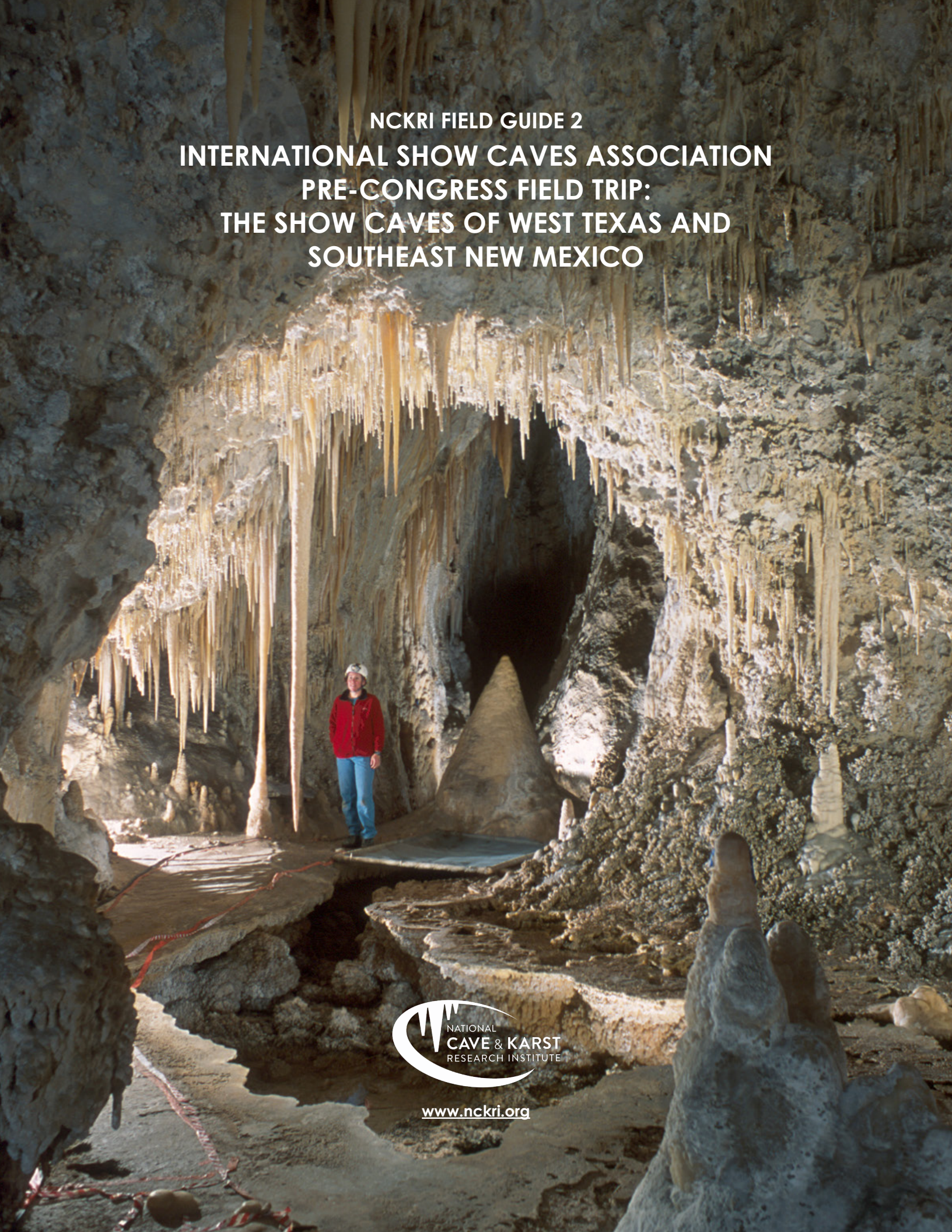

NCKRI FIELD GUIDE 2

INTERNATIONAL SHOW CAVES ASSOCIATION PRE-CONGRESS FIELD TRIP: THE SHOW CAVES OF WEST TEXAS AND SOUTHEAST NEW MEXICO

NATIONAL CAVE & KARST RESEARCH INSTITUTE

www.nckri.org

National Cave and Karst Research Institute
Field Guide 2

International Show Caves Association Pre-Congress Field Trip: The Show Caves of West Texas and Southwest New Mexico

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(all text and graphics by the author except where noted)

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Front cover photo: This is a seldom seen view of the bottom of National Geographic Pit in Carlsbad Cavern, New Mexico. Most people see the top of the pit while touring the Big Room. Jim White's mesquite and wire ladder hangs in the pit and is seen easily from the trail. Members of Dr. Willis T. Lee's 1923 National Geographic Expedition used that ladder to enter Lower Cave. White called this pit the "Hole in the Floor." It was renamed the "National Geographic Pit" after the expedition. National Park Service photo by Peter Jones.

Back cover photo: The Translucent Column is one of many beautiful features in the Palace of the Angels of Caverns of Sonora, Texas. It is also called the Wedding Room for the many people who were married amid its splendors.

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NCKRI Organization and Mission

NCKRI was created by the US Congress in 1998 in partnership with the State of New Mexico and the City of Carlsbad. NCKRI is administered by the New Mexico Institute of Mining and Technology (aka New Mexico Tech or NMT).

NCKRI's enabling legislation, the National Cave and Karst Research Institute Act of 1998, 16 USC, §4310, identifies NCKRI's mission as to:

1) further the science of speleology;
2) centralize and standardize speleological information;
3) foster interdisciplinary cooperation in cave and karst research programs;
4) promote public education;
5) promote national and international cooperation in protecting the environment for the benefit of cave and karst landforms; and
6) promote and develop environmentally sound and sustainable resource management practices.

NCKRI Field Guide Series

NCKRI uses this report series to publish informative guides to caves and karst areas, often in association with conferences. The reports are produced on a schedule whose frequency is determined by the timing of the conferences or other factors. This series is not limited to any topic or field of research, except that they involve caves and/or karst. Anyone using these guides is responsible for obtaining legal access to the properties described. Some properties, especially privately owned, are only accessible to conference field trips and for research under special conditions and are not open to the general public. All reports in this series are open access and may be used with citation. To minimize environmental impact, few or no copies are printed. They may be downloaded at no cost from the NCKRI website at www.nckri.org.

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International Show Caves Association Pre-Congress Field Trip: The Show Caves of West Texas and Southeast New Mexico

George Veni
National Cave and Karst Research Institute, Carlsbad, New Mexico, USA

Introduction

Trip Focus and Summary

This 3-day trip heads west from San Antonio, Texas, and showcases two of America's most renowned show caves. Nearly mid-day on Day 1, and halfway across the Edwards Plateau, one of the country's largest karst areas, we will stop at Caverns of Sonora. Many consider it among the most beautiful show caves on Earth. At the end of the day, we will cross into southeast New Mexico and spend the second day in Carlsbad Caverns National Park. This staggeringly impressive World Heritage Site contains many of the largest passages, rooms, and speleothems accessible in any show cave. We will be treated to two banquets at our hotel in the City of Carlsbad. Both banquets will include guest speakers who will make special presentations. The final day of the trip will start with a visit to the headquarters of the US National Cave and Karst Research Institute (NCKRI), and a return to Texas for lunch at Comanche Springs, once the largest karst springs in west Texas, before reaching San Antonio that evening.

In addition to enjoying these spectacular caves and interesting sites, the goal of this trip is to present different approaches to show cave management, public education on caves and karst, and the use of associated karst sites that can enhance show cave operations and education. This trip is organized as an event of the 2021-2022 International Year of Caves and Karst, which was established by the International Union of Speleology to reach and teach the world about the global value of cave and karst resources. The International Year is organized with over 260 partners from more than 50 countries, including the International Show Caves Association, the US National Caves Association, the US National Park Service, and NCKRI.

While this trip focuses on show caves in west Texas and southeast New Mexico, not counting parks and properties with occasional trips into caves with little or no infrastructure for the general public, the show caves of these two states are:

New Mexico:

1. Carlsbad Caverns National Park
2. Ice Cave and Bandera Volcano

Texas:

1. Cascade Caverns
2. Cave Without a Name
3. Caverns of Sonora
4. Inner Space Caverns
5. Longhorn Caverns
6. Natural Bridge Caverns
7. Wonder Cave

Sponsors

Many thanks are given to the management of Carlsbad Caverns National Park, the owners of Caverns of Sonora, and the City of Fort Stockton (owner of Comanche Springs) for entry, tours, and support, and to the owners of Natural Bridge Caverns for coordinating many of the logistics for this trip. The National Cave and Karst Research Institute is happy to organize this trip and provide this guidebook.

Logistics

Depending on the number of registrants, the group will travel in one or two 50-passenger coach buses, equipped with restrooms. Lunch will be provided each day. Breakfast on your own is included with your lodging at the Stevens Inn, our hotel in Carlsbad. Our two banquet dinners will be served at this hotel. No caving equipment is needed for any of the field sites. A camera, flash, comfortable hiking shoes, and hat for the sun are suggested. Water will be provided. Details are subject to change. Rain is not expected but could require a change in one destination.

The digital version of this field guide on the NCKRI website includes hyperlinks to the locations, organizations, and other items of interest.

NCKRI uses the International System of Units (the metric system) in its research and reports. However, in this field guide, road log distances are given in miles since those are the units used on highway distance markers.

Schedule

Day 1: 22 September 2022

8:00 a.m. – 11:30 a.m.: Meet in front of the Westin Hotel, board the bus parked in the street, and ride to Caverns of Sonora.

11:30 a.m. – 3:30 p.m.: Lunch and tour of Caverns of Sonora. Tour sizes are limited to 12 people to protect the cave, so tour times will be staggered with some leaving for their tour upon arrival, and then having lunch, and others eating before their tour.

3:30 p.m. – 7:30 (Central Time)/6:30 (Mountain Time) p.m.: Ride to and arrive in Carlsbad and the Stevens Inn.

[*The following times are in Mountain Time*.]

7:30 p.m. – 10:00 p.m.: Dinner at the Stevens Inn with a banquet presentation on Carlsbad Caverns National Park by Rod Horrocks, Chief of Cultural and Natural Resources.

Day 2: 23 September 2022

7:00 a.m. – 7:45 a.m.: Buffet breakfast on your own at the Stevens Inn. The restaurant opens at 6 a.m. and you are welcome to go early.

7:45 a.m. – 8:30 a.m.: Meet at the entrance to the hotel, be on the bus no later than 8 a.m., and ride to Carlsbad Caverns National Park.

9:00 a.m. – 11:30 a.m.: Expert guides will lead you in small tour groups through Carlsbad Cavern from the natural entrance to the Lunch Room. We will make arrangements at this time for anyone who may not wish or be able to walk in through the natural entrance.

11:30 a.m. – 1:00 p.m.: Take the elevator up to the Visitor Center for lunch, and then take the elevator back down into the cave with your guide.

1:00 p.m. – 4:00 p.m.: Tour the Big Room of Carlsbad Cavern with your guide. Return to the surface by the elevator.

4:00 p.m. – 4:45 p.m.: Visit the Bookstore and Gift Shop.

4:45 p.m. – 5:15 p.m.: Drive to Rattlesnake Spring.

5:15 p.m. – 6:00 p.m.: Visit Rattlesnake Spring.

6:00 p.m. – 6:30 p.m.: Return to the Stevens Inn.

7:00 p.m. – 10:00 p.m.: Dinner at the Stevens Inn with a banquet presentation on show caves in China by Erin Lynch, Carlsbad Caverns National Park Cave Specialist (former cave technician at China's Institute of Karst Geology).

Day 3: 24 September 2022

6:30 a.m. – 7:30 a.m.: Buffet breakfast at the Stevens Inn.

7:30 a.m. – 8:00 a.m.: Meet at the hotel entrance with all your luggage. Be on the bus no later than 8 a.m., and ride 5 minutes to the National Cave and Karst Research Institute.

8:05 a.m. – 9:00 a.m.: Tour the National Cave and Karst Research Institute.

9:00 a.m. – 11:30 a.m. (Mountain Time)/12:30 p.m. (Central Time): Depart for Fort Stockton and Comanche Springs.

[*The following times are in Central Time*.]

12:30 p.m. – 1:00 p.m.: Tour of Comanche Springs.

1:00 p.m. – 2:00 p.m.: Lunch in Rooney Park next to Comanche Springs.

2:00 p.m. – 5:00 p.m.: Drive to Junction.

5:00 p.m. – 5:30 p.m.: Restroom, snack, and leg-stretching stop at the Pilot truck stop.

5:30 p.m. – 7:15 p.m.: Drive to San Antonio and end the trip back at the Westin Hotel.

Day 1 Road Log for Figure 1 (next page)

Total miles	Miles since last landmark	Route Directions and Landmarks
0.0	0.0	Leave the Westin Hotel. Go immediately into the left (north) lane and turn left (north) on Navarro Street (first street).
0.1	0.1	Turn left (west) on Commerce Street (first street).
0.6	0.5	Turn left (south) on South Santa Rosa Avenue.
0.8	0.2	Turn right (west) on César Chavez Boulevard.
0.9	0.1	Turn right (north) on Interstate Highway 10. Stay in the right lane.
1.9	1.0	Interstate Highway 10 splits into upper and lower levels. Stay in the same lane and exit to the lower level.
8.8	6.9	Pass Loop 410
13.9	5.1	Pass Dezavala Road and drive over the Edwards Aquifer Recharge Zone for the next 2 miles. While the topography starts fairly flat, we're in the Balcones Fault Zone. The exposure of the Edwards Limestone in the fault zone is where water enters and fills (recharges) the Edwards Aquifer (Figure 2). This karst aquifer is the primary water supply for the San Antonio region. Notice the extensive urbanization over the recharge zone which reduces the amount of water that can enter the aquifer and reduces the cleanliness of the water. The elevation of the land rises gently as we cross the fault zone and continues to rise gradually all the way to Carlsbad. The trip starts at an elevation of about 200 m and ends at 1,100 m.
15.8	1.9	Cross Loop 1604 and leave San Antonio.
29.3	13.5	Pass the exit to Cascade Caverns, one of the oldest show caves in Texas, in continuous operation since 1932. The cave is a single passage to a room with a waterfall.
31.9	2.6	Pass the town of Boerne (pronounced "burn-ee"). Founded in 1849 as "Tusculum" by Germans of the Free Thinkers movement, it was renamed three years later in honor of German author and political satirist Karl Ludwig Börne. Boerne also leads to Cave Without A Name, the 8th longest cave in Texas at 5.7 km. It will be visited during the post-congress field trip.
39.1	7.2	Pass the exit for the community of Welfare, which began in 1848 with a general store. The town grew to 275 individuals in 1892 and has since declined to its current population of 36.
49.4	10.3	Pass the town of Comfort, which like many towns in this area known as the Texas Hill Country, was founded by German immigrants, in this case in 1854. It is home to the only remaining "hygieostatic" (loosely, a health station) bat roost. Built in 1918 to reduce mosquito populations, the roost is a shingled tower in a steep pyramid-shape. It stands 9 m tall and was designated a Texas State Landmark in the 1980s and included on the National Register of Historic Places.
63.8	14.4	Pass the City of Kerrville, site of the 15th International Congress of Speleology in 2009 at Schreiner University. Kerr County and Kerrville were founded and named in 1856 after Republic of Texas soldier and pioneer James Kerr. The area became an important cattle-raising and shipping point in the 1870s and has since diversified to become a regional economic center.
83.6	19.8	Pass the community of Mountain Home, population of 96. The area was settled in 1856. It is best known as a gateway to the Y.O. Ranch, a 202-km^2 ranch housing a variety of exotic animals. This family-owned ranch started in 1880 as a program to import exotic species from Africa. These animals thrive in this area because of its similar environment to parts of Africa.

Figure 2. *Streams that flow onto the Edwards Aquifer Recharge Zone rapidly lose their water underground into the aquifer. Much of the recharge occurs through caves and other karst features, as well as faults and other fractures (seen here as lines crossing the stream in the foreground).*

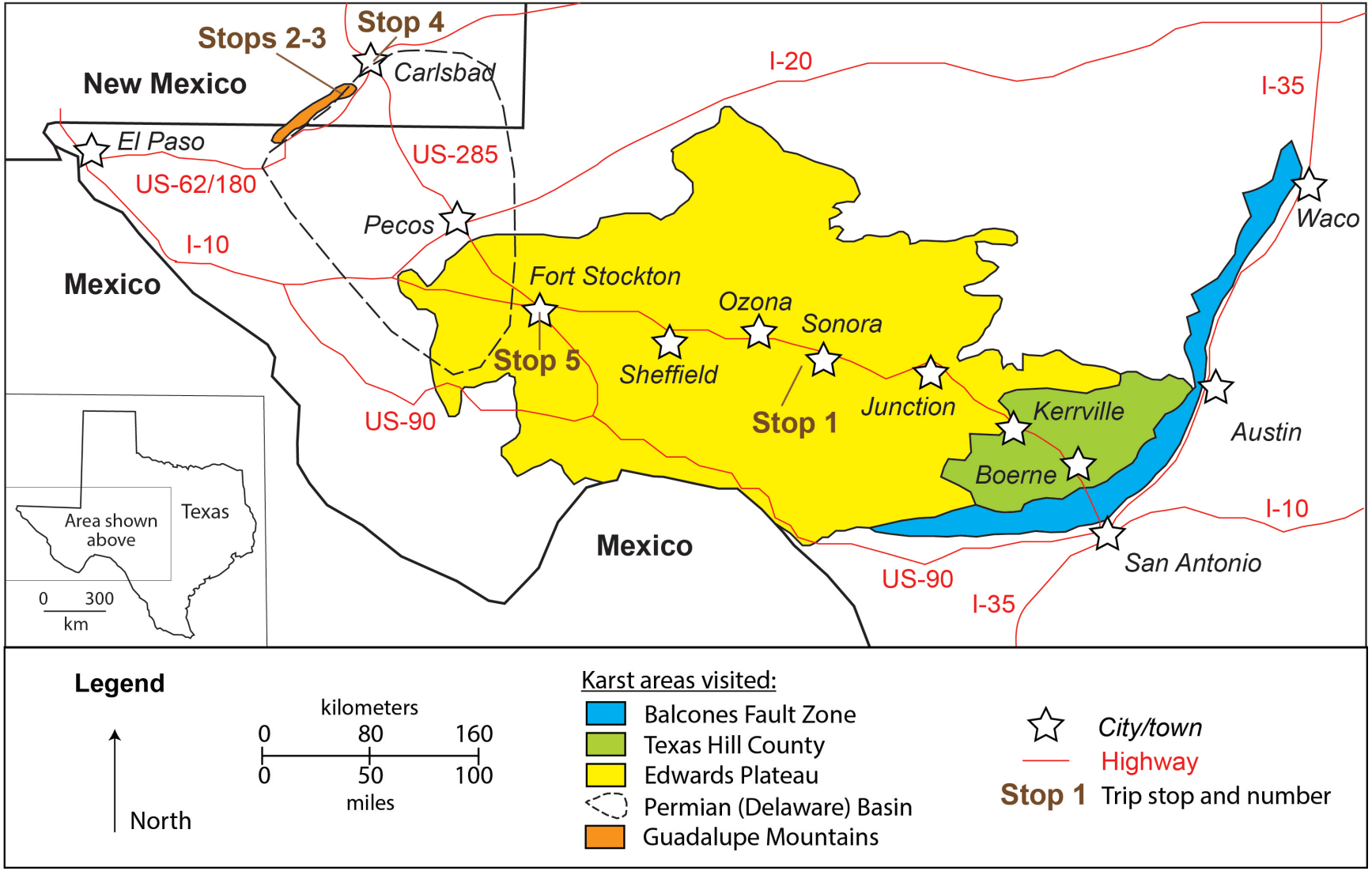

Figure 1. *Generalized highway map of field trip route, stops, and karst regions that will be seen along the way from San Antonio, Texas, to Carlsbad, New Mexico.*

Total miles	Miles since last landmark	Route Directions and Landmarks
106.5	22.9	Pass the community of Segovia, which was founded in the 1860s and named after the city in Spain. Despite ambitions, it never grew much. With a population of about 25, it is currently only a stop for supplies along the highway. Geologically, it is more notable as the name source for the Segovia Member of the Edwards Limestone, which is most of the rock we'll see for the next 120 miles and which contains many important Texas caves. Starting 2 miles after (northwest) the town you will see the first of 3 miles of road cuts where the rock is folded and brecciated (broken into small pieces). This results from the dissolution of the underlying Kirschberg section of the rock, which is more soluble gypsum, followed by collapse of overlying limestone. After the Kirschberg area, the Hensel Sand is exposed sporadically in road cuts to and a little past the town of Junction.
115.6	9.1	Pass the exit to the City of Junction, which has a population of about 2,600. We will stop here in two days as we return to San Antonio. Founded in 1876, Junction was originally named "Denman" after Marcellus Denman who surveyed and platted the new community. The name was quickly changed to "Junction City," and later simplified to "Junction," for its location at the confluence of the North and South Llano rivers which form the Llano River. We cross over the river 1.5 miles east of the highway exit, and the rivers join about 600 m left (south) of the highway. Junction is the seat for Kimble County and the commercial focus of the area's ranching industry.
119.3	3.7	Cross Bear Creek. To the left (south) near the junction of the creek with the North Llano River is what is described in the Texas Historical Landmark database as the "*Campsite of Marques de Rubi, 1767. In 1764 King Charles III of Spain ordered the Marques de Rubi, a Spanish army field marshal, to tour and inspect all presidios [Spanish forts] in New Spain. Rubi arrived in Mexico in February 1766, and was joined by Nicolas de Lafora, engineer and mapmaker. They made a tour of the Northwest and California territory and entered Texas on July 17, 1767. Rubi chose this location for his campsite July 23, 1767. His report suggested small Texas missions be closed. This was done in 1772. Only Goliad and San Antonio remained.*" In 1836, all defenders against the Mexican Army died in battle at the Alamo in San Antonio and over 400 prisoners from Goliad executed, which spurred further opposition to Mexico and led to Texas' independence as the only US state to have first been an independent country.
133.8	14.5	Pass the exit for the community of Roosevelt, located 800 m to the right (north) of the highway. Two military roads crossed this area during the Spanish-American War when future US President Theodore Roosevelt visited this area with his Rough Riders, One month later, before the town's founding in 1898, they made headlines with their famous charge up San Juan Hill. The town was named in Roosevelt's honor. Horses for polo and the US calvary were bred in the area and polo matches were hosted there in the 1920s. The town reached a population of about 100 by 1990 and has shrunk to about a dozen people today, mostly working at the century-old Simon Brothers Mercantile, which includes a post office.
163.3	29.5	Pass the exit for Fort McKavett State Historical Site, located 32 miles northeast on RR 864. The fort was established in 1852 for the 8th US Infantry to protect Texas settlers and serve as a rest stop for California-bound immigrants. In 1859, Fort McKavett was abandoned due to a decline in warfare with Native Americans. For his service at Fort McKavett, Sgt. Emanuel Stance became the first African American soldier to receive the Medal of Honor. The fort reopened in 1868 when hostilities between local Comanches and the settlers increased. From 1868 to 1883, Fort McKavett served as a major supply depot providing food and provisions for military campaigns, scientific and mapping explorations, and other forts in west Texas. By 1875, hostilities in the area had ceased and the fort closed in 1883. It was designated a state historic site in 1968 and is now open to the public.
166.8	3.5	Pass the exit for the City of Sonora, which was based on an 1885 settlement by Charlie Adams, a rancher and merchant from Fort McKavett. The community was named in 1887 for a family servant from Sonora, Mexico. Unlike cattle ranching, which dominates much of Texas, sheep and goat ranching has long thrived in the Sonora area. In 1916, a Texas Agricultural Experiment Station was established outside the city to study livestock disease and improve production methods. The Sonora Wool and Mohair Company, a cooperative organization, has led the industry regionally and has sponsored the National 4-H Wool Judging Contest since 1938. The population of the city peaked at about 6,000 in the 1970s with oil and gas exploration. It has since declined by about 50%.
174.9	8.1	Exit on Caverns of Sonora Road and turn left (south).
180.2	5.3	Turn left (southeast) and drive uphill onto Caverns of Sonora Road.
181.7	1.5	**STOP 1: Caverns of Sonora.** Park on the right in front of the pavilion. The Visitor Center is on the left. Orientation for lunch and trips into the cave will be held in the pavilion.

