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Field trip: Evaporite karst of the lower Pecos Valley, New Mexico

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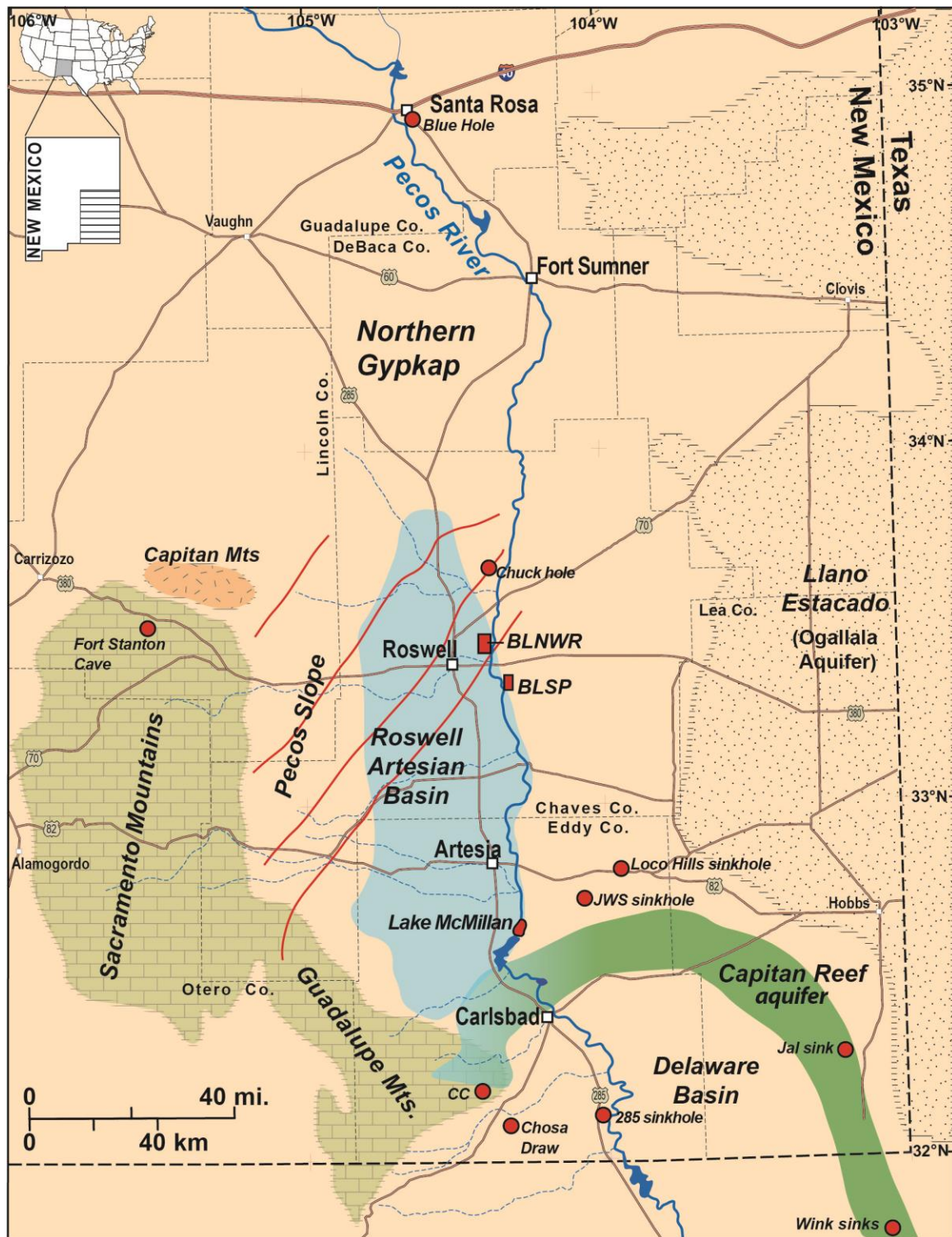
DEEP KARST 2016

FIELD TRIP: EVAPORITE KARST OF THE LOWER PECOS VALLEY, NEW MEXICO


Lewis Land
New Mexico Bureau of Geology and Mineral Resources
and
National Cave and Karst Research Institute



Pump jack in sinkhole that formed in aftermath of three days of heavy rain and flooding, Dagger Draw oil field, 2004.

