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1993, pp. 117-128. https://doi.org/10.56577/FFC-44.117

in:

Carlsbad Region (New Mexico and West Texas), Love, D. W.; Hawley, J. W.; Kues, B. S.; Austin, G. S.; Lucas, S. G.; [eds.], New Mexico Geological Society 44th Annual Fall Field Conference Guidebook, 357 p. https://doi.org/10.56577/FFC-44

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GEOLOGIC WALKING TOUR OF CARLSBAD CAVERN

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ASSEMBLY POINT. *The geologic scenic tour starts in front of the ticket desk, Carlsbad Cavern Visitor Center. This can also be a self-guided tour. The map of Carlsbad Cavern (Fig. 1) shows the general tour route and stop locations.*

STOP 1. Observation tower, Visitor Center. The Carlsbad Cavern Visitor Center is situated directly on top of the Capitan reef. To the northwest are the bedded strata of the backreef facies (Guadalupian Seven Rivers, Yates, Tansill Formations) and to the south the solution-subsided Gypsum Plain (Ochoan Castile Formation, Fig. 2). Between the elevated reef and subsided plain is the Reef Escarpment.

Carlsbad Cavern lies along the Reef anticline, which trends parallel to the Reef Escarpment. The cavern is developed primarily along a series of joints that are parallel to the reef front (N80°E) or perpendicular to the reef front (N 15°W). Passages are confined to the limestone reef, being "sandwiched" between backreef and forereef dolomitic rock. In general, caves of the Guadalupe Mountains are developed preferentially in one of four stratigraphic positions (Jagnow, 1977; Fig. 3): (1) below the Yates transition into the massive Capitan (e.g., Ogle and New Caves, Slaughter Canyon), (2) at the contact of the reef (massive) and forereef (breccia) members of the Capitan Formation (e.g., Carlsbad Cavern), (3) at the transition of the Capitan Limestone with the other members of the Artesia Group (e.g., Lechuguilla Cave) and (4) beneath the Yates contact with the Seven Rivers Formation (e.g., Cottonwood Cave and the McKittrick Hill caves).

STOP 2. Entrance to Carlsbad Cavern. The entrance to Carlsbad Cavern is developed in the Tansill Formation of Late Permian (Guadalupian) age. Note the tepee-like structure exposed in Tansill rock on the southeast side of the entrance. The origin of tepee structures is controversial, but the bulk of evidence seems to favor a shallow-subaqueous, tidal flat (peritidal) environment, similar to that found today around the Persian Gulf. Desiccation and thermal expansion/contraction caused initial fracturing and buckling of shallow-water sediments; later phases of crystallization caused the enlargement, fill and cementation of these structures (Assereto and Kendall, 1977). Tepee structures are often found associated with pisolites, which are tiny (1 cm or so), concentrically layered, pea-shaped rock bodies that form along the flanks (but not the crests) of tepee structures. There is a good tepee along the road just south of the Visitor Center south parking lot if you want to take a closer look at this type of structure.