Total miles	Miles since last landmark	Route Directions and Landmarks
188.5	6.8	Return to Interstate Highway 10 and turn left (west). After 8 miles, the topography becomes flat for several miles. If you look carefully, you'll see the landscape has many sinkholes only 1-4 m deep but barely noticeable because they are hundreds of meters in diameter. These occur in the Buda Limestone, which dissolves slowly compared to other limestones. Rainfall pools in the sinkholes, depositing clay-rich soils on their floors that allow them to dissolve laterally to widen but restricts them from deepening. Some do extend through the 6-m thickness of the Buda into the underlying Segovia Limestone, where extensive caves like Caverns of Sonora are formed.
214.8	26.3	Pass the exit for the town of Ozona, the Crockett County seat. Named after Davy Crockett, a hero of Texas' fight for independence, the county was organized in 1891 under a large oak tree, which still stands and shades the historical marker describing the event. The Davy Crockett Monument is a large statue in the city park on the town square. Ozona was first known as "Powell Well," after land surveyor E.M. Powell, when it was founded in 1891. In 1897, it was renamed "Ozona" for the high quantity of its open air, or "ozone" (clearly not understanding what ozone is and its detrimental effects on health at ground level!). A flood in 1954 killed 16 people and destroyed half of the homes in the town. Its current population is about 3,500. For the next 24 miles west of Ozona, you will see many sediment-filled caves in the highway road cuts, some filled with brightly-colored orange, red, and yellow silts and clays. See the regional geologic description for more information.
255.3	40.5	Pass the exit to Iraan, Sheffield, and Fort Lancaster. The first documented Europeans to visit the area were the Spanish expedition led by explorer Gaspar Castaño de Sosa, who traveled up the Pecos River in 1590. Permanent settlements were not established until much later. Iraan is not related to the country of Iran. Located 13 miles north of the highway along the Pecos River, it is pronounced "Ira-Ann," named after founders Ira and Ann Yates. It was established during the discovery of the huge Yates Oil Field in 1926, a part of the Permian Basin oil and gas-rich region that extends through a large part of west Texas and southeast New Mexico. Iraan has a population of about 1,200. Nearly 5 miles south of the highway is the town of Sheffield. The first settler was John Cannon, who arrived in 1888 and purchased land along the Pecos River, but it was named after Will Sheffield, its first postmaster in 1898. A few of the town's early pioneers were said to be outlaws seeking a refuge far from the law. Economic development of the community declined when the interstate highway bypassed the town around 1980. It currently has about 600 residents. Fort Lancaster State Historic Site is located near a crossing of the Pecos River 9 miles east of Sheffield. It was established in 1855 to protect travelers and was one of the most isolated military posts in Texas. It was abandoned from 1861 to 1867 due to the Civil War and reoccupied as a sub-post for the 9th Cavalry Regiment of African American "Buffalo Soldiers." In December 1867, 40 soldiers and officers held off roughly 400 Kickapoo Indians, making it the only US Army fort in Texas attacked by Native Americans. Fort Lancaster is also the only Texas fort to host military camels, which were part of an army experiment in transporting heavy loads through the desert. The fort was permanently abandoned in the late 1870s and is now open as a state historical site. Along the Pecos River valley and throughout much of this area, shelter caves are formed in the limestone cliffs and hills. They are characterized by entrances that are much wider than their heights, and which generally extend only a few meters into the hillsides (Figure 3).

Figure 3. *Shelter caves, estimated as 2-3 m high by 3-6 m wide, visible in a cliff from Interstate Highway 10 near Sheffield.*

Total miles	Miles since last landmark	Route Directions and Landmarks
285.0	29.7	Pass the exit for Bakersfield, located 700 m to the right (north). You won't see anything except one gas station and a storage building beyond it. Established in 1929 after the discovery of oil in the area, the community was named after J.T. Baker who hoped to develop the townsite. It grew rapidly to an estimated population of just over 1,000 in 1930. However, as oil production and prices plummeted with the Great Depression, the town was mostly abandoned. Buildings were sold for the lumber or moved off site. By 1945, Bakersfield had an estimated population of 50 residents and two businesses and has since declined further.
286.4	1.4	On the right (north) side of the highway is a distinctive breast-shaped peak. The peak's historical name is now widely seen as derogatory and is being changed. This feature is significant as an excellent example of a butte (from the French for "knoll"), a flat-topped hill formed where harder-to-erode rock covers an easier-to-erode rock. The harder cap rock in this case is the Fredericksburg Group, the westward equivalent of the Segovia Limestone. Where present, it protects the underlying Washita Group from erosion and its edges form cliffs that rise from the softer slopes of the Washita. Mesas (from the Spanish for "tables") are essentially large buttes and plateaus are large mesas. All can be seen in this area. There is no universally accepted definition of their sizes.
294.5	8.1	Pass the McKenzie Road exit. The electricity-generating windmills in this area are built high on mesas to capture more wind. Most in this region are built on the extensive landholdings of The University of Texas.
322.0	27.5	Exit right (north) on US Highway 285 on the west side of Fort Stockton and turn right (northwest). We will visit Fort Stockton and the Comanche Springs on the return trip. The city was established as a fort in 1859 near the springs, the largest springs in west Texas and an important stop on the road from San Antonio to El Paso, Texas. It was named for First Lieutenant Edward Dorsey Stockton of the US 1st Infantry, who died in San Antonio two years earlier. The fort was closed in 1886 and its name was applied to the surrounding and growing town. Farming was the major industry for the town, using water from the springs for irrigation. Since the 1920s, Fort Stockton's economy has been closely tied to the oil and gas industry. Its current population is about 8,300.
331.8	9.8	The limestone in this road cut is the last we'll see until New Mexico.
364.5	32.7	Drive over the middle of Toyah Lake ("Toyah" is a Native American word for flowing water). It is unlikely you will see any water. Toyah is a playa lake, a broad, flat, shallow lake that holds water for short periods after substantial rainfall, and then evaporates and sinks into the ground. This lake is 10 km long, has an average width of 2 km, but a maximum depth of only 3 m. The Davis Mountains are visible 75 km to the left (southwest) and slightly behind us. They are volcanic, formed 35 million years ago, cover about 50 km^2, and reach a maximum elevation of 2,555 m.
370.7	6.2	Cross Interstate Highway 20 and enter the City of Pecos. The highway goes 44 miles southwest to join Interstate Highway 10 and east into South Carolina, nearly to the Atlantic Ocean. Continue northwest on US Highway 285. Yuma Indians are believed to have first settled and irrigated the area in the 16th Century using water from springs and the Pecos River, located about 3 km to the right (east). Cattlemen moved in during the 1870s, followed by merchants and farmers when the Texas and Pacific Railroad was established here in 1882. The City of Pecos was founded two years later. The town became widely known for its cantaloupes, but most agriculture in the region declined in the 1970s because of excess groundwater pumping, lowering the level of the aquifer.
371.5	0.8	Historical marker #4071 on the right (northeast) at the Buck Jackson Arena: "*World's First Rodeo, held a block south of courthouse, July 4, 1883. Started with claims of cattle outfits—NA, Lazy Y, and W Ranchers—that each had fastest steer ropers. Settlers in town for Fourth of July picnic were spectators. The prizes were blue ribbons cut by pocket knife from new dress of a 4 year old girl in the crowd. Best roper was Morg Livingston of the NA; second, Trav Windham, Lazy Y. Others entered: Howard Collier, Fate Beard, Jim Mannin, George Brookshire, John Chalk, Jeff Chism, Jim Livingston, Jim and Henry Black, Brawley Oates, Henry Miller, E.P. Struckler*." This location is one of several claims of the "first" rodeo.
372.4	0.9	Pass the Lucius D. Bunton III United States Courthouse on the right (northeast). When you return to San Antonio, toast this late US district judge as you enjoy the karst groundwater from the Edwards Aquifer. In May 1991, the Sierra Club filed a lawsuit that pumping of the aquifer was threatening the flow of the Comal and San Marcos Springs and the endangered species they support. The judge ruled in this highly contentious case that the US Fish & Wildlife Service must set minimum spring flow standards for these springs, the two largest in the southwestern part of the USA. In response, the Texas Legislature created the Edwards Aquifer Authority to oversee groundwater use from the aquifer. The first pumping limits for Texas were written into the law, creating sustainable use standards for the aquifer.

Total miles	Miles since last landmark	Route Directions and Landmarks
372.7	0.3	West of the Pecos Museum to the left (west) next to the railroad tracks. This Texas Historical Landmark opened in 1963. The building was constructed in two phases, a saloon built in 1896 and a hotel in 1904. With 50 rooms filled with scenes and artifacts of American western heritage, there is a lot to see and learn in this museum. If you come on your own and don't have time to tour the museum, at least stop, stretch your legs, and read the six historical markers near the museum's entrance.
373.3	0.6	Leaving the City of Pecos
406.7	33.4	Solar farm on the right (northeast). This is a new development with more occurring throughout the region. Most infrastructure you'll see along the highway from here into Carlsbad will be pump jacks, pipelines, storage tanks, and drill rigs for oil and gas production. Flaring of wells is a common but decreasing practice.
410.3	3.6	Cross Farm Road 652 at Orla, which is Spanish for "border." This community was established as a "section house" for Pecos River Railroad maintenance workers in 1890. The town grew slowly but expanded quickly in the mid-1960s when it became a rural oil supply center, reaching a maximum population of 250 at the end of the decade. As railroad and oil needs declined, its population dropped to only two people by 2005 and Orla became known as a ghost town. About 10 years later, with a dramatic increase in oil and gas drilling in the region, the town's fortunes reversed to the active growth and new businesses you see. Through investments also in solar energy, as seen nearby, the population will no longer be dependent primarily on oil production.
414.7	4.4	Cross over Salt Creek. The abandoned railroad bridge to the right (northeast) is a roost for bats (Figure 4).
420.0	5.3	County Road 453 is on the right (northeast) with a stone historical marker #4216 on the southeast corner for Pope's Crossing of the Pecos River: "*Used by emigrants and the Southern (Butterfield) Overland Mail, which linked St. Louis and San Francisco with a semi-weekly mail, 1858-1861. Headquarters in 1855 of Captain John Pope, supervisor of the first deep well west of the 98th meridian. They struck water at 244 feet sank [drilled] to 1140 [feet] hoping to strike artesian flow. The well caved before its value could be determined. The $100,000 experiment pointed the way to deep well drilling in the Great Plains*."

Figure 4. *Abandoned railroad bridge over Salt Creek that now serves as a bat roost in the crevices of its structure.*

Total miles	Miles since last landmark	Route Directions and Landmarks
423.1	3.1	Historical marker #3876 on the right (northeast) for Red Bluff Dam located 4.8 km to the southeast: "*Constructed for irrigation and electrical power purposes in 1934-36. Dam is located on the Pecos River 8 miles south of the Texas – New Mexico state line. It impounds an 11,700-acre lake occupying parts of Reeves and Pecos counties Tex., and Eddy County, N.M. Floods first filled the reservoir in June 1937. Capacity is 310,000 acre feet of water. Main embankment—9,230 feet long—rises 105 feet above stream bed at highest point. Dam has a top width of 25 feet. These waters irrigate about 140,000 acres, which extend for about 100 miles along the Pecos River*." The Pecos River begins as a freshwater stream in northeast New Mexico but increases and decreases greatly in salinity along its length due to evaporation and the presence of highly soluble gypsum and halite rock. Water in the Red Bluff Reservoir is moderately to highly saline. Depending on the water level in the reservoir and the bus height, a portion of the reservoir might be visible. The river becomes a perennial freshwater stream due to inflows from large karst springs south of Interstate Highway 10 below Sheffield.
424.4	1.3	Leave Texas and enter New Mexico.
436.4	12.0	Notice a large sinkhole at the head of a short valley on the right (northeast). Two more sinkholes are nearby and may be visible if the bus is tall enough. In 2018, NCKRI published Report of Investigation 7 on a detailed search, geologic study, and geophysical survey of the 22 miles of this highway extending north of the Texas state line to the town of Loving. The purpose of the research was to identify and minimize the risk of sinkhole collapse following highway renovation. This and all NCKRI reports are available for free download from the Publications section of www.nckri.org.
440.6	4.2	Drive through the village of Malaga. Originally known as Kirkwell, it was founded by Swiss immigrants in the 1890s and renamed after the famous city in southern Spain. Italian laborers also settled and farmed this area using water from the Pecos River. The 2020 census sets its population at 160.
441.4	0.8	Drive over the Black River. Tomorrow we will see Rattlesnake Spring, one of the sources of the river.
445.8	4.4	Enter the town of Loving, founded by Swiss and Italian farmers in the 1890s, similar to Malaga. It currently has a population of about 1,400. The town was named in honor of Oliver Loving, as is a nearby Texas county. Loving was the business partner of Charles Goodnight. In 1866, they established the Goodnight-Loving cattle trail that ran 2,000 miles from Texas to Wyoming. In New Mexico, the trail followed the Pecos River north to Fort Sumner, where the government needed beef to feed the Navajos at the Bosque Redondo Reservation. In July 1867, Loving and "One-Armed" Bill Wilson were attacked by Comanches while driving cattle to Fort Sumner. Wounded, Loving held off the attack for two days and nights while Wilson went for help. With the assistance of Mexican traders, Loving made it to Fort Sumner, where he died of gangrene in September. Goodnight, fulfilling a promise to Loving, exhumed Loving's body and reburied him a year later in Weatherford, Texas. Their story was the basis of the fictional story in the book and movie *Lonesome Dove* by Larry McMurtry.
455.5	9.7	You have entered the City of Carlsbad. Merge with US Highway 62/180 and turn right (north) onto Canal Street. Carlsbad was originally called Eddy, after cattleman Charles Eddy, when established in 1888. Its location was dictated by the location of the Carlsbad Springs, the main source of water in the area. Upstream of these karst springs, the Pecos River is saline when it isn't dry. Mineral water spas were popular at the time and in an effort to promote growth and tourism, the town was renamed after the famous European spa, Karlsbad, in Bohemia, which is now Karlovy Vary in the Czech Republic. Farming was the first major industry for Carlsbad, but the city's economic strength was soon found underground. It began in mining with the discovery of a major source of bat guano, and that site turned to tourism in 1923 as Carlsbad Cave National Monument and redesignated as Carlsbad Caverns National Park in 1930. In 1925, potash was found east of town and Carlsbad potash dominated the American potash market for many years. Located at the edge of the oil and gas rich Permian Basin, Carlsbad also diversified into that industry. In 1979, the US Congress authorized the creation of the Waste Isolation Pilot Plant (WIPP), designed to store transuranic (a type of intermediate-level nuclear) waste in thick salt beds 660 m underground. This is currently the only permanent disposal site in the US for nuclear waste; the first shipment arrived in 1999. The combination of farming, various mineral extraction, waste storage, and tourism have kept Carlsbad's population and economy stable to slowly growing, even during national economic crises. The 2020 census sets the population of Carlsbad at 32,238.
456.4	0.9	Turn left (west) into and park at the entrance of the Stevens Inn, where we will stay for the next two nights. **End of Day 1 trip.**

Day 2 Road Log (see Figure 1)

Total miles	Miles since last landmark	Route Directions and Landmarks
0.0	0.0	Leave the Stevens Inn. Turn right (south) on Canal.
0.7	0.7	Notice the yellow sign next to the street in front of the Fairfield Inn/Marriott Hotel on the right (west): "*US Highway 285 South subject to sinkhole 1000 feet ahead*." We'll talk about it tomorrow when we pass the site as we drive back to San Antonio.
0.8	0.1	Pass the light with the left turn to US Highway 285. Continue straight on US Highway 62/180.
1.2	0.4	Pass the administrative offices of Carlsbad Caverns National Park and Guadalupe Mountains National Park on the right (west). Unfortunately, some phone map applications lead tourists here and not to the parks!
4.2	3.0	Pass the Cavern City Air Terminal on the right (west). During World War II, it was the Carlsbad Army Airfield and used to train US Army Air Force bombardiers. Bats accidentally destroyed several buildings here in an experiment designed to attach fire bombs to bats and release them over Japan; the project was canceled in favor of the atomic bomb (Couffer, 1992).
8.8	4.6	Pass Dark Canyon Road on the right (west). The road leads 33 miles to Sitting Bull Falls Recreational Area, a part of Lincoln National Forest. The falls are fed by karst springs whose water flows through a series of pools until reaching a canyon where it drops 46 m to create the falls. A small constructional cave is hidden behind the falls. Rather than being formed by limestone dissolved out of the rock, travertine deposited by the falls in front of the rock cliff created the enclosed space which is Sitting Bull Falls Cave. Continue straight on US Highway 62/180. Ahead to the right (southwest) are a series of low hills. They are the lower end of the Guadalupe Mountains. They rise higher and larger as we head southwest. To the northeast behind us, the Capitan Limestone and related rocks of the mountains dip underground and below the City of Carlsbad, where they form a karstic aquifer that provides drinking water for the town. The aquifer drains from the Carlsbad Springs, but the Capitan Limestone turns east from the City of Carlsbad, nearly reaching the state line, then heads south to the area of Fort Stockton, and then goes northwest to the southwest end of the Guadalupe Mountains where faults bring it back to the surface (see the outlined margin of the Delaware Basin in Figure 1).
18.5	9.7	Turn right (northwest) into White's City. Generally assumed to be named for Jim White, the primary early explorer of Carlsbad Cavern, it was named for Charles White who created this tourist resort gateway in the 1920s to what was then Carlsbad Cave National Monument. The original road to Carlsbad Cavern, an old guano mining trail, extends up a hill to the left (southwest) side of the town and has been converted to a 4-mile long hiking trail to the cave.
19.0	0.5	Enter Carlsbad Caverns National Park. We will follow Walnut Canyon most of the way to the visitor center. Several holes are seen along the drive, but none lead into any caves of known significance.
22.4	3.4	Pass a turn-off on the left (south) to an exhibit. A short trail leads to a shelter cave once used by Native Americans. The cave isn't visible from the road. Notice in the cliff that some rock tilts toward the left and others tilt toward the right into them. This is interpreted by some as an ancient slump into a large underlying, and currently unknown, cave.
25.9	3.5	**STOP 2: Carlsbad Caverns National Park and lunch.**
33.3	7.4	Return to US Highway 62/180 and turn right (southwest). Looking straight ahead, you'll see the rest of the Guadalupe Mountains which continue another 34 miles with the last 9 miles in Texas in Guadalupe Mountains National Park. The mountain El Capitan's 300-m high cliff forms the abrupt end of the Guadalupe Mountains (this mountain should not be confused with El Capitan in Yosemite National Park in California). The peak to the right of El Capitan is Guadalupe Peak, the highest point in the mountains and in Texas at 2,667 m above mean sea level.
36.7	3.4	Drive over the Black River, which is usually dry in this location.
38.6	1.9	Turn right (west) onto Eddy County Road 418. At this point you are near three karst-forming rocks. Behind you, southeast across US Highway 62/180, is Permian age gypsum; Parks Ranch Cave is about a mile to the east and with 6.6 km of passages is the second longest gypsum cave in the US. Ahead to the west are the limestone Guadalupe Mountains. In between the gypsum and mountains is a thick deposit of limestone gravel and cobbles, eroded from and washed out of the Guadalupe Mountains to cover the plain you are now riding on. These pieces of limestone have been cemented by calcite into a conglomerate rock which forms a small karst aquifer. Our next stop, Rattlesnake Spring, flows from this aquifer.