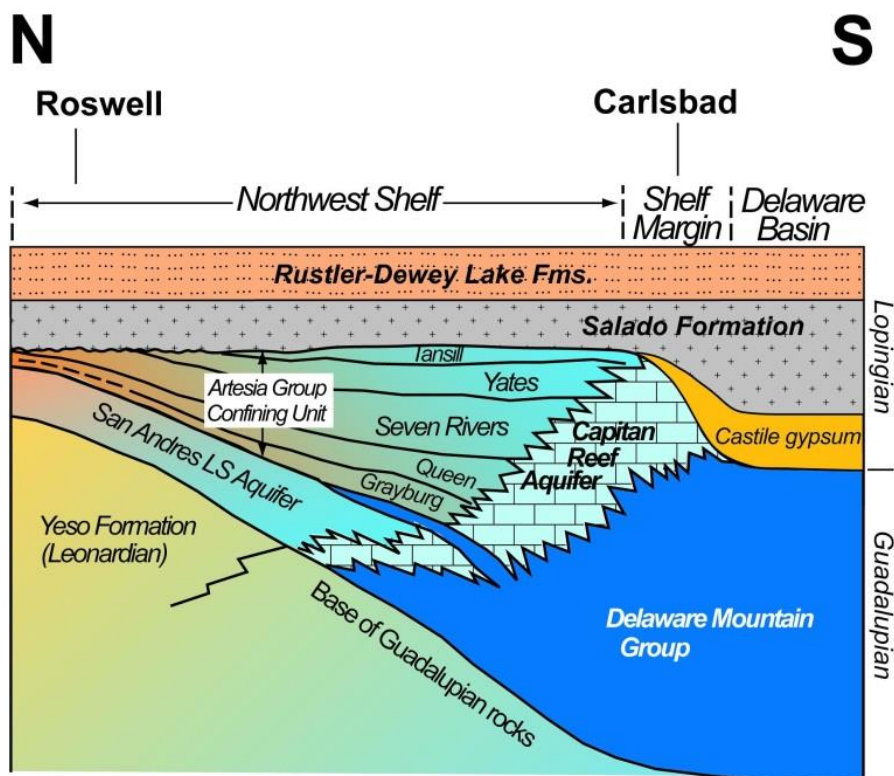


Hydrogeologic setting of lower Pecos Valley region, southeastern New Mexico. Red lines extending SW-NE across Pecos Slope are the Pecos Buckles, Laramide-age wrench faults. Red dots/rectangles/ovals are some of the more important sinkholes (several of which are of human origin) and karst features in southeastern New Mexico and west Texas. CC = Carlsbad Caverns. BLNWR = Bitter Lake National Wildlife Refuge. BLSP = Bottomless Lakes State Park.

Era	Period	Epoch	Northwest Shelf	Delaware Basin		
Cenozoic	Quaternary	Holocene	Pecos Valley alluvial fill			
		Pleistocene			Gatuna Formation	
	Tertiary	Neogene	Ogallala Formation			
		Paleogene			Sierra Blanca volcanics	
Mesozoic	Cretaceous					
	Jurassic					
	Triassic				Santa Rosa Fm./Dockum Grp.	
Paleozoic	Permian	Lopingian (Ochoan)	Rustler Fm.	Rustler Fm.		
			Salado Fm.	Salado Fm.		
				Castile Fm.		
		Guadalupian	Artesia Group	Tansill		Delaware Mountain Group
				Yates		
				Seven Rivers		
				Queen		
				Grayburg		
			San Andres Formation	Bone Spring Formation		
		Leonardian	Yeso \ Victorio Peak			
Wolfcampian	Abo Formation	Hueco Group				
Lower Paleozoic strata						

*lower portion of reef section includes the Goat Seep Reef.

Stratigraphy of the lower Pecos region, southeastern New Mexico.



Stratigraphic profile showing facies relationships of Permian strata in the lower Pecos valley.

Text is based in part on road logs in Land and Love (2006). Distances are given in miles for consistency with US odometers.

Vehicles assemble at NCKRI headquarters, 400-1 Cascades Ave. Proceed to intersection of Cascades Ave. and Park Dr. **Zero odometers and turn left** onto Park Dr.

0.3 miles: Potash mines locomotive on left; Lake Carlsbad, an impounded section of the Pecos River, on right. **Continue north through traffic circle** on Riverside Dr.

0.6 miles: **Bear left** and continue on Riverside Dr.

1.2 miles: Crossing Canal St.; bridge to right crosses Pecos River. **Continue straight** on Riverside Drive, one of the more prosperous neighborhoods in Carlsbad. Homes on the right side of the street have back yards facing the Pecos River.

