslide in Seven Rivers Escarpment, eastern shore of Lea Lake cenote. Large gypsum boulders are present on the lakebed in ~8 m water depth at the base of the escarpment. At least half a dozen submerged springs discharge from the lakebed at this location.

lake is popular with local scuba divers. Bottomless Lakes is New Mexico's first state park, established in 1933.

See the minipaper by McLemore for the folklore and geology of Bottomless Lakes State Park, p. 93.

Note that the sinkhole is formed in and at the base of the Seven Rivers Escarpment. Note also large rockslides on far side of lake (Figure 3.8). *0.2*

See the minipaper by Land for an expanded discussion of the geology and hydrology of the Bottomless Lakes cenotes, p. 95.

60.2 Depart Lea Lake parking lot. **Turn left** at stop sign and cross overflow canal. *0.2*

60.4 Road to Dexter to right. **Continue straight.** *0.2*

60.6 Dimmitt Lake entrance to right. **Bear left** and ascend escarpment. *0.6*

61.2 Stop 4: Overview of Lea Lake. Turn left into parking lot at Lea Lake overlook.

We are standing on the Seven Rivers Escarpment, in a geologic setting very similar to that at the McMillan Escarpment farther south. As at Stop 2, large fissures are formed in the Seven Rivers gypsum along the upper edge of the escarpment, and large rockslides can be observed where they have fallen into the lake, showing the continued morphologic evolution of the lake margin by mass wasting. The principal difference between this location and Lake McMillan is the presence of active discharge of artesian groundwater at the base of the Seven Rivers Escarpment, enhancing mass wasting processes. Several springs discharge from the lakebed in ~8 m water depth on the eastern margin of Lea Lake. **Exit parking lot and turn left.** *0.4*

FIGURE 3.9. Lazy Lagoon, formed in an abandoned channel of the Pecos River, appears to be a single body of water when water levels are high. In fact the lake consists of three sinkholes with a maximum depth >25 m. Note large rotated slump blocks on Seven Rivers Escarpment near center of image. See Plate 16A for a color image of this feature.

61.6 Driving on Seven Rivers gypsum and redbeds. Sinkhole lakes formed in Seven Rivers Escarpment at 10:00. *2.1*

63.7 Lazy Lagoon at base of escarpment to left, formed in an abandoned channel of the Pecos River (Figure 3.9). *0.3*

64.0 **Turn left.** *0.3*

64.3 Mountain bike trailhead to right. *0.4*

64.7 Descend Seven Rivers Escarpment past large slump blocks of Seven Rivers gypsum on left. *0.7*

65.4 Optional stop: Lazy Lagoon overlook. Park on shoulder to right.

During winter months, when water levels are high due to low levels of irrigation from the Artesian Aquifer, Lazy Lagoon

FIGURE 3.10. Overview of Lazy Lagoon during summer months, when water levels are low due to increased irrigation pumping from Artesian Aquifer. See Plate 16B for a color image of this feature.

appears to be a single body of water. It is in fact three sinkholes formed in an abandoned channel of the Pecos River, the southernmost of which is over 25 m deep (Figure 3.10). The Lazy Lagoon sinkholes contain the most saline water in the park, with TDS exceeding 37,000 ppm, greater than the salinity of seawater. View back to north shows excellent examples of mass wasting, with large gypsum slump blocks detached from escarpment. *0.6*

66.0 Dry sinkholes in escarpment to left. Residual karst mound to right. *0.3*

66.3 Stop 5: Cottonwood Lake

Turn left into Visitors Center parking lot.