Total miles	Miles since last landmark	Route Directions and Landmarks
40.7	2.1	Pass Black River at the low spot in the road. The Black River normally sinks about 100 m upstream (to the left, southwest) of this spot and reappears 17 km to the northeast at Blue Spring. Immediately before this river crossing, a road cut exposes the conglomerate rock.
40.8	0.1	Turn right (northwest) toward Camp Washington Ranch and Rattlesnake Spring. Continuing straight leads 8.9 miles to Slaughter Canyon and the trail to Slaughter Canyon Cave in Carlsbad Cavern National Park, where wild cave tours are offered.
41.0	0.2	Turn left (west) toward Rattlesnake Spring. Continuing straight leads 0.4 mile to Camp Washington Ranch Headquarters, a lodging resort used for group meetings and activities. Camp Washington Ranch has a spectacular display of tufa dams, similar to cave rimstone dams but much larger and on the surface (Figure 5). They formed when the local climate was wetter about 10,000 year ago or longer (their exact age has not been determined).
41.5	0.5	**STOP 3: Rattlesnake Spring, Carlsbad Caverns National Park.** Normally we would drive 0.3 mile further to the spring, but construction may have the road closed at the end of the picnic area where we might exit the bus and walk a few minutes to the spring. The Rattlesnake Springs Historic District was listed in the National Register of Historic Places on 14 July 1988.
44.4	2.9	Return to US Highway 62/180 and turn left (northeast). We will return to Carlsbad the way we came.
49.8	5.4	Pass Whites City.
54.8	5.0	Pass Black River Road (Eddy County Road 720) on the right (east). Blue Spring, where Black River flows again on the surface, is located about 6 km to the east.
67.4	12.6	Pass US Highway 285 on the right (east), the route we'll take tomorrow to return to San Antonio.
68.2	0.8	Turn left (west) into the parking lot of the Stevens Inn. **End of Day 2 trip**

Figure 5. *Flood debris (yes, it floods in the desert and violently!) covers part of a 2-m high tufa dam, one of many on Camp Washington Ranch. These dams are probably related to ancient flow from Rattlesnake Spring and presently non-flowing springs in the area, but their age and origin has not yet been studied.*

Day 3 Road Log for Figure 1 (some information is repeated from Day 1 road log)

Total miles	Miles since last landmark	Route Directions and Landmarks
0.0	0.0	Leave the Stevens Inn. Turn left (north) on Canal Street and into downtown Carlsbad.
1.2	1.2	Turn right (east) onto Greene Street (US Highway 62/180).
1.5	0.3	Turn left (north) on Park Drive at the railroad tracks. Do not cross the bridge over the Pecos River. The Pecos is a karstic river. Its uppermost reaches are in the Sangre de Cristo Mountains in northern New Mexico, but it does not have perennial flow until reaching the Blue Hole in the town of Santa Rosa, about 300 km north of Carlsbad. Santa Rosa is on the edge of a large subsidence area formed by dissolution of rocks in the subsurface. The Blue Hole is part of a group of water-filled sinkhole springs, some of which serve as parks, scuba diving training sites, and the main tourist attractions for the town. As the river flows south, it loses water underground and to evaporation until reaching the City of Roswell, 190 km downstream, where saline karst springs from Bitter Lake National Wildlife Refuge and Bottomless Lakes State Park increase its flow. The Bottomless Lakes (which do have bottoms, of course) are a series of large collapsed sinkholes. As the river flows another 110 km down to Carlsbad, it usually goes dry. At the north end of Carlsbad, the Carlsbad Springs rejuvenate the river with fresh water and are the life source for the city. They discharge water that enters the Capitan Limestone and associated rocks in the Guadalupe Mountains, which we visited yesterday. This section of the river is dammed and makes Carlsbad a unique desert community in this region with swimming, boating, water skiing, boat rides, and other activities.
1.9	0.4	Turn left (west) onto Cascades Avenue.
2.0	0.1	**STOP 4: National Cave and Karst Research Institute.**
2.1	0.1	Return to Park Drive and turn right (south).
2.5	0.4	Turn right (west) on Greene Street.
2.8	0.3	Turn left (south) on Canal Street (US Highway 285).
4.7	1.9	Notice the yellow sign next to the street in front of the Fairfield Inn/Marriott Hotel on the right (west): "*US Highway 285 South subject to sinkhole 1000 feet ahead*" (Figure 6). Turn left (southeast) immediately past the sign onto US Highway 285 toward Pecos, Texas.
4.8	0.1	Look at the empty lot on the right (south) to the left of the Circle S Feed Store. This is the location of a former brine well. To drill for oil and gas in parts of this region, it is necessary to drill through halite (rock salt). Fresh water can't be used to lubricate the drill bit because it dissolves the salt quickly, creating a void that makes drilling unstable. Instead, brine wells are created to deliberately inject fresh water into the salt, then pump out the resulting saltwater (brine) to use for drilling, since saltwater will not dissolve salt. This process creates a cavity at the brine well, which in this location became too wide, and was too shallow, and threatened to collapse. Three other brine wells collapsed in the region, creating sinkholes up to 100 m in diameter in 2008 and 2009. From 2019 to early 2022, this cavity was filled with sand and grout to prevent its collapse, which would have probably resulted in over $1 billion in damages and economic impacts. The Governor of the State of New Mexico and other dignitaries celebrated the completion of this project at NCKRI Headquarters on 1 June 2022. NCKRI co-chaired the Technical Advisory Committee for the project, and conducted one of the first geophysical studies of the cavity. That study is available as NCKRI Report of Investigation 2.

Figure 6. *Warning sign about the potential for a large sinkhole to form in US Highway 285 a short distance ahead. The brine well cavity that could have caused a catastrophic collapse is located in the area in front of the trees below the left side of the sign. A pile of sand, used in filling the cavity, is visible behind the white truck which is below "1000" in the sign.*

Total miles	Miles since last landmark	Route Directions and Landmarks
12.5	7.7	From this intersection of US Highway 285 with New Mexico (NM) Highway 31 is a sign that points left (east) to the town of Jal. If you follow NM 31 east to NM 128 and continue east to an unnamed dirt road and follow it south, you will find a marker about 24 km southeast of the US 285-NM 31 intersection that marks Project Gnome. This was the first nuclear detonation in the Plowshare Program, whose aim was to develop peaceful uses for nuclear explosions. On 10 December 1961, the 3.1 kiloton explosion created a 52-m diameter cave in rock salt almost 360 m underground. The Plowshare Program was canceled in 1977 because of negative public views on peaceful nuclear explosions.
14.4	1.9	Enter the town of Loving, founded by Swiss and Italian farmers in the 1890s. It currently has a population of about 1,400. The town was named in honor of Oliver Loving, as is a nearby Texas county. Loving was the business partner of Charles Goodnight. In 1866, they established the Goodnight-Loving cattle trail that ran 2,000 miles from Texas to Wyoming. In New Mexico, the trail followed the Pecos River north to Fort Sumner, where the government needed beef to feed the Navajos at the Bosque Redondo Reservation. In July 1867, Loving and "One-Armed" Bill Wilson were attacked by Comanches while driving cattle to Fort Sumner. Wounded, Loving held off the attack for two days and nights while Wilson went for help. With the assistance of Mexican traders, Loving made it to Fort Sumner, where he died of gangrene in September. Goodnight, fulfilling a promise to Loving, exhumed Loving's body and reburied him a year later in Weatherford, Texas. Their story was the basis of the fictional story in the book and movie *Lonesome Dove* by Larry McMurtry.
18.8	4.4	Drive over the Black River. We visited the head of the Black River at Rattlesnake Spring and vicinity yesterday. See this field guide's discussion of Carlsbad Caverns National Park for more information.
19.6	0.8	Drive through the village of Malaga. Originally known as Kirkwell, it was founded by Swiss immigrants in the 1890s and renamed after the famous city in southern Spain. Like the town of Loving, Italian laborers also settled and farmed this area using water from the Pecos River. The 2020 census sets its population at 160.
23.8	4.2	Notice a large sinkhole at the head of a short valley on the left (northeast). Two more sinkholes (one of which is shown below in Figure 7) are nearby and may be visible if the bus is tall enough. In 2018, NCKRI published Report of Investigation 7 on a detailed search, geologic study, and geophysical survey of the 22 miles of this highway extending north of the Texas state line to the town of Loving. The research goal was to identify and minimize the risk of sinkhole collapse after highway renovation. This and all NCKRI reports are available for free download from the Publications section of www.nckri.org.
35.8	12.0	Leave New Mexico and enter Texas.

Figure 7. *NCKRI's Dr. Lewis Land evaluates a collapse-formed sinkhole near US Highway 285 to determine the risk and minimize the potential for other sinkholes to form under the highway.*

Total miles	Miles since last landmark	Route Directions and Landmarks
37.1	1.3	Historical marker #3876 is on the right (northeast) for Red Bluff Dam, located 4.8 km to the southeast: "*Constructed for irrigation and electrical power purposes in 1934-36. Dam is located on the Pecos River 8 miles south of the Texas – New Mexico state line. It impounds an 11,700-acre lake occupying parts of Reeves and Pecos counties Tex., and Eddy County, N.M. Floods first filled the reservoir in June 1937. Capacity is 310,000 acre feet of water. Main embankment—9,230 feet long—rises 105 feet above stream bed at highest point. Dam has a top width of 25 feet. These waters irrigate about 140,000 acres, which extend for about 100 miles along the Pecos River*." The Pecos River begins as a freshwater stream but increases and decreases greatly in salinity along its length due to evaporation and the presence of highly soluble gypsum and halite rock. Water in the Red Bluff Reservoir is moderately to highly saline. Depending on the water level in the reservoir and the bus height, a portion of the reservoir might be visible.
40.2	3.1	County Road 453 is on the left (northeast) with a stone historical marker #4216 on the southeast corner for Pope's Crossing of the Pecos River: "*Used by emigrants and the Southern (Butterfield) Overland Mail, which linked St. Louis and San Francisco with a semi-weekly mail, 1858-1861. Headquarters in 1855 of Captain John Pope, supervisor of the first deep well west of the 98th meridian. They struck water at 244 feet sank [drilled] to 1140 [feet] hoping to strike artesian flow. The well caved before its value could be determined. The $100,000 experiment pointed the way to deep well drilling in the Great Plains.*"
45.5	5.3	Cross over Salt Creek. The abandoned railroad bridge to the left (northeast) is a roost for bats.
49.9	4.4	Cross Farm Road 652 at Orla, which is Spanish for "border." This community was established as a "section house" for Pecos River Railroad maintenance workers in 1890. The town grew slowly but expanded quickly in the mid-1960s as a rural oil supply center, reaching a maximum population of 250 at the end of the decade. As railroad and oil needs declined, its population dropped to only two people by 2005 and Orla became known as a ghost town. About 10 years later, with a dramatic increase in oil and gas drilling in the region, the town's fortunes reversed to the active growth and new businesses you see. Through investments also in solar energy, as seen nearby, the population will no longer be dependent primarily on oil production.
53.5	3.6	Solar farm on the left (northeast). This is a new development with more occurring throughout the region.
86.9	33.4	Enter the City of Pecos. Yuma Indians are believed to have first settled and irrigated the area in the 16th Century using water from springs and the Pecos River, located about 3 km to the left (east). Cattlemen moved in during the 1870s, followed by merchants and farmers when the Texas and Pacific Railroad was established here in 1882. The City of Pecos was founded two years later. The town became widely known for its cantaloupes, but most agriculture in the region declined in the 1970s because of excess groundwater pumping, lowering the level of the aquifer.
87.5	0.6	West of the Pecos Museum to the right (west) next to the railroad tracks. This Texas Historical Landmark opened in 1963. The building was constructed in two phases, a saloon built in 1896 and a hotel in 1904. With 50 rooms filled with scenes and artifacts of American western heritage, there is a lot to see and learn in this museum. If you come on your own and don't have time to tour the museum, at least stop, stretch your legs, and read the six historical markers near the museum's entrance.
87.8	0.3	Pass the Lucius D. Bunton III United States Courthouse on the left (northeast). When you return to San Antonio, toast this late US district judge as you enjoy the karst groundwater from the Edwards Aquifer. In May 1991, the Sierra Club filed a lawsuit that pumping of the aquifer was threatening the flow of the Comal and San Marcos Springs (Figure 8) and the endangered species they support. The judge ruled in this highly contentious case that the US Fish & Wildlife Service must set minimum spring flow standards for these springs, the two largest in the southwestern part of the USA. In response, the Texas Legislature created the Edwards Aquifer Authority to oversee groundwater use from the aquifer. The first pumping limits for Texas were written into the law, creating sustainable use standards for the aquifer.
88.7	0.9	Historical marker #4071 on the right (northeast) at the Buck Jackson Arena: "*World's First Rodeo, held a block south of courthouse, July 4, 1883. Started with claims of cattle outfits—NA, Lazy Y, and W Ranchers—that each had fastest steer ropers. Settlers in town for Fourth of July picnic were spectators. The prizes were blue ribbons cut by pocket knife from new dress of a 4 year old girl in the crowd. Best roper was Morg Livingston of the NA; second, Trav Windham, Lazy Y. Others entered: Howard Collier, Fate Beard, Jim Mannin, George Brookshire, John Chalk, Jeff Chism, Jim Livingston, Jim and Henry Black, Brawley Oates, Henry Miller, E.P. Struckler*." This location is one of several claims of the "first" rodeo.

Total miles	Miles since last landmark	Route Directions and Landmarks
89.5	0.8	Cross Interstate Highway 20 and leave Pecos. The highway goes 44 miles southwest to join Interstate Highway 10. To the east, Interstate Highway 20 extends into South Carolina, nearly to the Atlantic Ocean. Continue southeast on US Highway 285.
95.7	6.2	Drive over the middle of Toyah Lake ("Toyah" is a Native American word for flowing water). It is unlikely you will see any water. Toyah is a playa lake, a broad, flat, shallow lake that holds water for short periods after substantial rainfall, and then evaporates and sinks into the ground. This lake is 10 km long, has an average width of 2 km, but a maximum depth of only 3 m. The Davis Mountains are visible 75 km away ahead to the right (southwest). They are volcanic, formed 35 million years ago, cover about 50 km^2, and reach a maximum elevation of 2,555 m.
128.4	32.7	First limestone road cut. Back in cave country!
138.2	9.8	Cross over Interstate Highway 10, which extends right (west) to Los Angeles, California, and the Pacific Ocean and left (east) to San Antonio and beyond that, Jacksonville, Florida, and the Atlantic Ocean. Continue south on US Highway 285 and enter Fort Stockton. The city was established as a fort in 1859 near the Comanche Springs, the largest springs in west Texas and an important stop on the road from San Antonio to El Paso, Texas. It was named for First Lieutenant Edward Dorsey Stockton of the US 1st Infantry, who died in San Antonio two years earlier. The fort was closed in 1886 and its name was applied to the surrounding and growing town. Farming was the major industry for the town, using water from the spring for irrigation. Since the 1920s, Fort Stockton's economy has been closely tied to the oil and gas industry. Its current population is about 8,300.
139.0	0.8	Turn left (east) on West Dickinson Boulevard to follow US Highway 285.
140.0	1.0	Pass US Highway 385 on the right (south) that leads 140 miles to Big Bend National Park, a beautifully spectacular desert park.
140.2	0.2	Pass Main Street and Paisano Pete, "the World's Largest Roadrunner," on the right (south). Roadrunners are a desert bird native to the southwestern US and northwestern Mexico. It prefers to run quickly instead of flying, The roadrunner was popularized as the clever hero in a series of children's cartoons.
140.5	0.3	Turn right (south) to follow US Highway 285.
140.8	0.3	Turn right (west) on North Spring Drive.

Figure 8. *Glass-bottom boat tours give visitors the opportunity to see water flowing out of the Edwards Aquifer through the San Marcos Springs in Spring Lake. Guests can also see the endangered species supported by the springs (only a small corner of the lake is shown).*

Total miles	Miles since last landmark	Route Directions and Landmarks
141.0	0.2	**STOP 5: Comanche Springs Park.**
141.1	0.1	Turn left (south) slightly but veer right and park on the left near the picnic tables. To the right (north) side of the bus is a 3-m high cliff of marl (clay-rich limestone) which overlies the cavernous limestone of Comanche Springs. **STOP 6: Lunch in James Rooney Memorial Park.**
141.4	0.3	Return to US Highway 285 and turn left (north).
141.7	0.3	Turn right (east) on East Dickinson Boulevard (Interstate Highway 10 Business).
142.6	0.9	Historical marker on the left (north) states Pecos County was created on 3 May 1871, identifies the first officials (elected on 9 March 1875), notes Fort Stockton is the county seat, and records the discovery of oil in the nearby Yates Field in 1926.
143.4	0.8	Enter eastbound Interstate Highway 10.
166.6	23.2	Pass the McKenzie Road exit. The electricity-generating windmills in this area are built high on mesas to capture more wind. Most are built on the extensive landholdings of The University of Texas in west Texas.
171.4	4.8	Look quickly at the short road cut on the right (south). You might notice a series of small, closely spaced holes, many filled at least partly with sediment (Figure 9). They resemble a miniature cross section of Amazing Maze Cave, a hypogenic maze with almost 7 km of passages. They suggest hypogenic processes occur in this region beyond the immediate area of the cave.
174.7	3.3	On the left (north) side of the highway is a distinctive breast-shaped peak. The peak's historical name is now widely seen as derogatory and is being changed. This feature is significant as an excellent example of a butte (from the French for "knoll"), a flat-topped hill formed where harder-to-erode rock covers an easier-to-erode rock. The harder cap rock in this case is the Fredericksburg Group, the westward equivalent of the Segovia Limestone. Where present, it protects the underlying Washita Group from erosion and its edges form cliffs that rise from the softer slopes of the Washita. Mesas (from the Spanish for "tables") are essentially large buttes and plateaus are large mesas. All can be seen in this area. There is no universally accepted definition of their sizes.

Figure 9. *Small sediment-filled cave passages exposed in a road cut along Interstate Highway 10 that probably formed hypogenically. The red, white, and yellow ruler is 0.7 m tall.*

Total miles	Miles since last landmark	Route Directions and Landmarks
176.1	1.4	Pass the exit for Bakersfield, located 700 m to the left (north). You won't see anything except one gas station and a storage building beyond it. Established in 1929 after the discovery of oil in the area, the community was named after J.T. Baker who hoped to develop the townsite. It grew rapidly to an estimated population of just over 1,000 in 1930. However, as oil production and prices plummeted with the Great Depression, the town was mostly abandoned. Buildings were sold for the lumber or moved off site. By 1945, Bakersfield had an estimated population of 50 residents and two businesses and has since declined further.
205.8	29.7	Pass the exit to Iraan, Sheffield, and Fort Lancaster. The first documented Europeans to visit the area was the Spanish expedition led by explorer Gaspar Castaño de Sosa, who traveled up the Pecos River in 1590. Permanent settlements were not established until much later. Iraan is not related to the country of Iran. Located 13 miles north of the highway along the Pecos River, it is pronounced "Ira-Ann," named after founders Ira and Ann Yates. It was established during the discovery of the huge Yates Oil Field in 1926, a part of the Permian Basin oil and gas-rich region that extends through a large part of west Texas and southeast New Mexico. Iraan has a population of about 1,200. Nearly 5 miles south of the highway is the town of Sheffield. The first settler was John Cannon, who arrived in 1888 and purchased a tract along the Pecos River, but it was named after Will Sheffield, its first postmaster in 1898. A few of the town's early pioneers were said to be outlaws seeking a refuge far from the law. Economic development of the community declined when the interstate highway bypassed the town around 1980. It currently has about 600 residents. Fort Lancaster State Historic Site is located near a crossing of the Pecos River 9 miles east of Sheffield. It was established in 1855 to protect travelers and was one of the most isolated military posts in Texas. It was abandoned from 1861 to 1867 due to the Civil War and reoccupied as a sub-post for the 9th Cavalry Regiment of African American "Buffalo Soldiers." In December 1867, 40 soldiers and officers held off roughly 400 Kickapoo Indians, making it the only US Army fort in Texas attacked by Native Americans. Fort Lancaster is also the only Texas fort to host military camels, which were part of an army experiment in transporting heavy loads through the desert. The fort was permanently abandoned in the late 1870s and is now open as a state historical site. Along the Pecos River valley and throughout much of this area, shelter caves are formed in the limestone cliffs and hills. They are characterized by entrances that are much wider than their heights, and which generally extend only a few meters into the hillsides.
222.7	16.9	For the next 24 miles until reaching the town of Ozona, you will see many sediment-filled caves in the highway road cuts, some filled with brightly-colored orange, red, and yellow silts and clays (Figure 10). See the regional geologic description for more information.