2.4 miles: **Turn left** onto Landsun Drive.

2.6 miles: **Turn right** onto Westridge Road.

3.1 miles: Stop 1: Carlsbad Flume and Carlsbad Spring

Carlsbad flume is a large concrete aqueduct that crosses the Pecos and transports water of the Pecos River from Lakes Brantley and Avalon through the Carlsbad Irrigation District's South Canal (thus, according to Ripley's Believe It or Not, "the river that crosses itself") (**Figure 1**). This concrete structure was built in 1903 to replace the original wooden flume that was

destroyed by floods. Upstream from the flume, the Pecos is a losing stream and the streambed is usually dry except during the monsoon season, and when there are block releases from upstream reservoirs.



Figure 1: Carlsbad Flume during an upstream release of water from Brantley Reservoir.

The Pecos becomes a gaining stream immediately below the flume because of springs discharging into the river. Features to note include natural (undeveloped) spring pools and cemented Quaternary gravels that armor the stream bed.

Carlsbad spring, located ~200 m downstream of the flume is one of several springs that discharge into this reach of the Pecos River. Carlsbad spring used to discharge over 7,500 liters/min (~2000 gal/min), but its flow has been substantially reduced over the years due to pumping from the Capitan Reef aquifer, the principal source of drinking water for the City of Carlsbad. Additional discharge from the spring is derived from leakage from Lake Avalon and the Carlsbad Irrigation District's South Canal, and from irrigation return flow (Cox, 1967).

Return to vehicles and **continue west** on Westridge Rd, passing under flume.

3.2 miles: Stop sign. **Turn left** onto Callaway Dr.

3.4 miles: Traffic light. **Turn right** onto US 285.

3.8 miles: Turnoff to Living Desert State Park on left. **Continue straight** on US 285.

4.0 miles: 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-pisolite facies belt indicate deposition in the subtidal-intertidal environment of a backreef lagoon.

6.0 miles: WIPP bypass to right. The bypass was constructed to accommodate trucks carrying transuranic radioactive waste to the Waste Isolation Pilot Plant east of Carlsbad, where the radioactive material is sequestered in salt beds of the upper Permian Salado Formation. **Continue straight** on US 285.

8.7 miles: NM 524/Happy Valley bypass to left. **Continue straight.**

8.9 miles: **Turn left** onto CR 407/Douglas Fir Rd. Proceed on graded gravel road for ~0.3 miles and park on two-track, left side of road.

Stop 2: Motts karst subsidence basin

Walk up two-track across poorly exposed Yates gypsum to rim of basin. This circular depression, ~1km in diameter, was interpreted by Motts (1962) as a young solution-collapse feature (**Figure 2**). Tansill dolomites on the flanks dip steeply (45 - 60°) toward the center of this crater-like structure, which is floored by dolomite and gypsum of the Tansill Formation. Note small scale folds – mostly synclines – developed along the basin margin.

A secondary arcuate outcrop of Tansill dolomite is exposed in the interior of the structure. Such non-tectonic folds caused by subsurface evaporite 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).

Figure 2: Rotated beds on north flank of Motts subsidence basin.



Return to US 285 intersection. **Zero odometers and turn left.** Continue west on US 285.

0.7 miles: 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 and 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.

Roadcuts over the next few miles 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.

3.1 miles: Crossing Rocky Arroyo, a usually dry tributary of the Pecos River. The ridge on the horizon is the Seven Rivers Hills, a southeast dipping cuesta of the Seven Rivers Formation.

3.8 miles: **Turn left** onto NM 137/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.

8.6 miles: Rocky Arroyo to left. Over the next mile roadcuts to right expose backreef units of the Seven Rivers dolomite. Tufa deposits are abundant along the banks of Rocky Arroyo. The tufa deposits visible here and sporadically for the next few miles are Pleistocene spring deposits formed during a pluvial climate interval. Tubular structures in the tufa were formed by green algae.

8.9 miles: Roadcut exposures to right of "crinkle beds" in Seven Rivers dolomite (**Figure 3**). 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 left (south side of road). Indian grinding holes are present in the bedrock stream bed.



Figure 3:
Stromatolites in Seven
Rivers roadcut.

9.9 miles: Seven
Rivers dolomites
exposed in cliffs to
left.

10.1 miles: Note
shelter caves formed in
late Quaternary tufa
deposits in banks to
right.

10.2 miles: Cross Rocky Arroyo and bear right.