Cottonwood Lake straight ahead, a small cenote containing water that is fresh enough to support fish, although too brackish for them to reproduce. The lake is stocked with bass and rainbow trout. Note rockslide on far wall of sink.The visitors center has been recently renovated and contains excellent exhibits, including air photo images and 3-D models of all the sinkholes in the park. A trail along the escarpment continues south for ~500 m, crossing a dry sinkhole and terminating at Mirror Lake, a compound lake consisting of two cenotes that have grown together (Figure 3.11). Large gypsum fissures and small tectonic caves are formed in the upper margin of these sinks. Excellent examples of gypsum karren are exposed in bluffs along the north margin of Mirror lake. Note the pronounced west dip exposed in the walls of the Mirror Lake cenote. Regional dip is about 1° to the east. This local dip reversal is probably caused by subsurface dissolution of gypsum along the escarpment.

FIGURE 3.11. Overview of Mirror Lake, which consists of two cenotes that have grown together. Note the pronounced west dip well-exposed in the walls of the sink. Regional dip is ~1º to the east. This local dip reversal is caused by subsurface dissolution of gypsum along the escarpment. See back cover for a color image of this feature.

End of Field Conference

BOTTOMLESS LAKES STATE PARK

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Introduction

Bottomless Lakes State Park is located 14 mi southeast of Roswell, on the east edge of the Pecos River valley. The park is 4 mi long and the loop drive is 9 mi long. The park consists of approximately 1,611 acres and includes eight lakes; the Fin and Feather Club owns a ninth, Dimmitt Lake. Vaqueros (cowboys) reportedly gave the lakes their name (Young, 1984) after tying two or three ropes together and failing to reach the bottom. The greenish-blue color created by algae and other aquatic plants adds to the illusion of great depth. The lakes are actually sinkholes or cenotes formed by the underground dissolution of gypsum and salt causing the overlying rocks to collapse and form deep holes and underground caverns.

Tall tales and local folklore surround the lake system. One tells of a horse that fell into one of the Figure Eight Lakes, drowned, and was pulled out of the other. Numerous objects reportedly have been lost in the lakes, only to be retrieved later from Carlsbad Cavern or even the Gulf of Mexico. Stories abound of strong underground currents and giant turtles that lurk in the deep, murky waters.

The park has been a favorite recreational site since the turn of the century. It was established as a state monument on November 19, 1933, and became the first area set aside as a state park on July 6, 1935. It was one of four state parks established during the Depression era. Although the park was receiving state park funds, it did not become an official state park until April 18, 1959.

The Civilian Conservation Corps (CCC) constructed most of the original facilities, many of which are still being used. The park has been remodeled several times since its opening. Facilities at the park include covered tables, group shelter, bath house with showers, playground, volleyball areas, primitive camping sites, and sites with full hook-ups. During the summer, the park operates a gift shop and concession at Lea Lake with peddleboats. The sandy beach at Lea Lake is open all year; lifeguards are on duty only during the summer. Picnicking, camping, hiking, swimming (only at Lea Lake), scuba diving, and fishing (November through March only) are popular activities.

Lazy Lagoon (also No Name or Intermittent Lake) is the northernmost and largest lake with a water surface area of approximately 26.1 acres. It looks deceptively shallow but it is 70-90 ft deep in places. The white salt flats surrounding the lake are thin crusts of gypsum covering thick deposits of bad-smelling alkaline mud. Lazy Lagoon is formed by three sinkholes that are 90, 42, and 46 ft deep. In the summer, much of the lake evaporates except for the sinkholes. Lazy Lagoon lies along an abandoned channel of the Pecos River (Allen and Kottlowski, 1981).

The Visitor Center (interpretative center) lies in front of Cottonwood Lake, south of Lazy Lagoon. Cottonwood Lake is 30 ft deep and has a surface area of 0.52 acres. It was named for a large cottonwood tree that once grew on the shore. Near-vertical rock walls rise above the lake's surface, and very little vegetation grows along the sides. The lake is stocked with channel catfish and rainbow trout.

A hiking trail leads from Cottonwood Lake, through Lake-in-the-Making (a sinkhole without water) to a scenic view of Mirror Lake. Mirror Lake has a surface area of 3.44 acres and maximum depth of 50 ft. The lake is named after reflections of the surrounding red cliffs. Mirror Lake was once two lakes that were separated by a thin strip of land. The northern pond was too salty to support fish, but the southern pond was not. Today the ponds form a single lake that is able to support fish. Mirror Lake was created by three sinkholes; two are 33 ft deep and the third is 40 ft deep.