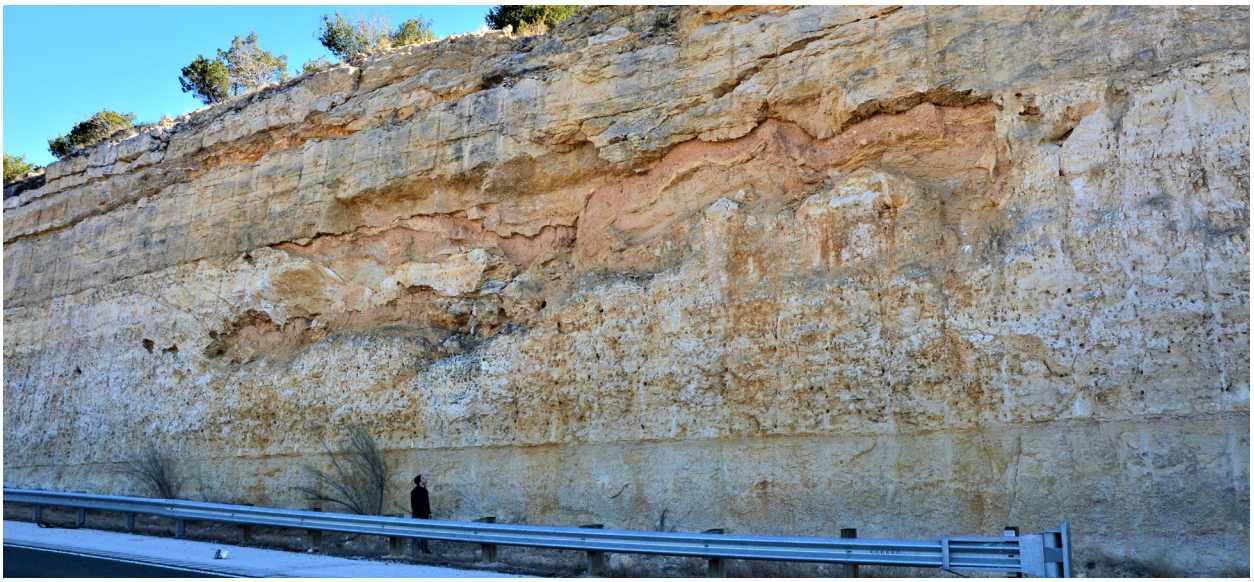

Figure 10. *This ancient, 23-m wide by 4-m high passage is filled with sediment and is one of many filled passages exposed in road cuts west of Ozona along Interstate Highway 10. Note the person below for scale.*

Total miles	Miles since last landmark	Route Directions and Landmarks
246.3	23.6	Pass the exit for the town of Ozona, the Crockett County seat. Named after Davy Crockett, a hero of Texas' fight for independence, the county was organized in 1891 under a large oak tree, which still stands and shades the historical marker describing the event. The Davy Crockett Monument is a large statue in the city park on the town square. Ozona was first known as "Powell Well," after land surveyor E.M. Powell, when it was founded in 1891. In 1897, it was renamed "Ozona" for the high quantity of its open air, or "ozone" (clearly not understanding what ozone is and its detrimental effects on health at ground level!). A flood in 1954 killed 16 people and destroyed about half the town's homes. Its current population is roughly 3,500. For most of the next 18 miles, the topography is flat. If you look carefully, you'll see the landscape has many sinkholes only 1-4 m deep but barely noticeable because they are hundreds of meters in diameter. These occur in the Buda Limestone, which dissolves slowly compared to other limestones. Rainfall pools in the sinkholes, depositing clay-rich soils on their floors that allow them to dissolve laterally to widen but restricts them from deepening. Some do extend through the 6-m thickness of the Buda into the underlying Segovia Limestone, where extensive caves like Caverns of Sonora are formed.
272.6	26.3	Pass the exit to Caverns of Sonora on the right (south).
274.5	1.9	Pass the last sediment filled cave on the right (south) in the road cut after the rest area.
280.7	6.2	Pass the exit for the City of Sonora. Based on an 1885 settlement by Charlie Adams, a rancher and merchant from Fort McKavett, the community was named in 1887 for a family servant from Sonora, Mexico. Unlike cattle ranching, which dominates much of Texas, sheep and goat ranching has thrived in the Sonora area. In 1916, a Texas Agricultural Experiment Station was established outside the city to study livestock disease and improve production methods. The Sonora Wool and Mohair Company, a cooperative organization, has led the industry regionally and sponsored the National 4-H Wool Judging Contest since 1938. The city's population peaked at about 6,000 in the 1970s with oil and gas exploration. It has since declined by about 50%.
284.2	3.5	Pass the exit for Fort McKavett State Historical Site, located 32 miles northeast on RR 864. The fort was established in 1852 for the 8th US Infantry to protect Texas settlers and serve as a rest stop for California-bound immigrants. In 1859, Fort McKavett was abandoned due to a decline in warfare with Native Americans. For his service at Fort McKavett, Sgt. Emanuel Stance became the first African American soldier to receive the Medal of Honor. The fort reopened in 1868 when hostilities between local Comanches and the settlers increased. From 1868 to 1883, Fort McKavett served as a major supply depot providing food and provisions for military campaigns, scientific and mapping explorations, and other forts in west Texas. By 1875, hostilities in the area had ceased and the fort closed in 1883. It was designated a state historic site in 1968.
313.7	29.5	Pass the exit for the community of Roosevelt, located 800 m to the left (north) of the highway. Two military roads crossed this area during the Spanish-American War when future US President Theodore Roosevelt visited this area with his Rough Riders, One month later, before the town's founding in 1898, they made headlines with their famous charge up San Juan Hill. The town was named in Roosevelt's honor. Horses for polo and the US calvary were bred in the area and polo matches were hosted there in the 1920s. The town reached a population of about 100 by 1990 and has shrunk to about a dozen people today, mostly working at the century-old Simon Brothers Mercantile, which includes a post office.
328.2	14.5	Cross Bear Creek. To the right (south) near the junction of the creek with the North Llano River is what is described in the Texas Historical Landmark database as the "*Campsite of Marques de Rubi, 1767. In 1764 King Charles III of Spain ordered the Marques de Rubi, a Spanish army field marshal, to tour and inspect all presidios in New Spain. Rubi arrived in Mexico in February 1766, and was joined by Nicolas de Lafora, engineer and mapmaker. They made a tour of the Northwest and California territory and entered Texas on July 17, 1767. Rubi chose this location for his campsite July 23, 1767. His report suggested small Texas missions be closed. This was done in 1772. Only Goliad and San Antonio [the Alamo] remained.*" In 1836, all defenders against the Mexican Army died in battle at the Alamo in San Antonio, and over 400 prisoners from Goliad executed, which spurred further opposition to Mexico and led to Texas' independence as the only US state to have first been an independent country.
331.9	3.7	Exit onto US 83 into Junction and turn right (south) on US 83 (Main Street). The City of Junction has a population of about 2,600. Founded in 1876, it was originally named "Denman" after Marcellus Denman who surveyed and platted the new community. The name was quickly changed to "Junction City," and later simplified to "Junction," for its location at the confluence of the North and South Llano rivers which form the Llano River. Junction is the seat for Kimble County and the commercial focus of the area's ranching industry.

Total miles	Miles since last landmark	Route Directions and Landmarks
332.0	0.1	Turn left (east) into the Pilot Truck Stop. **Stop for gas, restrooms, and snacks.**
332.1	0.1	Turn right (north) after exiting the Pilot Truck Stop, and turn right (east) on Interstate Highway 10.
333.6	1.5	Cross over the Llano River. The North and South Llano rivers join about 600 m to the right (south) of the highway. The hillside ahead on the east side of the river is composed mostly of the Hensel Sand, which occurs below the limestone units of the area. As we drive east and up out of the Llano River valley, we will be back in the limestone and for about 3 miles the limestone is folded (Figure 11) and brecciated (broken into small pieces) in road cuts. This results from the dissolution of the underlying Kirschberg section of the rock, which is more soluble gypsum, followed by collapse of overlying limestone.
341.2	7.6	Pass the community of Segovia, which was founded in the 1860s and named after the city in Spain. Despite ambitions, it never grew much and is currently only a stop for supplies along the highway, with a population of about 25. Geologically, it is more notable as the namesake for the Segovia Member of the Edwards Limestone, which is most of the rock we saw from the sediment-filled road cut caves west of Ozona to Kerrville, about 40 miles ahead to the southeast. It contains many important Texas caves.
364.1	22.9	Pass the community of Mountain Home; population of 96. The area was settled in 1856. The town is best known as a gateway to the Y.O. Ranch, a 202-km^2 ranch housing a variety of exotic animals. The family-owned ranch started in 1880 as a program to import exotic species from Africa. These animals thrive in this area because of its similar environment to parts of Africa.
383.9	19.8	Pass the city of Kerrville, site of the 15th International Congress of Speleology in 2009 at Schreiner University. Kerr County and Kerrville were founded and named in 1856 after Republic of Texas soldier and pioneer James Kerr. The area became an important cattle-raising and shipping point in the 1870s and has since diversified to become a regional economic center.
398.3	14.4	Pass the town of Comfort. Like many towns in this area known as the Texas Hill Country, Comfort was founded by German immigrants, in this case in 1854. It is home to the only remaining "hygieostatic" (loosely, a "health station") bat roost. Built in 1918 to reduce mosquito populations, the roost is a shingled tower in a steep pyramid-shape. It stands 9 m tall and was designated a Texas State Landmark in the 1980s and included on the National Register of Historic Places.

Figure 11. *Folded rock in Interstate Highway 10 road cuts are not from tectonic forces but dissolution of underlying gypsum beds that results in collapse and folding of these beds.*

Total miles	Miles since last landmark	Route Directions and Landmarks
408.6	10.3	Pass the exit for the community of Welfare, which began in 1848 with a general store. The town grew to 275 individuals in 1892 and has since declined to its current population of 36.
415.8	7.2	Pass the town of Boerne (pronounced "burn-ee"). Founded in 1849 as "Tusculum" by Germans of the Free Thinkers movement, it was renamed three years later in honor of German author and political satirist Karl Ludwig Börne. Boerne also leads to Cave Without A Name, the 8th longest cave in Texas at 5.7 km. It will be visited during the post-congress field trip.
418.4	2.6	Pass the exit to Cascade Caverns, one of the oldest show caves in Texas, in continuous operation since 1932. The cave is a single passage to a room with a waterfall.
429.9	11.5	Drive over the Edwards Aquifer Recharge Zone for the next 2 miles. The recharge zone is defined as the exposure of the Edwards Limestone in the Balcones Fault Zone where water enters and fills (recharges) the aquifer (Figure 12). The Edwards Aquifer is a karst aquifer and the primary water supply for the San Antonio region. Extensive urbanization over the recharge zone in this area reduces the amount of water that enters the aquifer and reduces the cleanliness of the water. The elevation of the land has gradually decreased from Carlsbad, where we started at 1,100 m above mean sea level. We end our trip at an elevation of about 200 m.
431.5	1.6	Cross Loop 1604 and enter San Antonio.
438.6	7.1	Pass Loop 410.
442.7	4.1	Exit right (west) to Interstate Highway 35 South right.
444.3	1.6	Exit right (west) to Interstate Highway 35 South right.
446.3	2.0	Exit right (west) to Interstate Highway 35 South right.
447.1	0.8	Exit right (west) to César Chavez Boulevard.
447.4	0.3	Turn right (east) on César Chavez Boulevard.
447.7	0.3	Turn left (north) on South Santa Rosa Avenue.
447.9	0.2	Turn right (east) on Dolorosa Street.
448.3	0.4	Dolorosa bends to the left and becomes Market Street at the courthouse (on the right, south). Continue straight on Market.
448.5	0.2	Park on the right side of the street in front of the Westin Hotel. **End of trip.**

Figure 12. *Surface water floods into many caves to recharge the Edwards Aquifer. Due to urbanization it carries many contaminants. Some are visible, as seen here in Blanco Road Cave. Often, the most hazardous are unseen.*

Regional Overview

This field trip extends 720 km from San Antonio, Texas to Carlsbad, New Mexico. It returns to San Antonio by the same route after a side-trip to Carlsbad Caverns National Park (Figure 1). It begins in downtown San Antonio at the lower end of the Balcones Fault Zone, then climbs up and to the northwest through the Texas Hill Country onto the Edwards Plateau. Most of our time on the bus will be spent crossing over the Edwards Plateau, one of the largest karst areas in the US. As we go west, the climate becomes progressively drier and the last section of the trip is through the relatively flat and oil-rich Permian Basin desert.

The region was once a Spanish territory and is located near modern day Mexico. Spanish/Mexican culture is common, such as in the name of where this International Show Caves Association Congress is planned: San Antonio. The city's origin dates to the founding of the Spanish Mission San Antonio de Valero in 1718. Later called the Alamo (Spanish for "Cottonwood"), this was one of five missions in the area around which the city grew. In 1821, San Antonio became part of Mexico when Mexico gained independence from Spain. In 1836, Texas won independence from Mexico and is the only US state to have been an independent country. Texas joined the US in 1845.

San Antonio and other communities in the region, especially along the Balcones Fault Zone, are karst cities in that they were settled just below major karst springs. While most histories focus on the Spanish, Mexican, and Texan/US activities of the region, the area was first settled and home for several thousand years to Native Americans, the most recent of which in San Antonio were the Payaya. Sadly, most Native American pre-history of the region is poorly studied, but some is found in the region's caves. Bement (1994) gives the most detailed account of archaeological deposits in caves of the region, focused on Bering Sinkhole located about 140 km northwest.

Many visitors are surprised by the distinct German heritage in the Texas Hill Country, immediately north of San Antonio. Once again, heritage is reflected in community names. During this and the post-congress trip, we will drive past or near Boerne, Fredericksburg, Luckenbach (made famous in a 1977 song by Waylon Jennings), and New Braunfels. The stone architecture of the older buildings in the region also reflects this heritage. The style has been used for many modern homes and businesses. Jordan (2021) provides an online summary history of the Hill Country, and several books examine the region's history in detail.

We'll follow Interstate Highway 10 northwest from San Antonio and then west from Junction to Fort Stockton over the Edwards Plateau. Note the steady decrease in population, vegetation, and precipitation (76 cm/year in San Antonio to 30-35 cm/year in Carlsbad). As we gain elevation, you'll see a gradual change of valleys to flatlands to buttes and mesas. Ranching is the traditional industry of the region. Once we reach Sonora, oil and gas operations begin to appear. They become dominant when we leave Fort Stockton and head northwest into New Mexico.

The following sections summarize cave geology, other cave and karst-related information, and show cave attractions for the following four regions we'll see during this trip (in east to west order):

- Balcones Fault Zone
- Texas Hill Country
- Edwards Plateau
- Permian Basin

Balcones Fault Zone

The Balcones Fault Zone extends west from San Antonio about 180 km to Brackettville, following US Highway 90, and northeast of San Antonio for 360 km, nearly to Dallas-Fort Worth, following Interstate Highway 35. It is an inactive fault zone formed where the relatively flat-lying rocks of the Edwards Plateau to the north and west slump down into the Gulf of Mexico Basin to the southeast. The Balcones Escarpment is formed by the Balcones Fault Zone. It is rarely seen as a cliff, but is eroded into a usually gentle-to-steep linear rise in topography—steeper where fault displacement is greater. For the purposes of this field guide, the Balcones Fault Zone region is the narrow area between the top of the Balcones Escarpment and highways 90 and 35 below it to the south and east, respectively.

Most cave and karst development occurs south of the latitude of the City of Waco. Faulting has lowered the rocks progressively toward the Gulf of Mexico. As a result, the youngest rocks are at the lowest elevations instead of the highest as normally expected (Figure 13).

The youngest cavernous rock is the Austin Chalk, which was deposited 85-89 million years ago during the Cretaceous Period. It forms the low to flat slopes in front of the Balcones Escarpment. If you visit the Alamo, the rock in the mission walls is Austin Chalk. In the San Antonio area, much of the Austin Chalk is limestone and it underlies most of the southern half of the city's north side. Robber Baron Cave, the only

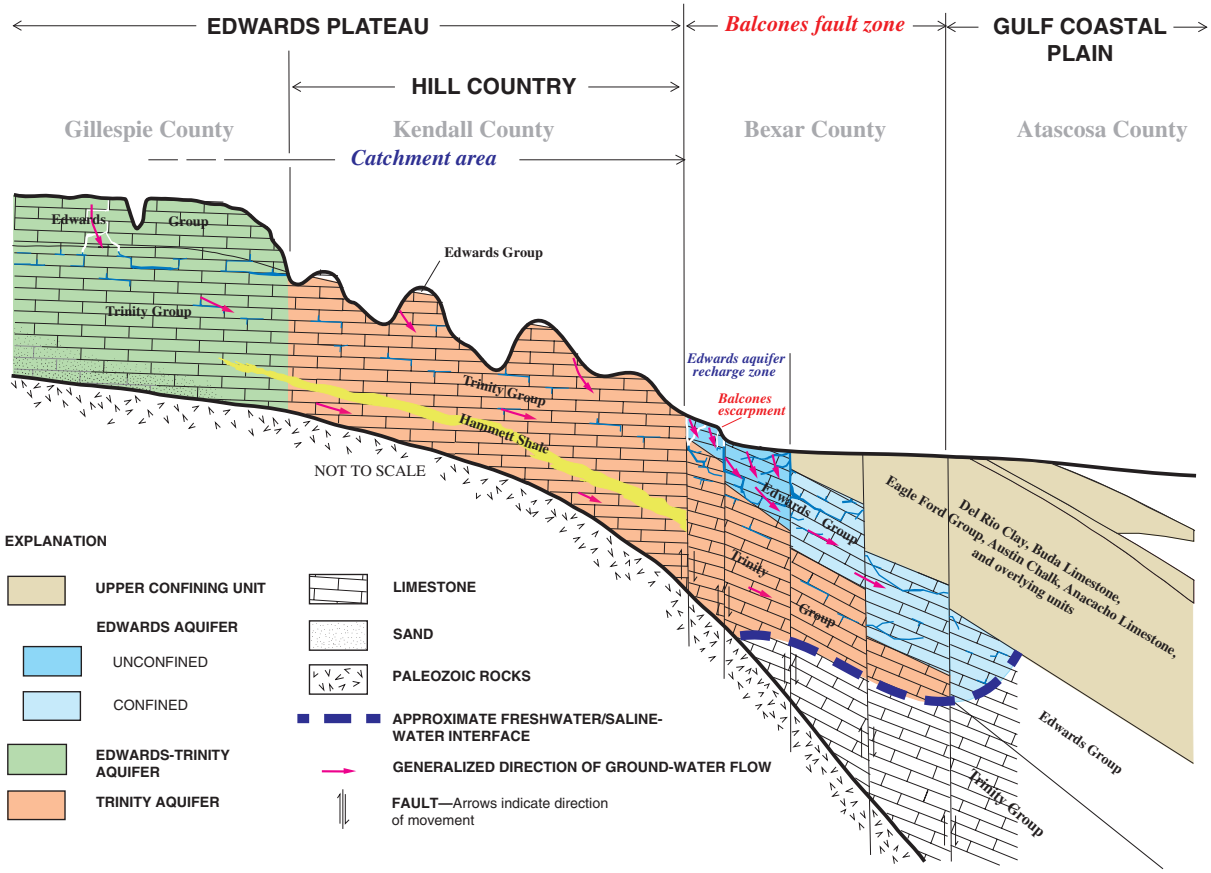

Figure 13. *North-to-south geologic cross section from the Edwards Plateau through the Balcones Fault Zone in Bexar County, where San Antonio is located; from Lindgren et al. (2004).*

show cave to operate in San Antonio (1923-1933), is a hypogenic maze of more than 1.6 km of passages in the Austin Chalk. The cave is owned by the Texas Cave Management Association (TCMA), which runs occasional educational tours through the cave. See TCMA's website for a detailed history of this fascinating cave (Figure 14).

The north half of San Antonio's north side is underlain by the Cretaceous age Edwards Limestone, deposited in a shallow sea 100-105 million year ago. This is the most cavernous rock in Texas and the most widely exposed, covering most of the Edwards Plateau. In San Antonio, it is 150 m thick and forms most of the steeper to vertical slopes in the Balcones Escarpment. Balcones Fault Zone show caves in the Edwards Limestone are Inner Space Cavern in Georgetown and Wonder Cave in San Marcos. Cobb Cavern is a former show cave northwest of Georgetown.

Some researchers assume that caves in this area form along faults. Kastning (1977) discusses how faults can have positive, negative, or neutral effects on groundwater flow and cave development. All three processes are seen in Natural Bridge Caverns (Kastning, 1983), which is on the edge of the fault zone. Veni (1988) found that even in the San Antonio area, the most intensely fractured portion of the fault zone, less than 0.5% of the caves are formed along faults. This low frequency of fault-guided caves is the result of faults being less common than joints, and sometimes formed by compression, which may fill the fault planes with calcite and clay, making them less permeable for groundwater flow and enlargement into caves. Joint control of caves is generally of first importance in the area's development of caves and karst features, with most enlargement occurring parallel to the local direction of Balcones faulting.

While you are in San Antonio, you will be drinking and washing with karst groundwater from the Edwards Aquifer. This aquifer is the primary water supply for the region and arguably the most productive aquifer in Texas. The Edwards Aquifer is a complex hydrologic system within the Edwards Limestone in the Balcones Fault Zone and is divided into four zones: drainage or contributing zone, recharge zone, artesian or confined zone, and saline zone. The drainage zone is the area

uphill of the Edwards Limestone in the Balcones Fault Zone, from which streams flow onto or cross the recharge zone, the exposure of Edwards Limestone within the fault zone where water enters the aquifer. The artesian zone is that area where the Edwards Limestone is down-faulted into the subsurface, and its groundwater is confined between upper and lower less permeable formations. The saline zone is the downgradient low permeability portion of the Edwards Limestone to the southeast, named for its high concentration of total dissolved solids.

The aquifer's largest springs occur where groundwater rises along fractures to discharge in stream valleys. San Antonio grew 3-6 km downstream of the San Antonio and San Pedro Springs. Pumping of the aquifer has lowered the water level so these springs often do not flow. For more information about the Edwards Aquifer, visit the website of the Edwards Aquifer Authority.