11.3 miles: This portion of the route begins a traverse through the famous transition from near-backreef dolomites to far-backreef evaporites and mudstones 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 west. Exposed in roadcuts to the left, massive beds of dolomite grade laterally into 60 m of Seven Rivers gypsum with red siltstone stringers. This transition from carbonate to evaporite facies also occurs within the Grayburg, Queen, Yates, and Tansill Formations.

12.8 miles: Seven Rivers gypsum and mudstone in bluffs to right. Junction with CR 401/Marathon Road to Indian Basin oil and gas field. **Bear left** to stay on NM 137.

14.2 miles: The famous Teepee structure to right is a conical hill of Seven Rivers Formation redbeds and gypsum capped by more resistant dolomites of the Azotea Tongue of the Seven Rivers Formation (**Figure 4**). 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.



Figure 4: The Teepee, a conical outlier of Seven Rivers redbeds and gypsum capped by Seven Rivers dolomite.

14.9 miles: Stop 3: Indian Basin overlook

Indian Basin oil and gas field (**Figure 5**), discovered in 1963, 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 Penn dolomites, which appear to have

been hydrothermally altered, are the main producing zone and have an average porosity of 6%. Cumulative production in Indian Basin is 2.7 TCF of gas and 100 million barrels of oil (Craig Corbett, 2006, written communication). The trapping mechanism in this gas field is composite: Structural, stratigraphic and hydrodynamic in nature. Regional dip of the Pennsylvanian carbonates is $\sim 2.5^\circ$ 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).

Figure 5: Pump jacks in Indian Basin field.



Return to US 285 intersection by same route. **Zero odometers and turn left.** Continue north on US 285.

3.0 miles: Turnoff to Brantley Lake boat launch to right.

Continue straight on US 285.

3.6 miles: Crossing 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.

4.5 miles: Turn left onto graded gravel road.

4.8 miles: Bear left at fork in road.

5.3 miles: Stop 4: Seven Rivers Hills gypsum caves and sinkholes

Park on right shoulder and prepare to hike ~300 m to caves and sinks.

Stop 4 is located at the base of the Seven Rivers Hills, which is generally regarded as the southern border of the Roswell Artesian Basin. The artesian aquifer in the Roswell Basin is formed in karstic limestones of the Permian San Andres and Grayburg Formations. These units crop out to the west on the Pecos Slope, where leakage from losing streams recharges the aquifer. The aquifer becomes artesian where the San Andres and Grayburg dip beneath evaporites of the overlying Seven Rivers Formation (**Figure 6**). In the early 1900s, when groundwater resources were first being developed in the area, many wells flowed to the surface, with hydraulic heads in some cases several tens of meters above ground level (Stafford et al., 2008). Evidence for artesian flow is also indicated by the presence of paleosprings and tufa deposits in the area. The presence of extensive caves and sinkholes formed in gypsum bedrock at this location invites speculation about their hypogene origin because of upward artesian flow of groundwater from the underlying artesian aquifer system.

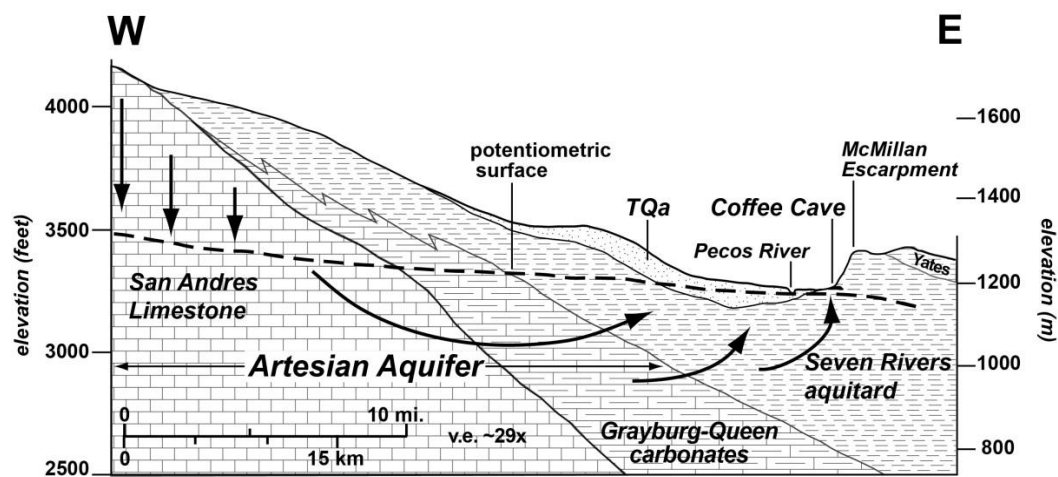


Figure 6: West-east hydrostratigraphic profile near Seven Rivers Hills (from Stafford et al., 2008).