Devil's Inkwell, the smallest of the lakes, is named for its steep sides and dark waters, the result of growth of algae and various aquatic plants along the bottom. It is 32 ft deep and has a surface area of 0.36 acres. Rainbow trout are stocked in the winter.

South of Devil's Inkwell lies Figure Eight Lake, which is actually two separate lakes formed by two sinkholes. At one time the water covered the strip of land between the two lakes and together formed the shape of a figure eight. The southern lake is 0.76 acres and 22 ft deep and the northern lake is 1.46 acres and 37 ft deep. Salt cedar trees border both shorelines.

Pasture Lake lies south of Figure Eight Lake and is the shallowest of the lakes at Bottomless State Park. It is 18 ft deep and has a surface area of 0.76 acres. It is uncertain as to the origin of the name, but some say it was named because of a large flock of ducks that once lived here, making it appear as a pasture. South of Pasture Lake is Picnic Dell, another dry sinkhole.

Lost Lake is found hiding along the escarpment in between Picnic Dell and Lea Lake. It is small (less than one acre) and accessible only by hiking.

Lea Lake is the most popular lake and the only lake where swimming is allowed. Most of the developed facilities are at Lea Lake. It was named after Captain Joseph C. Lea, a rancher, veteran of the Civil War, and early settler of Roswell. Lea rode with Clark Quantrill and Frank and Jesse James during the Civil War and was a friend of William Bonney, alias Billy the Kid. Three sinkholes, 40, 60, and 90 ft deep form the lake. A mesa overlook provides a bird's eye view of the park.

Rare and endangered species are found in the park. The small Pecos pupfish and rainwater killifish live in the lakes. The eastern barking frog and the cricket frog, also endangered species, live in the park. Their croaking can be heard throughout the day. Other animals include deer, skunk, snakes, lizards, jackrabbits, and birds.

Summary

Bottomless Lakes State Park is a chain of eight lakes, ranging in depth from 17 to 90 ft. They occupy sinkholes or cenotes formed by the underground dissolution of gypsum and salt causing the overlying rocks to collapse and form deep holes and underground caverns. The park has been a favorite recreational site since the turn of the century and in 1935 became the first area in New Mexico to be set aside as a state park.

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HYDROGEOLOGY OF BOTTOMLESS LAKES STATE PARK

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The sinkhole lakes at Bottomless Lakes State Park are formed in gypsum and mudstone of the mid-Permian Seven Rivers Formation, and are some of the larger and more impressive examples of the many sinkholes and other karst features that line the lower Pecos Valley. The Bottomless Lakes sinks are the product of subsurface dissolution of gypsum by upward leakage of groundwater from the karstic San Andres limestone, which comprises most of the artesian aquifer in the Roswell Artesian Basin (Martinez et al., 1998). The lakes are fed by submerged springs discharging from the artesian aquifer, and represent the discharge end of the regional hydrologic system in the Artesian Basin. In their position along the eastern edge of the Pecos River Valley, the sinks also illustrate the fundamental role that karst processes have played in shaping the morphology of the lower Pecos region (Land, 2003).

The Bottomless Lakes sinks may more properly be described as cenotes because of their deep, steep-walled morphology, similar to the cenotes formed in limestone bedrock on the Yucatan Peninsula in Mexico. The cenotes of the lower Pecos Valley are unusual in that they occur in a semi-arid setting, where annual evaporation rates exceed mean annual precipitation by a factor of 7 or more (Caran, 1988). The lower Pecos region is also unique in that it is one of the few areas in the world where sinkholes are actively forming in a region of groundwater discharge rather than recharge (Salvati and Sasowsky, 2002).