Most caves in the Balcones Fault Zone area are pits and/or down-sloping vadose (formed above the water table) passages formed to recharge water into the Edwards Aquifer. Geologically, they are young and thus small. Larger caves in the area are older and roughly horizontal. They are phreatic in origin (formed below the water table), created when the water table was much higher. As the water table dropped, they were abandoned by phreatic groundwater and modified by collapse and vadose water that dissolved domes and shafts in certain places and deposited calcite speleothems in others. The original phreatic morphology of some caves has been almost entirely overprinted by more recent vadose processes.

The Balcones Fault Zone area is one of the world's most biodiverse cavernous regions for terrestrial and aquatic cave-adapted fauna (Culver and Sket, 2000; Culver et al., 2003). Cave organisms are often classified based on their level of adaptation to that environment and range from occasional cave visitors (accidentals) to obligate cave species (troglobites). Troglobites (or stygobites if living in aquatic environments), due to their narrow ranges of tolerance and high endemicity, dominate the lists of taxa of concern and of endangered species.

Seven troglobitic species of karst invertebrates in the Austin region and nine troglobitic species in the San Antonio region are federally listed as endangered by the US Fish and Wildlife Service (USFWS) to insure their survival (USFWS, 1988, 1993, 2000). The listed species are six beetles, three harvestmen, one pseudoscorpion, and six spiders. The reason for this high number of endangered species is that species living in the caves and related voids along the Balcones Fault Zone have become physically isolated from each other through time by streams cutting through the blocks of faulted limestone, resulting in genetic isolation of the populations. This process results in endemism with the new species known only within small geographic areas that are vulnerable to impact by the region's growing urban centers.

Additionally, 13 aquatic karst species in the Balcones Fault Zone are listed federally as endangered and threatened with their ranges extending from New Braunfels to Salado, respectively 40 to 160 km northeast of San Antonio. The species are one amphipod, two beetles, two fish, seven salamanders, and one species of wild rice (USFWS, 2021). While some are aquifer species, most live in the flows of karst springs and commonly recede into groundwater habitat or interstitial spaces during periods of low spring flow.

For an excellent detailed discussion of caves and karst in the Balcones Fault Zone area, see Stafford and Arens (2014).

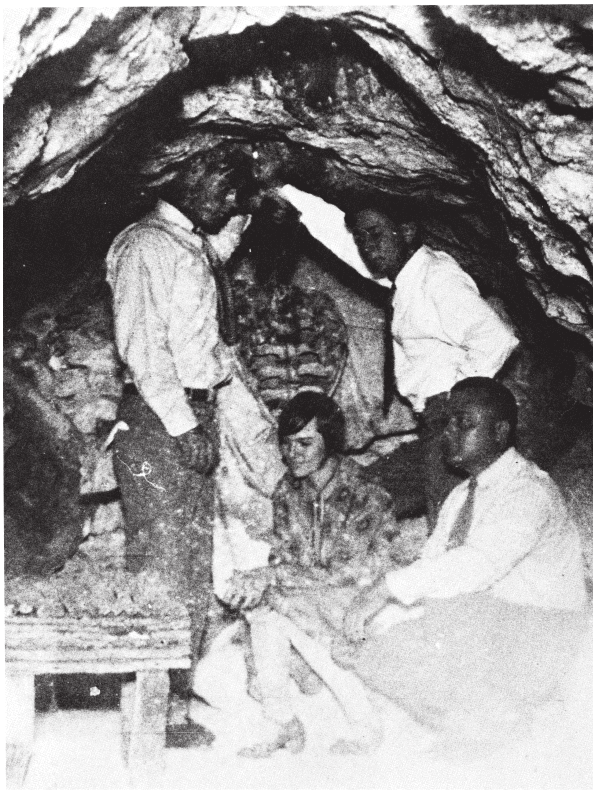

Figure 14. *Tourists in the Devil's Kitchen of Robber Baron Cave (ca. 1930) with a fake skeleton used to enhance the fables that the cave once served as a hideout for outlaws. Photographer unknown. Photo courtesy: Texas Cave Management Association.*

Texas Hill Country

The Texas Hill Country is as much a physical region as a cultural region, as described in the previous section. It is generally defined as the southeastern corner of the Edwards Plateau where it is incised by streams running down to the Gulf Coastal Plain. This stream down-cutting produces the region's namesake rolling to steep hilly topography, which we'll see for about the first 1.5 hours of the trip until we reach the town of Junction, where the Hill Country levels off up onto the Edwards Plateau. The Balcones Escarpment forms the region's southern and southeastern boundaries.

Geologically, most of the region is comprised of the 105-115 million year old Cretaceous Glen Rose Limestone, with 100-105 million year old Cretaceous Edwards Limestone capping hills and ridges. The Glen Rose is divided into lower and upper members. From north San Antonio to Kerrville, we will mostly drive through the upper member, which is locally about 118 m thick and characterized as a fossiliferous sequence of resistant limestones and dolomites alternating with less resistant beds of marl and clay to create a distinctive "stair-step" topography when eroded. Historically, the Upper Glen Rose has been considered hydrologically impermeable and non-cavernous, with many geologists ignoring the fact that most of Natural Bridge Caverns (Texas' largest cave by volume) and other large caves are formed in that unit.

Following extensive geologic study of caves in and around San Antonio, primarily by Zara Environmental and George Veni and Associates (2011) and dye tracing from the Upper Member of the Glen Rose into the Edwards Limestone (Johnson et al., 2010), the uppermost 39 m of the unit are demonstrated as highly cavernous. However, beyond the immediate San Antonio area, this section thins, becomes absent, and the Upper Member of the Glen Rose is poorly to non-cavernous.

During this trip we will only cross the western edge of the lower member of the Glen Rose. It is highly fossiliferous and averages about 70 m thick in this area. It contains two show caves, Cascade Cavern and Cave Without A Name (Figure 15), and one former show cave, Fairy Cave. Many of the longest caves in Texas occur in this area, including Honey Creek Cave, the longest cave in Texas with 33 km of stream passages. Additionally, the Texas Parks and Wildlife Department (TPWD) owns 14 state parks in the Hill Country. Most of the TPWD Hill Country parks contain notable caves and karst. Old Tunnel State Park protects an abandoned railway tunnel that is now occupied by over 3 million Mexican free-tailed bats.

Figure 15. *The Queen's Throne in Cave Without A Name (the guide is on the gravel trail, which is now curbed).*

Groundwater in the Texas Hill Country area is drawn primarily from the Trinity Aquifer, which includes the Glen Rose Limestone and other formations. There is little demand for water from the Upper Member of the Glen Rose Limestone because of its typically low yield and its occasional contact with gypsiferous zones that results in high sulfate concentrations. In contrast, the Lower Glen Rose Aquifer is highly karstified, yields much more groundwater, and contains many of the longest caves and underground streams in Texas. If you join the post-congress field trip, you'll see one of those underground streams in Cave Without a Name.

In 1989, the Middle Trinity Aquifer (which includes the Lower Glen Rose) was listed as a critical water supply area by the state of Texas (Groundwater Protection Unit, 1989). Rapid suburban growth in the region is putting considerable stress on the aquifer's water resources. Mace et al.'s (2000) groundwater modeling of the Trinity Aquifer shows the area may have its groundwater depleted by the year 2050 due to increased demand, and earlier if a drought-of-record is repeated. Additionally, the cavernous outcrop of the Lower Member of the Glen Rose Limestone makes it highly susceptible to contamination. Veni (1997) provides the most detailed hydrogeologic study of the Lower Glen Rose Aquifer to date.

The number of troglobitic species decreases from the Balcones Fault Zone into the Texas Hill Country and beyond due to less fragmented habitat, but the diversity of species types remains high. The only endangered species is the Golden-cheeked warbler (*Dendroica chrysoparia*) which is not truly karst related but breeds in the woody canopy of the Hill Country and adjacent areas. The diversity of karst species results from the area being an ecological crossroads, and past climatic and geological changes in the region. The most notable cave species is the Mexican Free-Tailed Bat (also known as the Brazilian Free-Tailed Bat). It produces the world's largest mammal colonies in several caves in central Texas, including the largest colony at Bracken Cave located near Natural Bridge Caverns.

Edwards Plateau

The Edwards Plateau is one of the largest karst regions in the USA. It is located at the southern end of the Great Plains Physiographic Province and is the most geologically distinct region of the Great Plains. For a general review of the karst of the Great Plains, see Veni (2009). The Edwards Plateau is located in central and west-central Texas, extending west from the Balcones Escarpment in the San Antonio-Austin area for roughly 500 km and north for 250 km from the escarpment's southern boundary west of San Antonio. It includes the Texas Hill Country region, which for this field guide is described above separately. Its western and northern margins are irregular, occurring where the Edwards and associated carbonate rocks pinch out or are eroded away. Kastning (1983) provides an extensive geologic analysis of the Edwards Plateau karst.

Broad, gently rolling uplands of carbonate rocks (limestone, dolomite, and marl [clay-rich limestone]) characterize much of the Edwards Plateau. The nearly flat-lying rocks dip gently to the south and southeast. Few faults are present except near the Balcones Fault Zone and in the Carta Valley Fault Zone, located about 85 km south of the town of Sonora. Much of the plateau's surface is bare limestone or limestone covered with thin to patchy soils.

On the basis of stratigraphy and hydrology, and their observed effects on cave development, Smith and Veni (1994) divide the plateau into seven subregions. The Llano Uplift (which includes Longhorn Cavern that will be visited during the post-congress field trip) is often included in discussions of the Edwards Plateau due to its proximity (e.g. Kastning, 1983), being surrounded by the plateau to the east, west, and south, but it is a geologically distinct area.

West of Kerrville, we will start climbing from the Texas Hill Country onto the Edwards Plateau. The Edwards Limestone appears again but it slowly changes with distance, as many rocks do. Throughout much of the field trip region, the limestone is divided into upper and lower units, but their names change as the characteristics of the rock change. For most of the distance we'll travel on the Edwards Plateau, those units are the Segovia and Fort Terrett formations. The Segovia is the upper and most exposed unit. Caverns of Sonora is formed in the Segovia, as are the Devil's Sinkhole (Figure 16) and Kickapoo Cavern, less visited but spectacular Texas state parks.

Figure 16. *Visitors look into the depths of the Devil's Sinkhole. This 42-m deep shaft opens into Texas' largest chamber, measuring 134 m long by 85 m wide, which is home to a colony of 3 million Mexican Free-tailed bats.*

Three types of caves predominantly form in the Edwards Plateau: stream, phreatic, and hypogenic. Stream caves occur along the margins of the plateau, where groundwater is concentrated and drains from the base of the Edwards Limestone. The Powell's Cave System is the second longest cave in Texas at over 26 km long, with 6.2 km in a stream passage and the rest in an upper level maze. Phreatic caves formed during phreatic conditions, when the water table in the aquifer was much higher. They tend to form large passages and single large rooms, such as the Devil's Sinkhole, the largest cave room in Texas at 134 m long by 85 m wide. Their entrances are usually formed by collapse into those passages and rooms. Hypogenic caves are a type of phreatic cave but formed by rising water. These caves are often mazes (Figure 17 shows the most extreme example) and are mostly found in the western half of the Edwards Plateau. Veni (2018) describes cave development in the Edwards Plateau, with an emphasis on the region's hypogenic caves.

The portion of the Edwards Plateau west of the Pecos River is the Stockton Plateau. One of the richest displays of Native American rock art in the US can be observed in the Trans-Pecos region of the Stockton Plateau and southwestern Edwards Plateau (the region near the confluence of the Rio Grande and Pecos River). Most occur in limestone rock shelters or cave entrances. The art displays five styles, of which the Pecos River Style is not only the oldest (3100–4100 BP) but is also the most colorful and dramatic (Figure 18). Use of caves in the region for shelter and mortuary practices dates from 12,100 to 14,500 years BP. See Turpin (1994) for a review of cave archeology in the area, and Boyd (2003) for a review of the rock art.

The deepest caves in Texas (Sorcerer's Cave is the deepest at 174 m) also occur in the Stockton Plateau, as well as the state's largest and oldest karst features. Freeman (1968) mapped 175 subsidence sinkholes within 24 km of the Rio Grande. About a third are

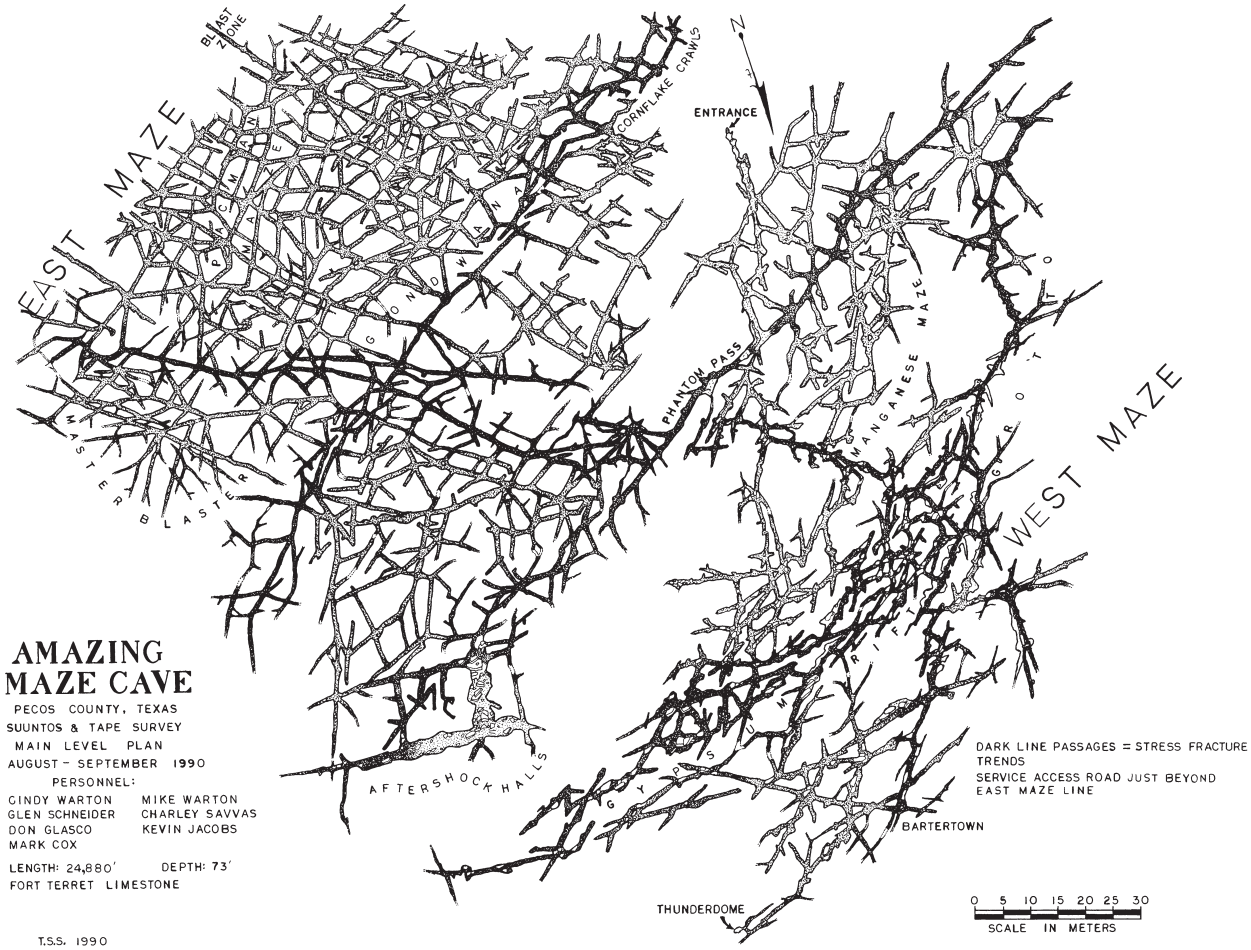

Figure 17. *Map of Amazing Maze Cave (from Elliott and Veni, 1994).*

Figure 18. *Pecos River Style rock art, estimated as about 4,000 years old, in Curly Tail Panther Shelter. The panther is approximately 2 m high and wide.*

roughly circular, averaging 100-200 m in diameter; the other two-thirds are linear, averaging 100–200 m wide and up to 2–3 km long. These sinkholes are as old as Oligocene or Miocene (roughly 30-20 million years), formed when groundwater dissolved conduits down the hydraulic gradient from the ancestral Rio Conchos (predecessor to the Rio Grande) to the Pecos River. The conduits grew until they collapsed. Continued dissolution removed much of the collapse material, allowing further subsidence upward as much as 90 m, often into overlying non-cavernous strata (Veni, 1994). Since the Miocene, surface erosion has removed all topographic expression of the sinkholes, which Freeman (1968) mapped as collapsed strata surrounded by undeformed rock. West of Ozona, many sediment-filled cave passages up to about 20 m wide are exposed in highway roadcuts. Their origin is unstudied but given their high elevation above the modern water table, they may have formed at the same time. Their orientation perpendicular to the east-west trending interstate highway suggests they have a generally north-south drainage pattern. See Stafford (2018a) for a study of the hypogenic caves of the Stockton Plateau.

At the northwest end of the Edwards/Stockton Plateau, the Segovia and Fort Terrett formations become the Fredericksburg and Washita. Like the Segovia, the Fredericksburg is a hard, dense limestone. However, the Washita is softer, richer in clay, and poorer in caves. The contact between the two is clearly visible along the highway in buttes and mesas—flat-topped hills with cliffs formed in the Fredericksburg that stand above the slopes of the softer Washita.

The Edwards-Trinity (Plateau) Aquifer is one of the more areally extensive karst aquifers in the country. It is an unconfined aquifer that extends across the Edwards Plateau. The aquifer is capped by Edwards Limestone, where the water discharges from springs along its basal contact with the Glen Rose Limestone, part of the Trinity Group of rocks. This spring flow supports the flow of several streams that cross the Hill Country. Although the aquifer is named for the two rock groups that store and produce water, most water in the region is drawn from the Edwards Limestone which is shallower and usually has a higher yield.

Some of the largest springs in Texas occur at the west end of the Edwards Plateau. We will visit the Comanche Springs in Fort Stockton, which went dry in 1961 due to high levels of groundwater pumping for agricultural use. About 87 km to the west around the village of Balmorhea, the San Solomon Spring Group continues to flow but at slowly decreasing volumes. Its highest elevation spring ceased flowing in 1999, although the reasons for the declining water levels in the San Solomon area are less clear than at Comanche. The largest spring of the group, namesake San Solomon Spring, is used as a giant swimming pool. In contrast, a large, constructed swimming pool replaced the natural Comanche Springs pool and functions as the recreational and social center of Fort Stockton. Veni (2013) reviews the hydrogeology of the San Solomon Spring Group and contrasts its use with Comanche Springs for conceptual development of ecologically and economically effective models of groundwater management.

Permian Basin

The Permian Basin underlies most of the western half of the Edwards Plateau. It extends almost from the border with Mexico north about 450 km nearly to the City of Lubbock, and from the City of Sonora 370 km west to the area of El Capitan, the peak at the southern tip of the Guadalupe Mountains. It is not a topographic basin but a tectonic one. As continents pushed against each other about 300 million years ago, this section of the Earth's crust was bent downward and filled with sediments. The most notable were deposited during its namesake Permian Period, which occurred 251 to 266 million years ago, and compressed and cemented into a variety of rocks. Within these rocks are the largest deposits of oil and natural gas in the US. Some of the richest oil deposits have accumulated in paleokarst, ancient and deeply buried karst.

The Permian Basin is not one uniform depression in the Earth's crust but is comprised of three sub-basins: Delaware, Midland, and Val Verde. For the purposes of this trip, we'll focus only on the Delaware, which is the westernmost basin and extends from about 30 km south of Fort Stockton northward 270 km to about 30 km north of Hobbs, New Mexico, and 180 km west from Fort Stockton to the El Capitan area.

Turning northwest onto US Highway 285 from Fort Stockton, we'll drive off the Edwards Plateau, and its limestone and Cretaceous age rocks, and onto extensive flat plains of alluvium. This alluvium is the uppermost and youngest deposit of an up to 6.7-km deep sequence of sediments in the Delaware Basin. The plains end as we cross into New Mexico and onto the Permian age Rustler Formation. This formation ranges from 76-204 m thick. It is comprised mostly of siltstone, sandstone, and dolomite but includes some gypsum which forms sinkholes and small caves. Prior to the highway renovation you'll see during this trip, the opening of sinkholes next to the highway (Figure 19) prompted the New Mexico Department of Transportation to contract NCKRI to conduct a geologic and geophysical investigation of the Rustler from the state line to where it ends near the town of Loving, so the highway can be reconstructed to avoid sinkhole damage (Land et al. 2018). Small sand dunes occasionally cover the Rustler. From Loving into Carlsbad, we will again be driving on alluvium.

When we leave the City of Carlsbad and drive southwest on US Highway 62/180 to Carlsbad Caverns National Park, we will see the most important rocks in the region in terms of caves and karst. The Guadalupe Mountains parallel the highway to the west and slowly rise to the southwest into Texas where they reach their highest elevation at Guadalupe Peak at 2,667 m above mean sea level. The mountains formed at the edge of the sea that once filled the Delaware Basin. Their southeast side was a massive reef, similar to today's Great Barrier Reef along Australia's eastern coast, and became the Capitan Limestone. Other limestones and rocks were deposited landward, to the northwest, but for this field guide we'll focus on the Capitan since it is the rock in which most of Carlsbad Cavern and other prominent caves have formed.

Figure 19. *The opening of this sinkhole along US Highway 285 prompted NCKRI's study to evaluate the potential for more sinkholes before the highway was renovated.*

East of US Highway 62/180, is a nearly flat to gently rolling plain comprised of two evaporite units: the Castile and Salado formations. Evaporites typically form in arid regions where a body of water is separated or nearly separated from the sea and less water flows in than evaporates. As a result, higher than normal salinity of the water leads to precipitation of minerals that form highly soluble rocks like gypsum and halite (rock salt). Some early geologists surmised that the limestone escarpment leading up to Carlsbad Cavern formed by faulting. Instead, it formed by the rapid (relative to the limestone) dissolution of the evaporites, which filled the ancient sea in front of the Capitan Reef.