About 1 km to the north 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 are pumped at rates greater than 3.8 m³/minute (>1000 gpm), and 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.

Return to US 285 intersection by same route. **Zero odometers and turn left.** Continue north on US 285.

The route for the next several miles crosses 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 ancestral Pecos River form a shallow water-table aquifer in the Roswell Artesian Basin.

1.4miles: Crossing South Seven Rivers Arroyo. Pecan orchard to right. Pecans are an important cash crop in the largely agricultural economy of the Artesian Basin.

2.5 miles: Gravels capped with soil in roadcuts are Seven Rivers terrace deposits.

5.1 miles: MP 55. Junction with CR 31 to Lakewood to right. Residents of Lakewood were evacuated due to flooding during extreme monsoonal rains in fall, 2013. Several sinkholes formed in the aftermath of the flooding, one damaging a small structure in the Lakewood RV park. **Continue straight.**

5.9 miles: Crossing North Seven Rivers Arroyo. Route continues north on broad, east-sloping plain.

7.7 miles: Partially-cemented Quaternary gravel terrace deposits in roadcut to right.

8.1 miles: MP 58. Crossing Fourmile Draw.

9.9 miles: For the next several miles the route crosses a relatively nondescript terrain composed of pediment gravels, caliche soil and alluvial deposits of the ancestral Pecos River. The principal features to notice are the dense concentration of pump jacks and other oil and gas infrastructure on both sides of the highway. The first oil discovery in southeastern New Mexico was made in this area in 1924. The field trip route passes through a portion of the giant Empire Abo Field, which produces oil and gas from Permian strata of the Abo reef complex, Yates and Grayburg Formations of the Artesia Group, the San Andres limestone, Wolfcamp carbonates, as well as upper Pennsylvanian carbonates and lower Pennsylvanian clastic reservoirs in the Morrow and Atoka Formations. These multiple pay zones overlie the Artesia-Vacuum Arch, an east-west trending structural nose that extends to the east for ~120 km into Lea Co., New Mexico (Kelley, 1971a). The Arch is almost completely covered by post-Permian beds; its principal surface manifestation is the high concentration of oil wells. Since 1960 >200 million barrels of oil have been produced from the Empire Abo field (Christiansen, 1989).

12.7 miles: 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.

13.7 miles: 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.

15.3 miles: Atoka Grocery on left. The village of Atoka grew along the ATSF railroad and is host to the Eddy County Arena. Note pecan orchards along both sides of the road.

17.3 miles: MP 67. Historic marker, showing the route of Castaño de Sosa's 1590-91 expedition up the Pecos River.

17.5 miles: Halliburton service company yard to right.

18.0 miles: Entering southern Artesia. The town acquired its name in 1903 because of the abundant resources of artesian groundwater that were discovered in the area around the turn of the 20th century, making the region an agricultural oasis. Principal crops include alfalfa, sorghum, chiles, and pecans. In recent years dairy farming has become increasingly important to the agricultural economy of the lower Pecos valley.

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

19.6 miles: Main Street Artesia, and junction with Highway 82. **Continue straight** and proceed north through town. Navajo Refinery to right. In addition to irrigated agriculture, Artesia is also a local center for oil and gas activity. Yates Petroleum corporate headquarters is located 3 blocks to the west. The Wellhead Brewpub, owned by one of the Yates family and one of only two brewpubs in the lower Pecos valley, is across the street from Yates' offices.

19.9 miles: Crossing Eagle Draw, an east-flowing tributary of the Pecos River.

22.1 miles: Artesia adult video store to left. **Bear right** onto Highway 2 and continue north.

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

27.6 miles: Bridge over Cottonwood Creek. This drainage is controlled by large levees on both sides of the channel for several km.

28.3 miles: 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 (Land and Newton, 2008).

29.5 miles: Crossing Walnut Creek.

30.6 miles: 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.

31.6 miles: Lake Arthur cemetery to left. Sierra Blanca, composed of igneous intrusives and volcanics, on western horizon at 9:00. Capitan Mountains batholith at 10:00.

35.1 miles: El Gomez bar on left.

38.9 miles: 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 (**Figure 7**).