Bottomless Lakes Park is located on the eastern margin of the Roswell Artesian Basin. The basin is generally characterized as a two-aquifer system, consisting of an eastward-dipping carbonate aquifer overlain by a leaky confining unit, which is in turn overlain by an unconfined alluvial aquifer (Figure 3.11). The carbonate aquifer is artesian to the east but under water table conditions in the western outcrop area, on the Pecos Slope. Within the carbonate aquifer, groundwater is stored in highly porous and transmissive zones of secondary porosity represented by vuggy to cavernous limestones, intraformational solution collapse breccias, and solution enlarged fractures, developed primarily in the San Andres limestone and to a lesser extent in the overlying Grayburg and Queen Formations. Much of the secondary porosity formed by subsurface dissolution of evaporites within the San Andres Formation during late Permian time. Slightly to moderately permeable rocks of the Artesia Group, including the Seven Rivers Formation, serve as the upper confining unit for the artesian aquifer. Thickness of the confining unit varies from 0 to ~300 m, thickening downdip to the east. Confining beds are truncated by erosion to the west (Welder, 1983).

Recharge to the artesian aquifer occurs by direct infiltration from precipitation, and by runoff from intermittent losing streams that flow eastward across the Pecos Slope. Enhanced recharge occurs through sinkholes and solution-enlarged fractures associated with the Pecos Buckles, wrench fault zones that extend SW-NE for several tens of km across the Slope (Motts and Cushman, 1964; Kelley, 1971). Groundwater flows east and south, down gradient from the recharge area, then upward through leaky confining beds into the alluvial aquifer, and ultimately into the Pecos River (Figure 3.11). Estimates of the time required for groundwater to move from the recharge area to discharge sites in the Artesian Basin vary widely, with some estimates as low as 4 to 7 years, equating to a particle flow velocity of 20 m/day (Rabinowitz et al., 1977). This is a remarkably rapid flow rate for groundwater, even in a karstic aquifer. Recent measurements of environmental tracers in springs and sinkhole lakes at Bitter Lakes National Wildlife Refuge suggest a groundwater residence time of 20 to 50 years (Land, 2005).

Mineral content of groundwater in the artesian aquifer is highly variable, with chloride concentrations ranging from 15 ppm in the unconfined, western part of the aquifer to as high as 7000 ppm east of Roswell. Chloride content also increases with depth and displays seasonal variations, lowest in the winter and spring, and highest in the fall after the irrigation season is over. The largest annual fluctuations occur in the freshwater-saltwater transition zone between Roswell and the Pecos River (Welder, 1983).

The Roswell Artesian Basin is one of the most intensively farmed areas in New Mexico, deriving virtually all of its irrigation water from groundwater stored in the artesian and alluvial aquifers. Since the inception of irrigated agriculture in the Artesian Basin more than a century ago, most of the discharge from the artesian aquifer has been from wells, although some natural discharge still occurs by seepage through fractures and solution channels in the overlying confining beds (Welder, 1983). Groundwater from the artesian aquifer discharges into the many springs and sinkhole lakes that line the Pecos River, and is manifest in the development of extensive wetlands above and below Roswell. These wetlands are visible along the river immediately west of Bottomless Lakes, and to the north at Bitter Lakes National Wildlife Refuge.

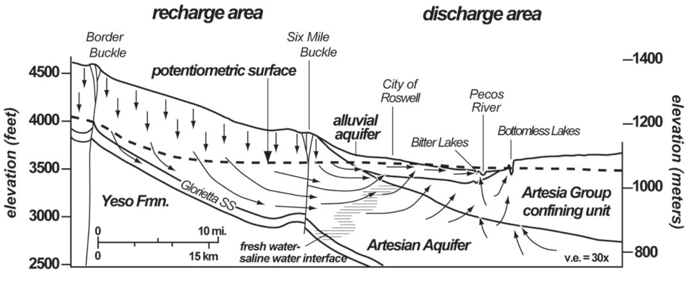

FIGURE 3.11. Schematic cross section of the artesian aquifer system in the vicinity of Bottomless Lakes State Park.