The Castile Formation is up to 480 m thick and comprised mostly of gypsum. Land on the Castile is sparsely used for agriculture and serves primarily as the base to drill through to find oil and gas. Above it, the halite Salado Formation, named from the Spanish "sal" for salt, thickens eastward like the Castile, and reaches a thickness of 700 m, but has more diverse economic use.

The Salado holds the country's only permanent repository for transuranic (a type of intermediate level radioactive) waste 650 m underground at the Waste Isolation Pilot Plant (Figure 20), located about 53 km southeast of the City of Carlsbad. It is also mined for two products. First, the Salado holds one of North America's largest deposits of potash (a salt, usually potassium chloride, used in fertilizers and other products). Second, solution mining of the Salado extracts brine by drilling wells into the salt, injecting freshwater down the wells to dissolve the salt, and pumping up the resulting brine. Oil and gas companies use the brine to more effectively drill through the salt into underlying petroleum deposits. This solution mining process can create enormous salt cavities, three of which collapsed in the region in 2008 and 2009. In 2022, the State of New Mexico finished filling a fourth cavity within the City of Carlsbad that otherwise would certainly have collapsed. NCKRI conducted one of the first geophysical studies of the cavity, which is described in NCKRI Report of Investigation 2.

Cave and karst development in this area is diverse. Most caves in the Guadalupe Mountains, and certainly the largest, are hypogenic. Groundwater rich in hydrogen sulfide migrated west and up from the Delaware Basin. When it reached the water table where more oxygen was available, the hydrogen sulfide mixed with the fresh water to form sulfuric acid—a much stronger acid than the carbonic acid that creates most caves. As the sulfuric acid dissolved the limestone, gypsum was created as a byproduct and deposited in the newly formed caves. The oldest known sulfuric acid caves in the Guadalupe Mountains formed along the water table 11 to 12 million years ago. Since then, the water table in the Capitan Limestone has steadily lowered, and in doing so created new caves at lower elevations. The Big Room in Carlsbad Cavern formed roughly 4 million years ago. The elevation of the water table in the Capitan Limestone is currently at the level of the Pecos River in the City of Carlsbad where it flows from springs into the river. If caves are currently forming from sulfuric acid, it is happening east of the Pecos, unseen and deeper underground. See DuChene et al. (2017) for the most current description of cave development in the Guadalupe Mountains.

Figure 20. *Stacks of transuranic waste permanently deposited in a carved salt tunnel of the Waste Isolation Pilot Plant.*

As dry as the climate around Carlsbad may seem, it is too wet to develop caves and karst features in the salt of the Salado Formation, which crumbles on the surface to a clay-like soil. In contrast, many extensive and well-developed caves are formed in the gypsum of the Castile Formation. The longest is Parks Ranch Cave, the second longest gypsum cave in the US with 6.6 km of passages (Figure 21).

Stafford (2018b) describes multiple cave and karst forming processes in the Castile Formation. Like most caves in the adjacent Capitan Limestone, most Castile caves are hypogenic. Unlike the Capitan caves, there is no evidence of sulfuric acid development since gypsum can dissolve in pure water with no acid involved. Additionally, many of the Castile hypogenic caves are modified by epigenic processes, where modern water flows down into them, altering their shapes and features from those that formed by hypogene, upward flowing water. Caves that formed entirely by epigenic water are usually small, in part because they are young features but primarily because the inflowing surface water becomes saturated with gypsum and can't dissolve additional rock. Parks Ranch Cave is a notable exception.

Breccia pipes are less known but important karst features in the Castile. They form hypogenically by water rising along a fracture, dissolving open a cavity, followed by a partial collapse of the roof. This allows dissolution of the roof and further collapse, leading to more upward dissolution, more collapse, more dissolution, etc. These pipe-like structures range from a few meters to about 100 m in diameter and can rise hundreds of meters through the rock. Their breakdown

Figure 21. *Flood-dissolved scallops cover many of the walls and floor of Parks Ranch Cave, formed in the Castile Gypsum.*

is later cemented together. When the land surface erodes down to intersect these breccia pipes, the uncollapsed gypsum of the Castile Formation erodes more rapidly than the cemented gypsum breakdown causing the breccia pipes to stand as low mounds to abrupt 30-m high hills above the surrounding landscape. These hills are known locally as "castiles" and provide the name for the gypsum formation. Unfortunately, none are visible from our trip route. Stafford (2018b) also describes a related brecciation process where halite is dissolved between slightly dipping beds of gypsum.

While there isn't enough time during this trip to see the Castile Formation karst from more than the bus window, we will stop at a less common karst type: conglomerate. A conglomerate is a deposit of at least partially rounded stream-deposited cobbles and gravels. Where they are cemented together, they form a rock, and where the rock is sufficiently soluble, it can form a conglomerate karst. Limestone conglomerates form where a steep stream cuts through limestone hills and flows onto a flat or low relief plain. Losing its steep gradient, the stream lacks the energy to push or carry its limestone cobbles or gravel further and deposits them on the plain, thickest where the stream first reaches the plain and thinning outward.

Conglomerate karst occurs in small patches around the world. Italy's Montello Hill is referred to as the "classical karst" of conglomerate rocks (Ferrarese and Sauro, 2005) but most conglomerate karsts are poorly studied. One conglomerate karst that is beginning to see some research is at Carlsbad Caverns National Park where Slaughter Canyon (and smaller canyons to a lesser degree) spills onto the evaporite plain and deposits cobbles of Capitan and associated limestones. The rocks are well cemented and solutionally enlarged conduits have formed, but no caves are known. No formal name has been applied to this unit beyond its basic geologic description: Quaternary gravel. The Quaternary Period extends from 2 million years ago to the present. We will see this conglomerate rock on the way to Rattlesnake Spring (Figure 22).

The Quaternary gravel serves as a locally important karst aquifer, providing water to several wells for agriculture and to springs that sustain the flow of the Black River, a tributary to the Pecos River. Its water is an important contribution into the Pecos to meet New Mexico's obligations for sharing surface water with the downstream State of Texas. The Black River also provides the only habitat in New Mexico for the Texas hornshell mussel, *Popenaias popeii*, which the US Fish and Wildlife Service lists as an endangered species (USFWS, 2018). Hale (1955) characterizes groundwater in the Quaternary gravel as moving through large pores and conduits based on aquifer tests and water table mapping. He reports wells yielding up to 4,900 L/minute.

Figure 22. *Limestone cobbles and gravel eroded from the Guadalupe Mountains are cemented to form a conglomerate rock in which a karst aquifer has formed.*

Two significantly larger karst aquifers occur in the area: the Castile and Capitan aquifers. The Castile Aquifer is poorly studied. Its water is very hard and has high sulfate concentrations, making it non-potable for humans and of limited agricultural use. In contrast, water in the Capitan Aquifer is fresh and of excellent drinking quality. It is recharged, stored, and transmitted through the Capitan Limestone in the Guadalupe Mountains. Dye tracing by Goodbar (2009) shows that some water in the Castile flows into the Capitan, and vice versa. Capitan Aquifer groundwater levels are over 100 m lower than the conglomerate aquifer near Carlsbad Cavern and drain northeast, as the Capitan Limestone dips in that direction, to discharge from springs along the Pecos River in the City of Carlsbad (Figure 23). These springs are the reason the City of Carlsbad is located where it is, and why it has a thriving water-based economic sector. Despite the City of Carlsbad being the only significant user of water from the Capitan Aquifer, which is also the city's primary water source, much more research is needed to understand this groundwater system. It is described based on too few wells and only general geologic mapping. New Mexico is a large state but has a small population and thus fewer funds than more populated states to study aquifers and other natural resources.

Summary

The show caves of west Texas and southeast New Mexico are some of the most renowned in the US and include one of the largest and one of the most famous karst areas in the country. Caverns of Sonora and Carlsbad Cavern are the highpoints of the trip, yet they occur amid areas of diverse and ancient to modern cave and karst development. Both caves are well developed for tourism and provide opportunities for the public to learn about their magnificent underground wonders.

Beyond these two caves, the region offers the public many options to learn about and enjoy caves and karst. Wild cave tours are available. Karst springs create historic and modern focal points for communities. However, drying of the climate in this region, and the southwest US as a whole, will adversely impact the region's water resources. Thoughtful and long-term adaptive strategies will be required to preserve the economic viability of the region's communities.

Figure 23. *Carlsbad Spring is located in a park at the north end of the City of Carlsbad. It is actually one of a group of springs that restore the flow of the Pecos River (the others and largest are submerged and generally unseen) and are the life-source for the city's existence and much of its economy.*

Field Trip Stops

Stop 1. Caverns of Sonora

Caverns of Sonora is internationally recognized as one of the world's most beautiful show caves and is registered as a National Natural Landmark. The first known entry of Mayfield Cave, as it was initially called based on the family name, was in 1905. For the next 50 years it was known essentially as a passage that led 40 m off the body-sized entrance to a fork. After about 80 m, each passage rejoined in a 25-m long by 20-m wide by 15-m high room called the Devil's Pit. Several small passages extended off these, but none were considered noteworthy and the cave was often described as "undecorated" because it had few stalactites and stalagmites as seen in many caves.

One of the passages to the Devil's Pit reached it at ceiling level. A steep ledge extended high above the rocky floor along a wall, and it looked like a passage might continue on its far side. In September 1955, a small group braved "The Ledge" and discovered one of the most densely decorated caves in the world.

An immediately recognized challenge was the need to protect the cave. For several years it was only referred to as Secret Cave. Despite secrecy, increasing visitation resulted in both cumulative damage through exploration and visitation, and destruction through accidents. One of the cavers visiting Secret Cave was Jack Burch. He concluded and convinced the owners that the best way to protect the cave was through "conservation by commercialization," where it could be properly gated and monitored, while satisfying public curiosity for access.

Some people felt the cave could not be developed for tourism without significant destruction of its profuse speleothems (Figure 24). However, Jack's innate skills and talents as a caver allowed him to see where and how to weave paths and bridges, and to do so with the utmost care to make the cave accessible with little adverse impact. He revolutionized show cave development through his work on what would open to the public as Caverns of Sonora. He wanted to share his caving experience of the natural appearance and beauty of caves with the public, which meant light bulbs, wires, and other infrastructure had to be carefully and often cleverly hidden. In later years, he refined his techniques in developing other show caves, using tools and funds not available to him in the early years at Caverns of Sonora.

On Saturday, 16 July 1960, the cave opened to the public. The trail led to the Devil's Pit, beyond the

Figure 24. *The Valley of Ice was one of the first highly decorated passages in Caverns of Sonora traversed by a trail and lighting for tourists.*

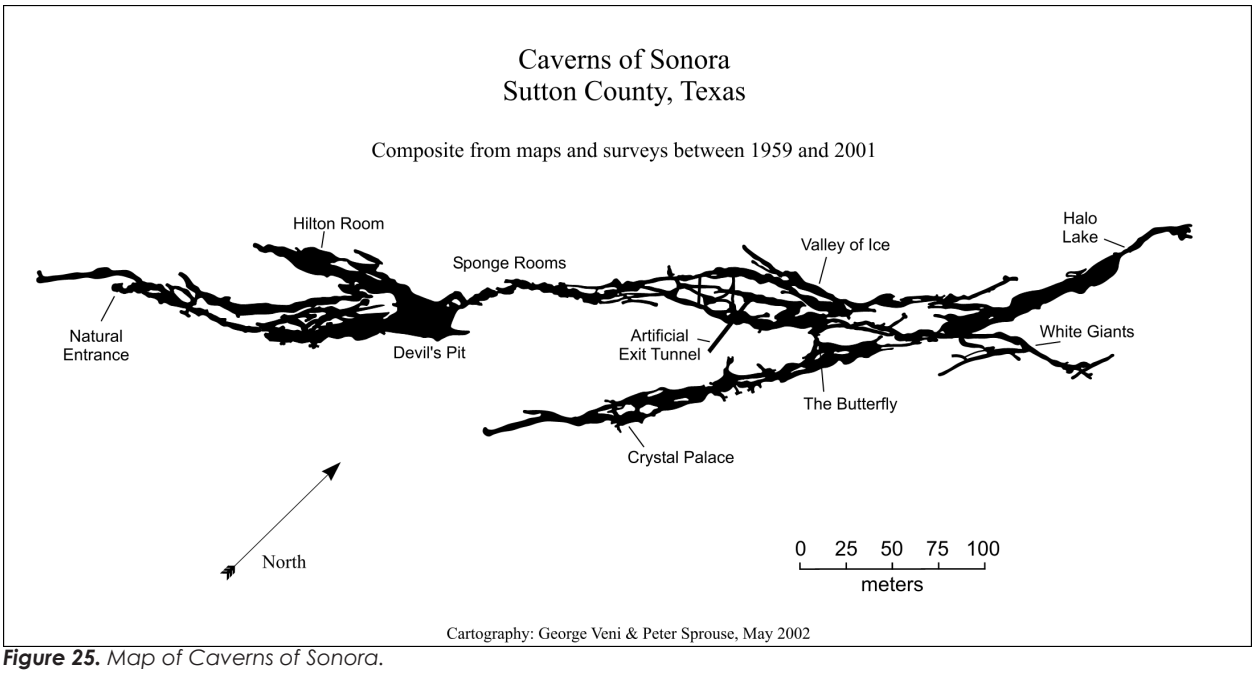

Figure 25. *Map of Caverns of Sonora.*

infamous ledge, through the Sponge Rooms, Narrows, the modestly named "First Pretty Part," and the War Club Room to the Palace of the Angels, and then out by the same path. Jack soon realized that a back entrance was needed to show more of the cave and so the tours would not need to backtrack. In some of the cave's narrow passages, two-way traffic with groups passing each other isn't possible without damaging the cave. By 1962, the cave's trails opened access to the Valley of Ice, Corinthian Room, Crystal Palace, and ended at the landmark Butterfly before leaving via the newly built Exit Tunnel. In 1979, Jack made a final addition to the tours by extending trails to the cave's north end to see the Christmas Tree Room, Horseshoe Lake, Hall of the White Giants, Halo Lake, and the Lower and Little Lower Rooms, culminating in about 900 m of total trails through the cave.

Caverns of Sonora is only partially surveyed to a length of 2.2 km and a depth of 37 m (Figure 25). Jack Burch estimated its full length at 9-10 km. The cave is arranged as a maze of stacked parallel to near parallel passages, nearly as interconnected vertically as horizontally. Four major passage levels are known. There is generally little breakdown in the cave, except where passages of different levels intersect. Most of the passages are highly decorated, with a density and variety of calcite speleothems seldom seen, especially helictites, and which make Caverns of Sonora internationally famous. The "undecorated" walls of the cave's historic part are actually covered in complex crusts and coatings that need study and may give important insights on the cave's origin (Figure 26).

Immediately upon entering Caverns of Sonora, it is clearly not a typical cave. Klimchouk (2007) was first to propose a hypogenic origin for the cave based on the presence of passage shapes and features common in hypogenic caves that included cupolas and its maze pattern. He also pointed to the absence of scallops and other epigenic features. Additional evidence subsequently noted includes the absence of organic material in the cave's sediment (except for passages in the immediate vicinity of the entrance), which appears formed from the insoluble fraction of the limestone that remained from the dissolution of the cave.

Condensation-corrosion patterns on the cave's speleothems, walls, and ceilings demonstrate a pattern of closed-system convective airflow where air deeper in the cave is warmed slightly by the geothermal gradient causing it to rise, cool in the upper levels, where it then sinks to the bottom of the cave for the process to repeat. This pattern is commonly seen in hypogenic caves with recently developed entrances but rarer in epigenic caves. Carbon-14 dating of bone-rich organic soil washed in from the cave's entrance indicates the entrance developed about 3,000 years BP (Rickard Toomey, unpublished analyses, 1993).

The most compelling evidence for Sonora's hypogenic origin revolves around the fault that extends through the eastern half of the cave. Onac et al. (2001) suggest the cave may be hypogenic based on the occurrence of gypsum and uncommon minerals, especially metatyuyamunite, found in the cave's lowest level along the fault. This was the second reported cave

Figure 26. *The Sponge Rooms seem undecorated passages to many but are covered in fascinatingly complex crusts that will likely give greater insights to the origin of Caverns of Sonora.*

occurrence of metatyuyamunite, the first occurring by hypogenic processes in Spider Cave, Carlsbad Caverns National Park, New Mexico (Polyak and Mosch, 1995), indicating a possible hypogenic origin for Sonora. However, Onac et al. (2001) note other, though less probable potential causes for the metatyuyamunite, and lacking a clear source for the uncommon mineral decline to propose the cave as hypogenic.

Building on newer observations and developing a model for hypogene cave development in the Edwards Plateau, Veni (2018) describes the cave as hypogenic. Using landscape erosion rates to estimate when groundwater circulation was first possible to begin creating the cave, he estimates that age as 13.8 million years. Continuing the modeled erosional pattern, the lowest known level of the cave would have formed 8.8 million years ago. The two available speleothem dates from the cave of 139,833 years (+5,285 years or -5,054 years) and 293,334 years (+35,812 or -26,927 years) easily fall within that time the cave would have existed for those speleothems to form. Veni also identifies the Late Pennsylvanian to Early Permian Canyon Sandstones 1.8 km below the surface as a possible source of sulfate and rare elements to account for the cave's gypsum and uncommon minerals. He further notes the 2.1-km deep Lower Ordovician Ellenburger Group, a major paleokarstic oil reservoir, as another potential source for these minerals.

The hypogenic origin of Caverns of Sonora seems clear based on morphologic and sedimentary evidence. But the origin of some elements from the deep hydrocarbons in the area remains to be proven by analysis. Jones et al. (2021) attempted to prove this hypothesis by isotopic analysis of the cave's gypsum (Figure 27), expecting the sulfur to be isotopically light as at Carlsbad Cavern and other caves with such origins. However, the results were isotopically "medium," neither light nor heavy. What this means is unclear. Sulfate samples from both above and below the cave are now being collected for analysis and comparison to the gypsum results to help unravel the mysteries of this amazing cave's origins.

Figure 27. *The complicated relationship of gypsum (tent-like speleothem in the middle of the photo) to calcite speleothems is under study in Caverns of Sonora.*

Stop 2. Carlsbad Caverns National Park: Carlsbad Cavern; all Stop 2 sections written by Rodney Horrocks.

Carlsbad Cave National Monument was first established in October of 1923 when Calvin Coolidge signed a Presidential Proclamation that included 2.9 km^2 of land around the Natural Entrance. In 1930, Congressman Cramton asked the National Park Service (NPS) for a bill to change the Monument to a National Park. NPS Director, Arno B. Cammerer, argued that the name shouldn't be "Carlsbad Cave National Park" but "Carlsbad Caverns National Park," which implied a grander cave. Recognizing the cavern as a world-class treasure led to this site to become the birthplace of cave management in the US in 1972, and recognition as a World Heritage Site in 1995.

As you enter the park, the Carlsbad Caverns National Park entrance sign is a popular photo spot for visitors. The limestone ridges on both sides of the road are the famous Capitan Limestone. This limestone formed as part of a reef deposit that runs around the edges of the Permian Basin, an inland sea that existed in this basin 260-270 million years ago. However, to be technical, this wasn't a reef, especially not like the coral reefs we have today. It was composed of muddy mounds with lots of algae, sponges, brachiopods, and bryozoan animals mixed in with the sediment. You can see many of these animals preserved as fossils in nearby rocks. You will ride up to the cavern along Walnut Canyon.

Walnut Canyon didn't always look like it does today. 14,000 years ago, near the end of the last Ice Age, this area was covered by grasses and pine trees. The animals that lived here during that time were not the same as the ones found today. Mammoths, mastodons, ground sloths, saber tooth tigers, American lions, camels, and horses were all found in this area. Today, their bones can be found in the many caves found in the park. There are 122 caves that have been documented to date in the park and fossil bones have been found in 29 of them so far. About 7,500 years ago, desertification started in this area and by 4,500 years ago became the Chihuahuan Desert you see today.

Even today, there are many unusual animals that live in this desert, which include desert centipedes, ringtail cats, and javelinas. The desert centipedes look like something out of *Jurassic Park* and they love to run up your pants and will subsequently bite your leg. The ringtail cats (though called this, they are not cats) are nocturnal, so you're not likely to see them. If you are lucky, you may spot the small pig-like javelinas. You may also see what superficially appear to be small brown bighorn sheep. These are actually exotic African sheep introduced to private ranches in the Guadalupe Mountains in the 1950's. Called Barbary Sheep, they have now spread throughout the desert southwest. Although the park considers them an exotic, the State of New Mexico considers them a game animal.

Looking out from the Visitor Center on top of the Guadalupe Mountains Escarpment, you'll see the Delaware Basin, which contains one of the richest oil deposits in the US. It is estimated that there is as much oil in this basin as there is in Saudi Arabia. Recent technological advances, like fracking and horizontal drilling, have made it possible to access more of this oil than ever before, which has resulted in recent oil booms in the area. The City of Carlsbad recently swelled from 28,000 people to an estimated 100,000 during the oil boom of the 2010s. In front of you are thousands of pump jacks. You can't see them from this vantage point. But if you came to this same point at night, the lights and flares from these operations light up the basin, making it look like a megalopolis. Visitors attending the Bat Flight, when bats emerge from the cave in the evening to feed, often point at these lights and ask what city they are looking at. The Park has been working with the Bureau of Land Management to prevent any drilling near the boundaries of the park. We hope to work with oil and gas operators who have lights visible from the Visitor Center, to install night sky compliant lights on their equipment. In 1986, the Lechuguilla Cave Protection Zone was established north of the park to protect that world class cave from oil and gas drilling.