Figure 7: Artesian well discharging into Hagerman Canal.

Pumping from the shallow aquifer has resulted in a significant cone of depression in agricultural areas west of town.

40.5 miles: Historic bridge to right over the Rio Felix, another of the now dry tributaries of the Pecos River.

40.8 miles: Red bluffs east of Pecos River at 2:30 are formed in Seven Rivers redbeds and gypsum.

45.2 miles: Entering village of Dexter, home of the Dexter Demons. As the Pecos Slope descends to the east toward the river, the potentiometric surface approaches 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.

45.8 miles: **Turn right** and cross railroad tracks onto First St./Shawnee Road East (NM 190).

46.6 miles: 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.

47.1 miles: Dexter Fish Hatchery entrance to right. The Dexter National Fish Hatchery and Technology Center was established in 1931 to meet the demand for warm water game fish; its main focus was to supply local waterways with sport fish via rearing at the Center. After the Endangered Species Act was established in 1973 the hatchery mission was transformed from a facility that raised fish for recreational purposes to a facility that would house and protect endangered fish species. The Center is the only federal facility in the nation dedicated to holding, culturing and studying fishes facing extinction.

47.3 miles: 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 mg/l.

47.9 miles: Sharp bend to left onto Wichita Road.

48.2 miles: Zuber Lake Farm and artesian well to right. Rock-walled mound in front of house is an intermittently-flowing spring.

48.7 miles: Crossing Pecos River. Note banks 3 – 4 m high with natural levee sloping to the east. The banks are lined with Catclaw and Salt Cedar (Tamarisk), an invasive species. Water in this reach of the Pecos River is quite brackish, with TDS >2,000 mg/l. Lakes along the river are a combination of oxbows and sinkholes.

49.0 miles: **Sharp left turn** to north.

50.4 miles: Bear right, staying on paved road, and begin ascending Seven Rivers escarpment. For the next five miles the route crosses extensive exposures of Seven Rivers gypsum and mudstone.

51.9 miles: Sacramento Mountains on western horizon; Sierra Blanca on skyline at 8:30. Capitan Mountains batholith 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.

56.4 miles: 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.

56.8 miles: Stop sign. **Turn left** toward Bottomless Lakes State Park.

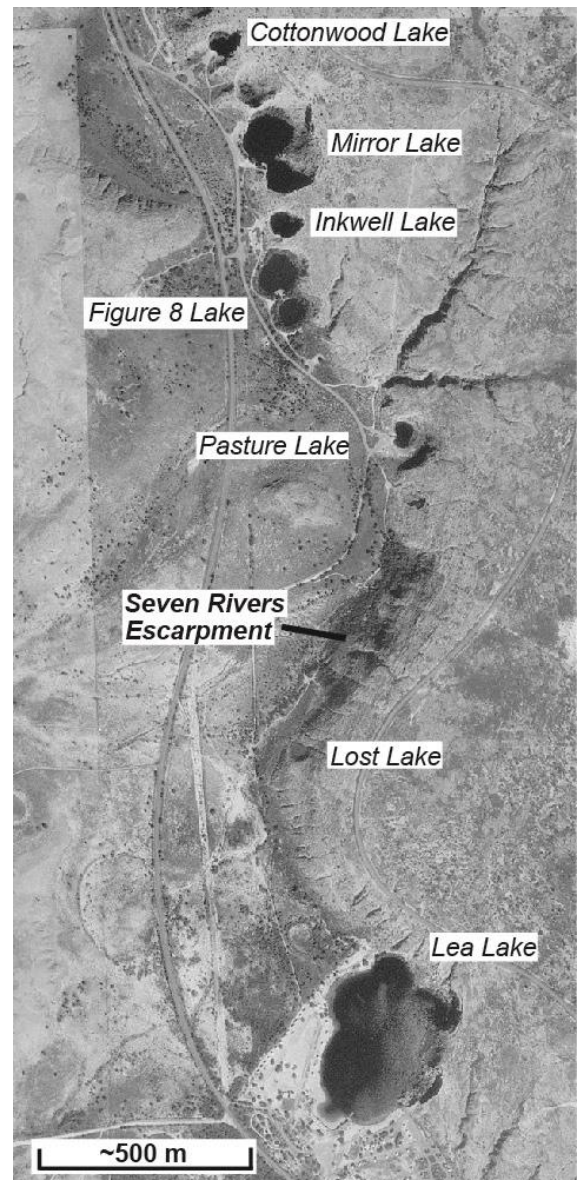
57.0 miles: Cross Lea Lake overflow canal; **turn right** into Lea Lake parking lot.