Eight cenotes lie within the park boundaries, formed for the most part within the Seven Rivers escarpment adjacent to an abandoned channel of the Pecos River, which now flows ~2 km west of the park. Lea Lake, the southernmost and largest of the cenotes within the park, formed through the coalescence of three smaller sinkholes, and has a maximum depth of 27 m. The gentle (~1°) eastward regional dip of the area is locally reversed along the escarpment, where strata of the Seven Rivers Formation dip abruptly southwest by as much as 40°. This local dip reversal, which is best viewed in the walls of Mirror Lake, is probably the result of subsurface dissolution of gypsum in the vicinity of the sinkholes and consequent slumping of overlying beds. Mirror Lake, which actually consists of two coalesced sinkholes separated by a barely submerged ridge, has a maximum depth of 15.2 m in the deeper southern lobe.

All of the lakes are fed by discharge from submerged springs issuing from the underlying artesian aquifer. Discharge from the springs has caused subsurface dissolution of evaporites within the Seven Rivers Formation, localized subsidence, and upward propagation of collapse chimneys, which ultimately formed the cenotes (Land, 2003). Spring sapping at the base of the Seven Rivers escarpment has also resulted in oversteepening of the eastern walls of the sinks, causing occasional rockslides and other mass-wasting events, an indication of the active role gypsum karst processes continue to play in shaping the eastern margin of the Pecos River Valley.

Water in all the lakes is brackish to saline with high sulfate concentrations, owing to passage of the discharging water through subsurface layers of gypsum and halite (Martinez et al., 1998). Water quality in the lakes is also affected by the original mineral content of groundwater in the artesian aquifer, which is saline in the vicinity of Bottomless Lakes. Total dissolved solids (TDS) in all the lakes has progressively increased since measurements began in 1927, possibly due to westward migration of the freshwater-saltwater interface in the artesian aquifer (Welder, 1983). Lea Lake, the largest and deepest of the sinkhole lakes, has a TDS content of ~9,500 ppm. Lazy Lagoon, which consists of three sinkholes formed in an abandoned channel of the Pecos, with maximum depth of ~25 m, has the highest TDS in the park, around 38,000 ppm, greater than the salinity of seawater. In spite of the brackish water quality within the lakes, some of the cenotes, including Cottonwood (TDS = 6,000 ppm; depth = 9.1 m) and Mirror Lake (TDS = 29,500 ppm), are stocked with fish.

In the early history of settlement in this area, most of the cenotes at Bottomless Lakes overflowed into wetlands along the eastern shore of the Pecos River, but the progressive decline in hydraulic head in the artesian aquifer (up to 70 m in some areas) caused lake levels to fall, so that now only Lea Lake overflows. In 1975, a catastrophic rockslide occurred on the steep eastern wall of Lea Lake, and the resulting lake surge caused significant damage to a pavilion on the opposite shore. No measurements of lake discharge are available prior to 1976 (probably because there was no discharge overflow before that date). However, the rockslide apparently opened new spring sources in the lake bed, as indicated by a significant increase in flow from the lake and the flooding of adjacent grazing lands with several million gallons per day of saline and alkaline water. A culvert was installed to convey the increased flow into wetlands west of the park, but the lake continued to flood an adjacent parking lot and camping area during the winter. In 2002, the park completed construction of a more efficient drainage canal to capture all of the discharge, resulting in a substantial increase in the measured flow volume from the lake. As discharge continued to increase, a second drain was installed in 2005. On January 14, 2006, the New Mexico Interstate Stream Commission measured a combined discharge of 576.2 liters/s (20.35 cfs) from both drains.

The increased flow from Lea Lake, amounting to roughly 18 million m^3/yr (~14,600 acre-ft/yr), has caused an expansion of wetlands to the west, which are now hydraulically connected to the Pecos River, and a net gain in streamflow downstream from the park, an interesting phenomenon in a semi-arid region that is currently experiencing an extended drought.

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