The Park recently celebrated the Lechuguilla Cave survey reaching the 150-mile (241.5-km) mark. Located in the ridge to the north of Walnut Canyon, there is almost no chance that Lechuguilla Cave will be connected to Carlsbad Cavern, which is located in the ridge to the south of Walnut Canyon. Currently, exploration and research in Lechuguilla Cave has been suspended during the COVID-19 pandemic.

The Visitor Center has a theater, bookstore, cafeteria, and a gift shop. The Gift Shop is operated by a concessionaire, Carlsbad Caverns Trading Company, and the Book Store is operated by Western National Parks Association. The Visitor Center surrounds an elevator shaft that was built in 1931. It can be used to access the Underground Lunchroom and the Big Room. However, the majority of visitors walk in the Natural Entrance, descending 229 m to the Big Room, and then exit the cavern by the elevator, a total of a

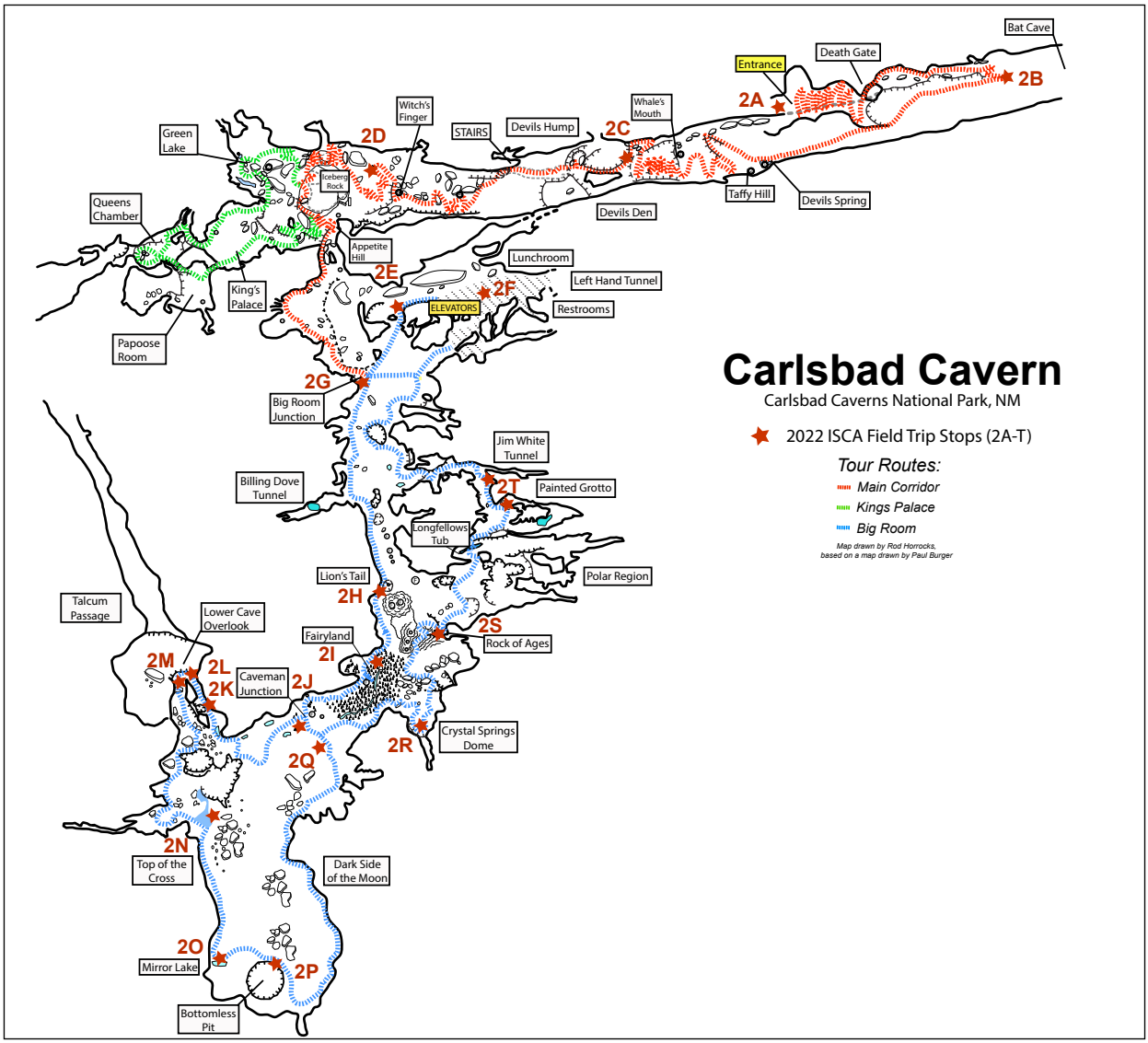

Figure 28. *Partial map of Carlsbad Cavern with the tour routes and numbered trip stops.*

5.6-km long cave trail. Although, most guided tours have been suspended due to COVID-19, we have recently restarted the Kings Palace Tour.

Carlsbad Cavern has been known since the 1860s-1870s and was originally called Bat Cave. The first recorded exploration beyond the twilight zone was by16-year old local ranch hand, Jim White, in 1898. Dr. Willis T. Lee, in his article in the January 1924 issue of the National Geographic Magazine, referred to the cave as "Carlsbad Cavern," which was apparently the first time the cave was referred to by that name in print. He stated that "cavern" distinguished the cave from "any other old hole in the ground." Indeed, Carlsbad Cavern is one of the great show caves of the world. The locations of the following Carlsbad Cavern stops are shown above in Figure 28.

Stop 2a. Carlsbad Cavern: Natural Entrance

The natural sinkhole surrounding the cave's entrance was converted into an amphitheater of stone benches for educational programs, and especially to watch the bats fly out for the cave in the evenings.

You can see a ring midden near the top of the Amphitheater. These stone rings are where the leaves of the Mescal plant were roasted by Native Americans. Indeed, this plant was the major portion of the Mescalero Apache diet. It was probably a major dietary component of the Basket Makers, Archaic, and Paleoindians that proceeded them as well. Other evidence of Native American awareness of the cavern are red and black pictographs in the Natural Entrance area. All caves are sacred to the Apache people as their creation stories say they came from underground.

The pictographs at the entrance of the cavern told the Apache that this was a sacred place. These pictographs were meant to speak only to the Apache people. An Apache legend states that a Medicine Man who wanted to make big medicine had gone into the cave. The next time he was seen he was walking out of the cave playing a drum; however, he was never seen again after that. Every year on the anniversary of his disappearance, the Apache would return to the entrance and leave food for him. In fact, after the cave was made a National Monument, Apache occasionally asked park personnel if they had heard drums in the cave on the anniversary of the Medicine Man's disappearance.

The Natural Entrance (Figure 29) is in a backreef deposit known as the Yates Formation. The entrance is hypothesized to be a former spring where upwelling water emerged when the cave was first being dissolved 4-6 million years ago. On the right-hand side of the trail, you can see a "Tepee Structure" in the rocks; an unusual feature thought to have formed due to gypsum crystal growth and evaporation of shallow sea water in a backwater lagoon 260-270 million years ago.

In January of 1925, the volunteer custodian of the Monument, William Frank McIlvain, decided to build a temporary stairway into the Natural Entrance. He swung a deal with the Carlsbad Chamber of Commerce to donate $1,500 to build a flight of wooden stairs, which made the cavern accessible to the masses. Up to that point, visitors were lowered two at a time in a guano bucket down a 55-m deep pit into Bat Cave. At first, they were going to place the stairs along the old guano bucket route, however, they realized that such an expanse would frighten some tourists. After they cleared the rock ledges of loose rocks, they started at the bottom of the entrance and built 216 steps upward to a platform. The bottom section rose 27 m and connected to the lip of the undercut ledge and then the stairs zig-zagged up to the platform at the end of a switch-backing entrance trail. The stairs were 1.3-m wide and rose a total of 81 m. When the project was finished in late March of 1925, they were considered a significant improvement over the two-person guano bucket.

Unexpectedly, by 1930 the stairs were the subject of almost all complaints from park visitors. It was

Figure 29. *The Natural Entrance of Carlsbad Cavern in June of 2022. This entrance wasn't used by tourists until 1925, when the City of Carlsbad built a wooden staircase, which was removed when a short tunnel, now known as the Death Gate, was built in 1930. The gate got its name due to three separate incidents of drunk people falling or getting stranded while trying to bypass the gate in the 1980s. Photo courtesy of Rod Horrocks.*

decided that a 13-m long tunnel, at a cost of $1,500, would be completed to intersect a ledge in the Main Corridor, and make the wooden stairs unnecessary. In February 1930, work started on excavating the Entrance Tunnel with an air compressor and drill. With the completion of that project on April 16th, Superintendent Boles stated, "Completion of this trail will mean more to our visitors than the installation of an elevator." However, by the end of that year pressure to build an elevator into the cavern only increased.

Stop 2b. Carlsbad Cavern: Bat Cave

The main bat colony (referred to as both Brazilian and Mexican Free-tailed bats), which ranges from 400,000-500,000 bats, roosts in the passage known as "Bat Cave" and is largely a maternity colony. Between April and October, they emerge at dusk as they corkscrew out of the Natural Entrance and fly over 1,000 visitors watching the bat flight from the stone benches in the Amphitheater. The bats return just before dawn as they individually dive back into the entrance and glide back to their roosting site. The main colony roosts in domes in the back of the Bat Cave, far from park visitors. A smaller population of 1,000 Cave Myotis (*Myotis velifer*) bats roosts past the Underground Lunchroom in the Left Hand Tunnel. Migrating bats also use Carlsbad Cavern as a stopover during their travels, causing the population to swell late in the year.

In March of 1903, Abijah (Bije) Long located a mining claim using four rock cairns above Bat Cave. In June, Bije filed a placer mining claim, which he called "The Big Cave Mining Claim" on "valuable deposits of petroleum, guano, clay and other kindred substances" along with 81,000 m^2 of land above the cave. By 1921, when the last shipments of guano were made from Bat Cave, an estimated 45,000 kg of guano, with a reported valued of $5 million, had been removed. Due to the difficulty of making a profit mining guano and shipping it to the orange groves of California, the guano claim was sold five different times during those 18 years, from a low of $500 up to a high of $75,000. Jim White worked with nearly all the claim owners.

The NPS took control of the cave in October of 1923 and Jim White was appointed Chief Ranger and given a $155/month salary and free housing at the Monument. He was allowed to keep all revenue he received from giving tours as well. He charged $3 per visitor, with a minimum of $15 per tour. On his tours, the first and last person would carry a lantern. Jim White took 5,000 visitors through the cave between 1923-1926, which amounted to over $15,000 for him, in addition to his National Park Service salary.

Stop 2c. Carlsbad Cavern: Devils Den, Fossils, and Balloon Ballroom

The first stairs in the cavern were installed during Dr. Willis T. Lee's Scientific Expedition in 1924, which was funded by the National Geographic Society. They were built by Jim White, Dana Lee, and six laborers filling gunny sacks with dirt, tying them off, and rolling them down to Devils Den, where they were stacked into staircases. However, these stairs began failing within a year. They were replaced with wooden stairs, but due to the high humidity required constant repair and replacement. By 1948, the park decided to replace all the stairs with switch-backing trails or tunnels. The Park started paving the trails with asphalt in 1949, completing that project by 1952. In 1961, emery chips were added to the asphalt trail to prevent visitors from slipping. Beginning in 1978, the asphalt trails were resurfaced by adding a layer of epoxy resin and emery chips on top of the asphalt.

At the bottom of Devils Den Pit, the bones of a juvenile Ground Sloth, a Nothrotheriops, were found in 1947. The sloth apparently entered the cave on its own power and died, and its bones were washed down this pit when flood waters entered the cave. The larger bones were deposited at the bottom of this pit while the smaller bones were washed deeper into a lower passage where the water pooled at a sand bank. Other significant fossils found in the cavern include the bones of an American lion, discovered near the Bat Cave seating area, not far from the Natural Entrance. Bones of fossil bats are found throughout the cave and in many areas in large numbers. Numerous dessicated bats are also found in several areas of the cavern.

In October of 1982, Ron Kerbo and Michael Queen used helium balloons, microfilmental cord, and rope to hook a stalagmite on a ledge in the ceiling 61 m above the floor of the Main Corridor. After a hair-raising climb, they discovered an 11-m long decorated room, which they named the Balloon Ballroom.

Stop 2d. Carlsbad Cavern: Iceberg Rock

The largest rock to fall in the cavern was Iceberg Rock, which fell sometime between 333,000 and 513,000 years ago, based on age dating of a stalagmite on top of Iceberg Rock and stalactites underneath. The rock is estimated to weigh around 180 million kg. It is suspected that a clay-filled joint in the bedrock wall was the weak point where the rock broke from the ceiling. Its fall impacted the cave significantly as it broke numerous large sections of the ceiling in the Scenic Rooms and probably toppled the 24-m high stalagmite known as the Fallen Titan.

Stop 2e. Carlsbad Cavern: Grape Arbor

Grape Arbor (Figure 30) was the site where cave lighting designer, Rod Horrocks, chose in 2015 to set up an example scene of his lighting design using six types of new LED lights. Park staff approved his design concept at this site before it was applied to the rest of the cavern.

Horrocks divided the cavern into 145 lighting scenes composed of individual features or groups of features. Each was defined as a group of speleothems, a side passage, a dome, a pit, or an alcove that was easily separated from adjacent scenes. He typically used 1-9 lights for each scene with the average being six. In a few scenes, like the Devils Hump, the Chandelier, and the Hall of the Giants, he used dozens of lights. Horrocks placed the lights in such a manner to bring out the texture of the speleothems and walls. He also used shadow and contrast to highlight features for which the cave is famous. In Carlsbad Cavern, that meant huge chambers, large speleothems, profuse decorations, and complex mazes. He used blackness to evoke mystery and brought out natural colors by highlighting them. A large percentage of previously unlit features that were highlighted in the LED lighting system were located in the ceiling, lit through the use of powerful LED spotlights. Horrocks was also able to eliminate all the lights that previously had to be accessed by rope and/or challenging climbs. He found he could actually do a better job illuminating the same features with spotlights from the safety of the cave floors. The system was designed so that a radio controller and a ruggedized laptop could be used to communicate with the power supply unit for each group of lights. The new system allowed the designer to adjust the intensity and color temperature of each high-tech light from the comfort of the trail.

Adjustments to the intensity, from 0-100% and adjustments to the color temperature, from 1800-4000 K, could be made. However, the only light temperatures used were 2700 or 3000 K, which were found to significantly discourage, but not eliminate, lampenflora growth in the cavern. Horrocks designed a total of 1,100 fixtures in this new system. The new LED lights reduced the cave's energy consumption by 85% from the previous incandescent and fluorescent lighting system. Unfortunately, the electronics in the new system also made it vulnerable to lightning strikes. Within a few years, over 250 lights had been damaged by lightning strikes that hit the surface near the Visitor Center. These are still being repaired.

Figure 30. *The Grape Arbor was named because the popcorn resembles grape clusters. Using an ultraviolet light in this area highlights the variety of minerals found in these speleothems, which show up as purple, green, red, and blue. The original trail used to extend through this area after going over Apatite Hill. Photo courtesy of Rod Horrocks.*

The first lighting system in the cavern dates back to February of 1925, when NPS Director Stephen Mather, encouraged the park to build a cave lighting system like the one found at Luray Caverns, Virginia, USA. The first lighting system was installed in 1926 by Jack Emmert. He used flood lights mounted on top of poles beginning at the foot of the 216 wooden stairs in the Natural Entrance and continued down to the Kings Palace. After lighting up the Scenic Rooms, Mr. Emmert ran out of money, so he had to light the trail up to the Big Room with small lanterns that were placed alongside the trail. At the Kings Palace, visitors picked up gasoline lanterns which they carried into the Big Room for additional light. Beginning in October 1926, William A. Oglesby, from the Westinghouse Company, joined Mr. Emmert pro bono in designing the lights in the Big Room. Jack finished the lighting project in the summer of 1928.

Stop 2f. Carlsbad Cavern: Underground Lunchroom, Elevators, & Civil Defense Site

In May of 1928, the Amphitheater Lunchroom was constructed where the tall passage leading to the Left Hand Tunnel leaves the Big Room. The Cavern Supply Company employees hauled supplies in backpacks to the Amphitheater Lunchroom, where they served cold lunches on trays. These box lunches were included in the $0.75 tour ticket price. A year later, due to overcrowding and dripping water in the Amphitheater Lunchroom, the Lunchroom was moved to a new location in the start of Left Hand Tunnel, where it currently exists today.

In 1930, pressure increased to build an elevator from the surface to the Underground Lunchroom. In January of 1931, Charles H. Dunning, a miner from Phoenix, Arizona, USA, started work on a 2.7-m square elevator shaft. This shaft was excavated from the bottom and the surface simultaneously and the miners worked 24 hours a day on the project. The blasting debris from the bottom of the shaft was hauled by rail car to the Amphitheater Lunchroom, where it was piled and leveled out. Nearly 10,800 kg of dynamite were used in the project. The 230-m deep shaft was completed in August of 1931 at a cost of $68,225. The shaft took 96 days to excavate. When the shaft was completed and before an elevator was installed, the famous actor and humorist Will Rogers was lowered down the shaft. The Pacific Elevator Company installed the first elevator between August and December of that year with a 35-horsepower motor at a cost of $18,429. At the time, this was the second longest elevator in the country after the Empire State Building.

Once the elevators were installed, sewage from the Underground Lunchroom's bathrooms was carried each night to the surface in large metal garbage cans and dumped into the Visitor Center septic system. In October of 1933, a drinking fountain was installed once a water system had been installed in the elevator shaft. By 1937, the cost of the box lunches was reduced to $0.60 in response to the Great Depression. In February of 1939, construction of a sewage pumping system was started in the elevator shaft and completed by 1941. Today, sewage is pumped 230 m vertically to the surface, where it is piped to sewage lagoons in a nearby basin.

In February of 1963, Carlsbad Cavern was declared an official fall-out shelter for up to 1,200 people in case of nuclear conflict. This was later increased to 25,000 people. In February, two "Fallout Shelter" signs were installed in the cavern, one in the Underground Lunchroom and the other in the Out Elevator Lobby. At that time, the park gave the Civil Defense Agency permission to store emergency supplies in Pickle Alley, located just off the Underground Lunchroom. In April 1963, tons of Civil Defense supplies, including food, water, and medical supplies, were stored at that location. These weren't removed from the cavern until 1989, after many of them had been significantly degraded in the cave's 95% humidity.

In 1993, there was a lot of controversy about removing the Underground Lunchroom due to environmental concerns. The head of the Cavern Supply Company was instrumental in getting the support of Congressman Joe Skeen to add an amendment to a US Department of the Interior Appropriation Bill that prohibited the park from spending any federal money to remove the Lunchroom from the cave.

Stop 2g. Carlsbad Cavern: Big Room, Speleogenesis, & Trays

The Big Room Junction is located at the north end of the Big Room. The Big Room is actually a series of halls that are connected together and counted as one large room, with ceiling heights up to 76 m. The volume of this room is the second largest cave room in the Western Hemisphere and the largest in North America (Walters, 2017).

The large rooms in this cavern were formed from hydrogen sulfide that rose from oil and gas deposits in the adjacent Delaware Basin and intersected the water table to form sulfuric acid. Where the acid degassed to condense on ceilings and walls, the chemical reaction replaced the limestone with gypsum, which then peeled off and fell into the brine below and recrystallized into 3.6-4.6 m thick gypsum deposits on the floor. This process caused the rooms

to increase to the huge proportions we see today. Most of this gypsum on the floor was later dissolved by dripping water after the cave drained. This process happened around 3-4 million years ago. The Big Room developed along faults that parallel the reef and others that run perpendicular to the reef.

Along the right-hand wall of the Big Room are unusual popcorn speleothems called "trays." These are thought to have formed immediately above beds of gypsum that once covered the floors of the room. As those deposits dissolved away, the trays grew horizontally above the top of the undulating gypsum bed, which explains why they are not perfectly horizontal.

Stop 2h. Carlsbad Cavern: Hall of Giants

In the early 1920s, people thought the giant stalagmites in the Hall of Giants resembled the tops of domed capital buildings and so they named these speleothems "domes." The three largest were named Giant Dome and Twin Domes (Figure 31).

Behind you is the Lions Tail stalactite and the popcorn line. Found in very few caves, popcorn lines form at the interface where cool dry air sinks into a cave from its entrance and with warm moist air flowing outward. The resulting popcorn covers all cave surfaces below the popcorn line.

Stop 2i. Carlsbad Cavern: Fairyland

This unusual area is thought to be the result of drip tubes that formed in the gypsum bed on the floor, which were then calcified before the gypsum was dissolved away. These calcified drip tubes were then covered in the popcorn that was deposited below the Popcorn Line, creating these unusual speleothems that superficially resemble stalagmites.

Stop 2j. Carlsbad Cavern: The Chandelier

The drapery stalactites overhead that make up the Chandelier are one of the iconic speleothems in Carlsbad Cavern (Figure 32). The stalagmite forest below these stalactites was named the Garden of the Gods. The floor of this area has seen extensive restoration projects since the 1980s. These projects found magnesium flares and still-full Coca-Cola bottles that had been stashed near the stalagmite known as the Caveman in the 1920s. The Chandelier and Caveman also mark the location of the short-cut back to the Underground Lunchroom for visitors who don't have time to see the back part of the Big Room.