57.1 miles: Stop 5: Lea Lake sinkhole, Bottomless Lakes State Park. Vans park in parking lot. Field trip participants assemble by lake shore.

Figure 8: Digital orthophoto image of Bottomless Lakes State Park, showing flooded cenotes. All 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.

Lea Lake sinkhole is the only lake in Bottomless Lakes State Park where swimming is permitted. Because of the clarity of the water, the lake is popular with local scuba divers. Bottomless Lakes is New Mexico's first state park, established in 1933. The sinkhole lakes are formed in gypsum and mudstone of the 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 (**Figure 8**).

The Bottomless Lakes sinkholes 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 (Caran, 1988). The cenotes of the lower Pecos Valley are unusual in that they occur in a semi-arid setting, where annual evaporation rates may exceed mean annual precipitation by a factor of 7 or more. 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).

These sinkholes, and the many others that occur in the lower Pecos valley, 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 (**Figure 9**) (Martinez et al., 1998; Land and Newton, 2008). The lakes are fed by submerged springs discharging from the artesian aquifer, and thus represent the down gradient end of the regional hydrologic system in the Artesian Basin. Discharge from the springs has caused subsurface dissolution of evaporites

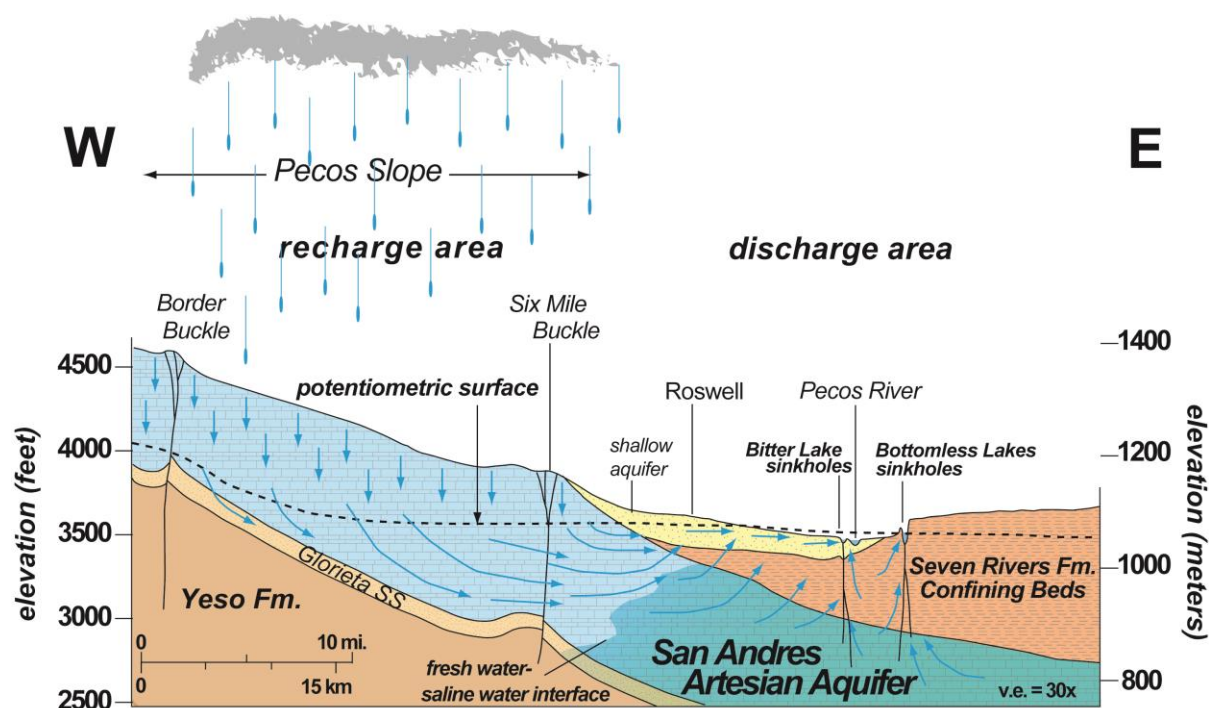


Figure 9: West-east hydrostratigraphic section of the artesian aquifer system in the vicinity of Bottomless Lakes State Park. Recharge occurs by direct infiltration from precipitation, and by runoff from intermittent losing streams that flow eastward across the Pecos Slope west of Roswell. Groundwater 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.

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 fundamental role that gypsum karst processes have played in shaping the morphology of the lower Pecos Valley.

The gentle ($\sim 1^\circ$) 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, 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 (Quinlan¹, unpublished report, 1967).

Bottomless Lakes occurs on the saline side of the fresh water/saline water transition in the Roswell Artesian Basin (**Figure 9**), thus water in all the lakes is brackish, with Total Dissolved Solids (TDS) content ranging from ~ 6000 to $38,000$ mg/l. In spite of the high mineral content, some of the lakes are periodically stocked with fish.

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 substantial natural discharge still occurs 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 Lake National Wildlife Refuge (Land and Newton, 2008).

Figure 10: Rockslide in Seven Rivers Escarpment, eastern margin of Lea Lake cenote.



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 (**Figure 10**), 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 appears to have been associated with an increase in spring discharge and the opening of new spring outlets in the lake bed, as indicated by a significant post-rockslide 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

¹ The late James F. Quinlan very precisely summarized the geology and hydrology of Bottomless Lakes State Park in the text and graphics of an unpublished Christmas card he circulated among friends in 1967.

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 m³/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 until recently was experiencing an extended drought.

Field trip participants return to vehicles and proceed to Stop 6. **Zero odometer** at visitor pay station, exit parking lot and **turn left** onto loop road.

0.4 miles: Begin ascent of Seven Rivers Escarpment. Dimmit Lake to right.

1.0 miles: **Turn left** into scenic overlook parking lot.

Stop 6: Lea Lake scenic overlook.

We are standing on the Seven Rivers Escarpment, in a geologic setting very similar to that at the Seven Rivers Hills farther south. Large fissures are visible 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 the Seven Rivers Hills is the presence of active discharge of artesian groundwater at the base of the Seven Rivers Escarpment, enhancing mass wasting processes. At least half a dozen springs discharge from the lakebed in ~8 m water depth at the base of the escarpment, suggesting that spring sapping may have played a role in initiating the 1975 rockslide.

Field trip participants return to vehicles and proceed to Stop 6. **Exit parking lot and turn left** onto loop road.

3.7 miles: Lazy Lagoon at base of escarpment to left. During winter months, when water levels are high due to low levels of irrigation from the Artesian Aquifer, Lazy Lagoon 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. The Lazy Lagoon sinkholes contain the most saline water in the park, with TDS exceeding 37,000 mg/l, greater than the salinity of seawater.

3.9 miles: **Bear left**, and begin descent of Seven Rivers Escarpment. Over the next mile the route passes large gypsum slump blocks detached from the escarpment.

5.0 miles: Lazy Lagoon sinkholes to right.

5.9 miles: Dry sinkholes in escarpment to left.

6.2 miles: Turn left into Bottomless Lakes visitors center parking lot.

Stop 7: Cottonwood Lake cenote, Mirror Lake, and Bottomless Lakes visitors center.

Cottonwood Lake is a small cenote containing water that in the past has been fresh enough to support fish, although too brackish for them to reproduce. Note rockslide on the far wall of the sink. The visitors center contains excellent exhibits, including air photo images and a 3-D model of all the sinkholes in the park.



Figure 11: Mirror Lake, view to south. Note rotated beds exposed in southern margin of cenote.

A trail along the escarpment continues south for ~300 m, crossing a dry sinkhole and terminating at Mirror Lake, a compound lake consisting of two cenotes that have grown together (**Figure 11**). A climb to the top of the escarpment reveals large gypsum fissures and small tectonic caves formed in the upper margin of the sinkholes. 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 the result of subsurface dissolution of gypsum along the escarpment.

Field trip participants return to vehicles. **Zero odometer**, exit visitors center parking lot, and **turn left** onto loop road.

2.0 miles: Pass Lea Lake entrance and **turn right** onto Wichita Road, following same route back to Carlsbad.

10.8 miles: **Turn right** onto Shawnee Road.

13.0 miles: In Dexter, **turn left** onto Highway 2 and continue south toward Hagerman.

36.4 miles: **Turn left** onto Highway 285, drive straight through Artesia.

58.9 miles: Begin crossing Seven Rivers Hills; Brantley Reservoir to left.

72.0 miles: Entering city of Carlsbad; Tracy Dome/C-Hill to right. US-285 becomes W. Pierce St.

74.6 miles: **Bear right** onto South Canal St.

75.1 miles: **Turn left** onto Church St.

75.6 miles: **Turn right** onto Park Dr. and return to NCKRI headquarters.

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