Stop 2k. Carlsbad Cavern: Jumping Off Place & National Geographic Society

When Jim White found this pit in 1906, he called it the "Jump Off." In November of that year, Jim White and Pete Smith used double ropes to be lowered down

Figure 31. *Hall of Giants was named for these three immense stalagmites in the Big Room of Carlsbad Cavern. Photo courtesy of Rod Horrocks.*

Figure 32. *The Chandelier is one of the most iconic speleothems found in Carlsbad Cavern. The forest of stalagmites below was called the Garden of the Gods in the 1920s. Photo courtesy of Rod Horrocks.*

and hauled back up the Jump Off by a group of guano miners. The name of this 27-m deep drop was eventually changed to the "Jumping Off Place." Lower Cave, which can be seen at the bottom of the Jump Off, is the youngest portion of Carlsbad Cavern, forming only 3 million years ago. If you look closely, you can see trails on the floor far below you. The famous bed of cave pearls in Lower Cave, that is known as the Rookery, is located in a portion of Lower Cave that is behind you and beneath the Big Room.

In April of 1924, Jim White built a 61-m long walnut rung ladder that he placed in the "Hole in the Floor," located 30 m back from the edge of the Jump Off. After Willis T. Lee's National Geographic Expedition descended this ladder, the name of the pit was changed to "National Geographic Pit" (see the front cover of this field guide for a photo of the bottom of the pit). Lee's trip report and Roy V. Davis' photos were published in National Geographic Magazine in January of 1924. The response to this article was so great, the National Geographic Society provided $16,000 in funding to pay for Dr. Lee to conduct an extended six-month long scientific expedition of the cavern and surrounding mountains.

Stop 2l. Carlsbad Cavern: Gypsum Tunnels

In April of 1936, two short tunnels were excavated through the gypsum beds near the Jumping Off Place to replace the wooden stairs that went up and over this gypsum ledge. With the completion of those tunnels, all stairs were eliminated from the Big Room.

A light has been added in one of the drip tubes located directly above the trail in the first tunnel. This light creates a spot on the floor. It is interesting to sit back and watch visitors' reaction to this spot. About 50% duck their head and scurry underneath in the tunnel while 50% stop and look up the tube to see the source of the light. These tubes were excavated by dripping water. There wasn't enough dripping water in this area to completely dissolve this gypsum bed, as further evidenced by the lack of stalactites overhead. Numerous interesting drip tubes and associated features can be observed further along the trail.

Stop 2m. Carlsbad Cavern: Top of the Cross and The Spirit World

The Top of the Cross is at the intersection of a fault paralleling the reef front and another perpendicular to that reef. In May of 1955, the amphitheater seating, which can seat 270 people, was added to this area. Today, this seating is only used for special programs, such as the New Mexico Philharmonic Quartet that performed here in November of 2016. The acoustics are fantastic!

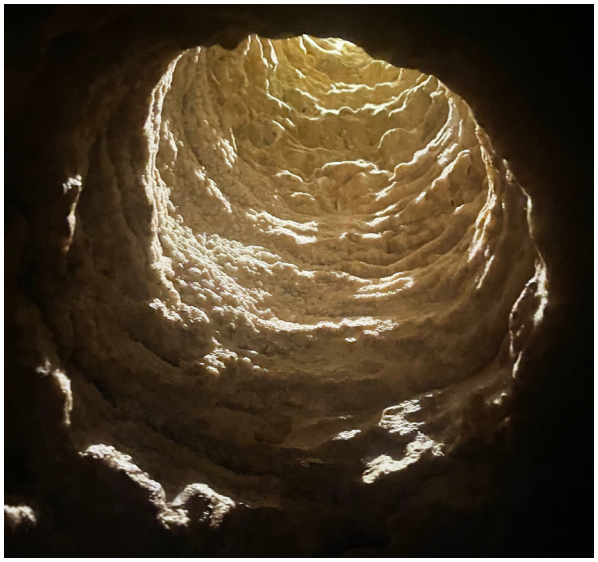

Figure 33. *This drill tube in a 4.3-m thick gypsum bed was created by dripping water. The tube was intersected when a short tunnel was excavated through the bed to eliminate a set of the wooden stairs that went up and over the bed. A gypsum chandelier can be seen underneath this gypsum bed where it hangs over the deep pit into Lower Cave. Photo courtesy of Rod Horrocks.*

In December of 1985, Ron Kerbo, Michael Queen, and Jim Goodbar used helium balloons, microfilmental cord, and a balsa wood hoop to hook a stalagmite 78 m up in Top of the Cross Dome. They used the cord to pull a climbing rope over the stalagmite and back to the floor where they anchored it. They tested the stalagmite when they hung and bounced on the climbing end of the rope. When the stalagmite held, Kerbo climbed 78 m to a decorated level they named The Spirit World. They reclimbed this rope on three separate evenings over a four-day period to continue their explorations. By the fourth day they completed a 55-m long traverse around the top of the dome to continuing passage on the opposite side. The resulting discovery went 113 m before pinching 7.3 m before intersecting Liberty Dome, the dome above Bottomless Pit. In October of 2013, Shawn Thomas and Derek Bristol climbed a rift in the ceiling of this passage that opened into an even higher level that they named Halloween Hall. There are now five levels in this section of the cave that cover a total vertical relief of over 120 m between the lowest and highest levels. The passages found at the bottom of the large pit in front of you lead to an area that has been named Middle Earth. The Lower Cave passages are found below Middle Earth and form the lowest level in this area of the cave.

Stop 2n. Carlsbad Cavern: Bottomless Pit

This 43-m deep pit was once lit by a light at the bottom. The light was removed in 2015 so visitors would stop asking why this pit was called "Bottomless Pit," as they could clearly see the bottom! In July of 1976, Tom Rohrer, Ron Kerbo, Ben Robinson, and Lee Mellinger climbed the dome over Bottomless Pit. The Superintendent wouldn't allow them to climb when visitors were present in the cavern, in case they fell, so they started their climb after the cavern closed for the night. Mostly bolts were used in the climb, which took five nights to complete. Since they reached the top of the dome at midnight on July 4th, they named it Liberty Dome. In 2018, the dome was reclimbed by Derek Bristol so he could map the unsurveyed dome and verify that there were no continuing passages off the top. Derek was able to climb the dome in four hours using modern dome climbing techniques. No continuations were found.

Stop 2o. Carlsbad Cavern: Mirror Lake

A sign with the upside down words, "Mirror Lake" was placed on the far side of this pool so that visitors could correctly read the reflection in the surface of the pool (Figure 33). A few years ago, water started dripping into the pool at an increased rate. The resulting ripples now make it difficult to read the sign. Signs were used to identify many features throughout the cavern, however, most have been removed.

Stop 2p. Carlsbad Cavern: Guano Deposit

The bat guano deposits seen in this area have been dated to 35,000 years ago. These bats were probably the ancestors of the free-tailed bats that roost in Bat Cave today. It is unclear why this particular roost was abandoned.

Stop 2q. Carlsbad Cavern: Lily Pads

Between 1924 and 1971, this was an important stop along the guided tour route. The "Lily Pads" are shelfstone deposits that mark the level of a now dry pool. Many were full of water during the last ice age, over 14,500 years ago. They probably dried up around 7,500 years ago. Park staff used to fill this and other pools with water, an unnatural practice that was abandoned in the late 1970s with the advent of more enlightened thinking.

Figure 34. *If you wait for the ripples from dripping water to stop, you can read the sign, which was written upside down and placed on the opposite side of Mirror Lake. Like most pools in Carlsbad Cavern, this pool level has dropped significantly during the on-going drought. The water takes from 3-6 months to travel from the surface to reach the cave 229 m below. Photo courtesy of Rod Horrocks.*

In January of 1972, guided tours were switched to self-guided tours due to the rapidly increasing number of visitors. Hand-held interpretive radios were added to take the guides' place. Although this allowed the park to not turn away any visitors, and despite park rangers walking along the trails, the decreased scrutiny of visitor behavior has led to a tremendous amount of vandalism in the form of broken speleothems, graffiti, and garbage thrown into pits and pools.

Stop 2r. Carlsbad Cavern: Crystal Spring Dome

This is one of the largest actively growing speleothems in the cavern. It is estimated that only 5% of the speleothems in the cavern are actively growing today. The conditions that created many of them are no longer active. Some of the largest have been cored and dated. It appears that most grew in the last 500,000 years.

Stop 2s. Carlsbad Cavern: Rock of Ages

In July of 1928, America's greatest baritone, Cameron McClean, took a tour of the cavern. After a flare was burned on a tour in the Big Room at the large column known as the Rock of Ages, he offered to sing the hymn *Rock of Ages* to express his feelings. The performance brought many visitors on the tour to tears. This performance, along with the flare and the practice of turning off lanterns located along the trail, lead to an idea for a "Ceremony of Lights" program to be performed at the Rock of Ages. This program eventually evolved into the "Rock of Ages program. This program was offered on every tour up until 1944, when the Director of the NPS ordered it shut down. It was the most remembered part of early visitors' experience at the park.

Stop 2t. Carlsbad Cavern: Painted Grotto, Dolls Theater, & photographers

Painted Grotto (Figure 35) and Dolls Theater are some of the most iconic features found in Carlsbad Cavern and are often photographed.

The first photograph in the cave was taken in 1908 by a young George Adams from Carlsbad. When he missed meeting up with Jim White for a tour, he and his friend went in the cave on their own and George took a self-portrait at the white column in what would later be known as Devils Spring. George used a Kodak camera and a flash gun that was ignited by sticking a match through a hole in a magnesium foil shield.

One of the cave's most influential photographers was Ray Vesta Davis, who started photographing the cavern around 1922. His "8 x 10" camera, wooden tripod, and other equipment weighed 34 kg. He displayed 48 cave prints in his studio in Carlsbad, which attracted a lot

Figure 35. *Painted Grotto is another of the iconic scenes found in Carlsbad Cavern. It is lit the same way as in the previous cave lighting system, which was designed by Ray Grenald in 1974. This is the only scene in the Cavern that didn't changed when the new LED lighting system was installed in 2015. Photo courtesy of Rod Horrocks.*

of attention to the cave. His photos were influential in Willis T. Lee investigating the cavern, in the National Geographic Society funding expeditions and publishing Davis' photos, and in the creation of the Monument and then the National Park.

One of the most well-known photographers to work in the cavern was Ansel Adams, from Yosemite, California, USA. He spent a day photographing in the cavern in 1936 and then again in 1947. However, Adams was deeply dissatisfied with his resulting photographs. He specialized in using natural lighting and found using the cave lighting a frustrating experience. Nymeyer and Halliday's (1991) book describes the early history of the cave, its photography at that time, and of Carlsbad Caverns National Park.

Stop 3. Carlsbad Caverns National Park: Rattlesnake Springs, written by Rodney Horrocks.

Rattlesnake Springs Picnic Ground (Figure 36) is a popular site for local people from nearby communities. It is a rich cultural landscape that surrounds Rattlesnake Spring and creates a lush oasis surrounded by creosote bush, mesquite, yucca, and snakewood of the Chihuahuan Desert. To the northwest, the Guadalupe Mountains escarpment marks the horizon. If you look closely, you can see the Visitor Center of Carlsbad Caverns National Park on top of the escarpment.

In 1938, a Civilian Conservation Corps (CCC) camp was established at this site. The camp consisted of a central parade ground surrounded by four long barracks buildings, a school, recreation hall, kitchen and mess hall, adobe house, and a garage. From 1943-1950, the US Army occupied this site and several of the CCC era camp buildings were demolished. The military used the site for recreation and added a swimming pool and tennis court. Five rows of cottonwood trees, spaced 26 m apart, were planted in 1946 and the area was converted to a picnic ground. The only features left from these camps are the tennis court, that can be seen in the middle of the picnic ground, and a nearby foundation amid the trees.

Figure 36. *This beautiful site makes for very pleasant picnics when the wind is gently rustling through the leaves of these 76-year old cottonwood trees. Photo courtesy of the National Park Service.*

In recognition of its significant role in our nation's history, Rattlesnake Springs was placed on the National Register of Historic Places in 1988. Today the Nature Conservancy owns a strip of land to the south of this property, which includes the outflow from Rattlesnake Springs, while CARC owns Washington Ranch to the north. The CARC site is used as a wedding and event center.

The area has been listed as an Important Birding Area (IBA) by the Audubon Society, and attracts a large number of migrating birds. Over 330 species of birds have been documented at this site, including some federally listed threatened and endangered species and some sensitive state-listed species, such as the Southwestern Willow Fly Catcher and the Bell's Vireo. The Monarch Butterfly also migrates through this area.

About 500 m west of the picnic grounds is Rattlesnake Spring (Figure 37). It has been an important source of water from Paleoindian times to the present. The most recent tribe to inhabit the area were the Mescalero Apache. In 1855, a US Army regiment led by John Pope, was sent to remove them from this area and relocate them onto a reservation. They spent 25 years chasing the Apache in the adjacent Guadalupe Mountains before they finally relocated them. Between 1858-1861, the historic Butterfield Trail had a spur road that went first to nearby Blue Springs, then here to Rattlesnake Springs, then west to Pine Springs, and then on to Guadalupe Point, where it joined a southern spur of the Butterfield Trail. The Butterfield Trail was used by immigrants heading to California.

The Rattlesnake Springs area was acquired by the National Park Service in 1934 for the primary purpose of ensuring a reliable domestic water supply for Carlsbad Caverns National Park. This and Blue Spring, 17 km to the northeast, are the only sizable, springs in this area. In the 1880s, this site was settled by Henry Harrison. He initiated construction of a gravity-fed irrigation system, fenced the property, planted an orchard, increased water flow from the springs, enlarged the pond, and dug shallow irrigation ditches, known in the southwest US by the Spanish

Figure 37. *The Army walled up the Rattlesnake Spring lake in order to create a swimming hole in the 1940s. This pond is 1-1.5 m deep and hosts lots of fish, some exotic and some native. An attempt to drain the pond to remove the exotic fish failed when the pumping couldn't overcome the natural spring flow. Photo courtesy of Rod Horrocks.*

term, "acequias." While horse and cattle grazing were Harrison's primary activities, he also homesteaded. Army crews later lined the marshy pond with limestone walls, expanded the irrigation system, added a gravel service road with culverts, and created irrigated plots that were planted with grass.

Carlsbad Caverns National Park now has a nearby well that taps into the conglomerate karst aquifer that the spring originates from. That aquifer extends as much as 30 m below the surface and originates from underneath Slaughter Canyon in the nearby Guadalupe Mountains. This once calcite-saturated groundwater deposited tufa dams in the nearby Black River. Today, the water is shared with Washington Ranch to the north and with the Nature Conservancy to the south.

Stop 4. National Cave and Karst Research Institute, (NCKRI)

NCKRI was created by the US Congress in 1998 in a partnership of the National Park Service, State of New Mexico, and the City of Carlsbad. NCKRI's enabling legislation, the National Cave and Karst Research Institute Act of 1998, 16 U.S.C. §4310, identifies NCKRI's mission as to:

1. further the science of speleology;
2. centralize and standardize speleological information;
3. foster interdisciplinary cooperation in cave and karst research programs;
4. promote public education;
5. promote national and international cooperation in protecting the environment for the benefit of cave and karst landforms; and
6. promote and develop environmentally sound and sustainable resource management practices.

NCKRI is administered by the New Mexico Institute of Mining and Technology, and accepts tax deductible donations through NMT's non-profit, 501(c)(3) status.

NCKRI Headquarters is located at the Cascades of Carlsbad, a new social/retail center for the City of Carlsbad that is currently under development. NCKRI based its headquarters in this location to enhance its ability to reach and meet with the public. The 1,609-m² facility includes a laboratory, classroom for conferences, board room for smaller meetings, and administrative offices.

Some parts of NCKRI Headquarters are still in development:

- It is the world's only building constructed with a bat roost as part of its structure. The problem is that bats haven't moved in! The problem may be related to a nearby roost that was discovered recently, or to the public safety lighting around the building. A team of bat biologists is reviewing roost temperature, humidity, video, and other data to help understand why bats aren't present. Once occupied, the NCKRI roost will become a bat research facility and a station to teach the public about the many benefits bats provide to humanity.
- NCKRI has received donations of hundreds of books, maps, photos, and publications. Currently they are stored in boxes as funds are sought to install compact book shelving.
- The majority of the ground floor (foyer, lobby, and hall) is designed to become a cave and karst education science center. The exhibit design is complete and state-of-the-art, but like the library, funds are sought to construct it.

The remaining section of NCKRI Headquarters that is in development, but essentially complete except for some setting-up details, is the DropZone (Figure 38). This $255,000 outdoor exhibit, courtesy of a City of Carlsbad Lodgers Tax grant, fills NCKRI's courtyard. It includes a 9-m tall rock-climbing wall to a catwalk designed to teach cave rope climbing, rappelling, cable ladder, and safety and rescue rigging skills. The DropZone is expected to expand NCKRI's educational outreach by attracting people to NCKRI where they will learn about the importance of caves and karst. Two rolling educational exhibits accompany the DropZone and temporary exhibits are in development. The DropZone is expected to open to the general public by the summer of 2023, and prior to that by limited appointment.

While NCKRI's research and programs range widely, they have included many show caves and activities to benefit show caves. Some recent examples include:

- A study of lampenflora in Carlsbad Cavern and development of non-toxic control methods superior to bleach, which is commonly used. The results of the study are being prepared for publication.
- Guide training at Caverns of Sonora.
- Geophysical studies at Natural Bridge Caverns.
- Geomicrobiology and speleogenetic research at Caverns of Sonora, Lehman Cave in Great Basin National Park, USA, and Frasassi Cave, Italy.

NCKRI is dedicated to conducting cave and karst research, management, and education programs that may have broad use and application. For more information, and to partner with NCKRI, visit www.nckri.org.

Figure 38. *View of the top of DropZone at NCKRI. Starting in 2023, guests will climb up the rock wall to the catwalk, rappel down, or climb up on ropes or a cable ladder. The DropZone will also be available to support search and rescue, fire, police, and other specialized vertical/rope skills teams.*

Stop 5. Comanche Springs Park.
Comanche Springs (Figure 39) were the largest spring system in west Texas and the type locality of the endangered Comanche Springs pupfish (*Cyprinodon elegans*). It is a group of karst springs that flowed an average 1,200 L/s when monitored from 1922-1947. The springs have a long record of Native American activity and are the reason Fort Stockton was settled. Over the years, they served as the primary source of water for drinking, irrigation for agriculture, and as a superb swimming hole and social center for the community.

As drilling for water became more widespread and possible in west Texas, Clayton Williams, Sr., and other farmers west of Fort Stockton, began drilling irrigation wells in 1951 that tapped into the part of the Edwards-Trinity Aquifer that fed the springs, causing their flow to decline. A lawsuit was filed to stop the pumping. In 1954, the Texas Court of Civil Appeals ruled in favor of Williams by upholding "the rule of capture." This doctrine holds that landowners do not own the groundwater beneath their lands but have the right to "capture" as much as they want, no matter the impact on other groundwater users, as long as the water is put to "reasonable use." This decision also avoided needing to understand the complex ground-water flow conditions of the aquifer and by default agreeing with the 1904 Texas Supreme Court decision that groundwater was "too mysterious to regulate."

By the late 1950s, Comanche Springs began to go dry due to the pumping and eventually ceased flowing in 1961. Since that time the springs have flowed rarely and only following periods of sustained major rainfall. One benefit of the lowered water table is that it allows access into the normally water-filled cave that fed the springs. The natural entrance to the cave, formerly Big Chief Spring, was originally submerged by 5.5 m of water. It is now dry and enclosed in a metal cage near the end of the swimming pool. The artificial and now main cave entrance is at the old Government Spring wading pool, which provides access through six metal barrels welded end-to-end to a total depth of 5.8 m.

The cave has an estimated 1.2 km of known passages. They are joint-controlled and form along three main levels at about 3, 6, and 9-12 m below the entrance. Those at the 3 m and 6 m levels average 1 m wide by 1-2 m high, and make up most of the cave's explored length. In at least five locations they cross over pits that drop to the water table. Submerged passages and probably larger diameter passages lead off from these pits to the cave's lower level, but an attempt to dive

Figure 39. *Big Chief Spring, the largest of the Comanche Springs, once flowed from the area under the grated roof structure near the middle-lower part of the photo. The original spring pool is now filled by the swimming pool and surrounding paved area with the blue stars.*

one pit with scuba found the passage mostly filled with sediment which prevented exploration.

Veni (1991) hypothesizes the Comanche Springs were originally 10-13 m lower in elevation and the outlets of flow from the cave's lower level passages. However, Pleistocene valley-fill deposits filled the Comanche Creek Valley, occluding the springs and forcing their water to develop the modern, higher passages and spring outlets. Dating of the valley deposits near Comanche Springs may indicate the time of the waters' upward diversion, from which the rate of enlargement of the upper passages could be determined.

For a few years after spring flow ceased, the decades-long social activities ceased at the former spring pool along the north edge of James Rooney Memorial Park until the modern swimming pool was built. Optimism remained that spring flow would be restored, and the pool was built on a series of pillars to allow spring water to flow under the pool and even support by buoyancy some of the pool's weight. Occasional optimism continues that the flow of Comanche Springs can be restored. Mace et al. (2020) provide a detailed history of the springs and propose a water marketing model that could reduce pumping and restore spring flow.

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Goodbar (2009) made a good start with dye tracing in the Carlsbad Cavern region. NCKRI is continuing such studies, including this dye trace 100 m above where the Black River sinks underground. NCKRI photo by Michael Jones.

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This trip and congress are part of the celebration of the International Year of Caves and Karst.

Many caves remain to be explored and studied in west Texas and southeast New Mexico. While most will never be show caves, all have potentially great value to the regions' water supplies, ecosystems, culture, and toward enhancing humanity's knowledge of the world.

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