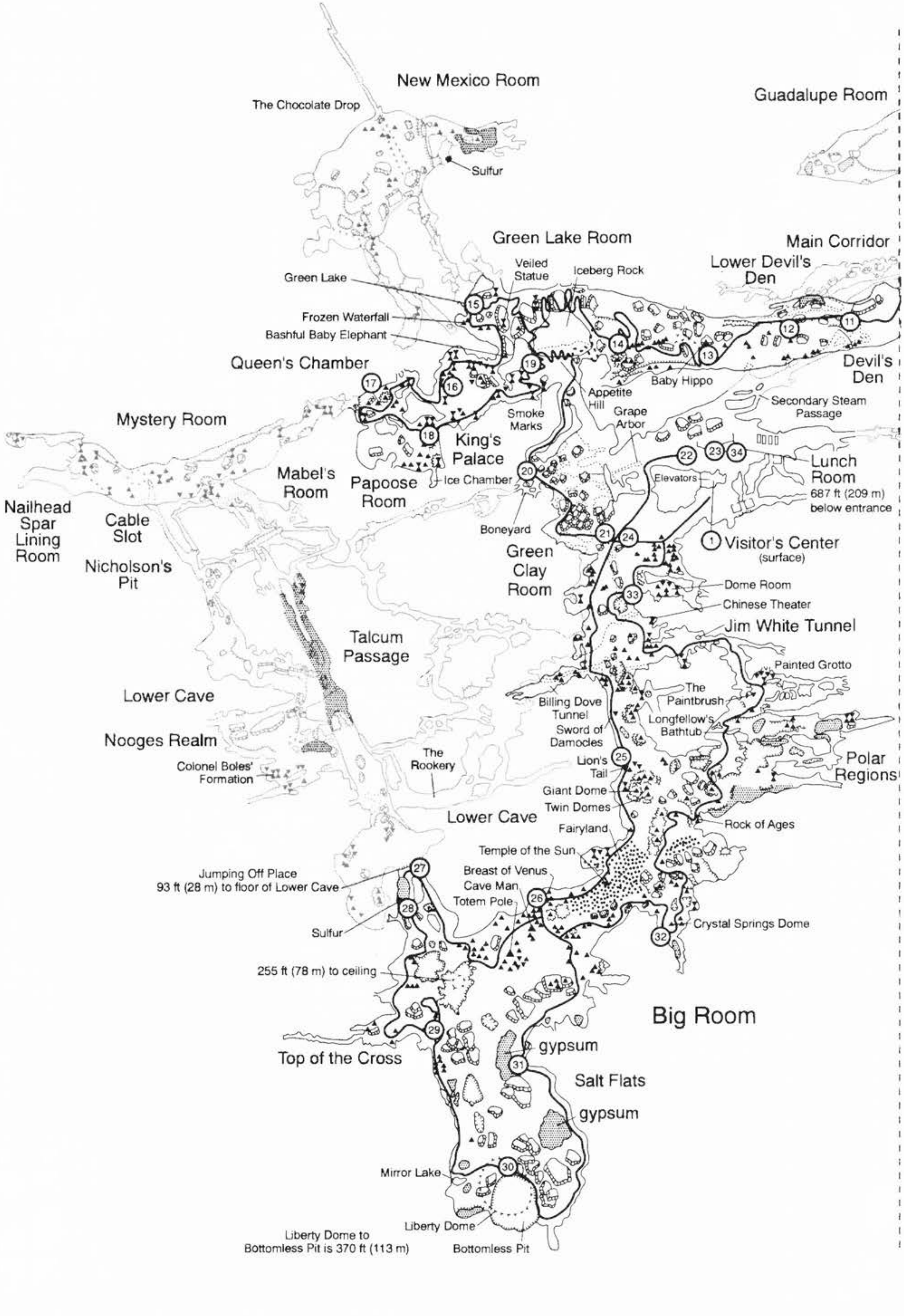
The entrance to Carlsbad Cavern represents a paleospring. This spring was a former discharge point for water recharging in the Guadalupe Mountains, just as Carlsbad Springs at Carlsbad, New Mexico, is the discharge point today. The entrance paleospring was operative — I Ma (million years) or so ago, but had ceased functioning by the time the Big Room level was being excavated (-0.75-0.85 Ma; Hill**,** 1987). Note the morphology of the entrance passage—how steeply it cuts across bedding. This is typical of bathyphreatic caves where water takes a deep course through the limestone and ascends under hydrostatic pressure along joints, bedding planes and at the contact of the reef with forereef and backreef facies (Fig. 4). As the water table in the Capitan reef dropped, corresponding to the continued solution-subsidence of the Gypsum Plain and lowering of regional base level, horizontal levels of cave passage were developed at the water table. These caves cut across the earlier, bathyphreatic, more vertically oriented caves (e.g., Bat Cave cuts across the steeply dipping Entrance—Main Corridor Passage). Note also how large the entrance is. There must have been a lot of water discharging from the entrance of Carlsbad Cavern when it was functioning as a discharge spring.

STOP 3. Proceed down entrance switchbacks. Stop at last switchback before straight trail and first tunnel. Note the blocky calcite spar crystals on the north-facing trail-cut just above eye level. This type of spar **Hill** (1992) named "thermal spar" because of its characteristic isotopic signature of $\delta^{18}0$ ~ —11 to —14 per mil **(PDB).** Thermal spar is pervasive throughout most of the Delaware Basin margin, not only in the Guadalupe Mountains but also in the Apache Mountains and Glass Mountains. Thermal spar is characterized by large, euhedral, scalendohedral and/or rhombohedral calcite spar crystals a few millimeters to 30 cm or more in length; it is usually milky white rather than transparent and is often described as "blocky calcite spar." Thermal spar fills pore spaces between boundstone fabrics in the Capitan Limestone. It is present in both primary and secondary pore spaces throughout the Capitan massive and forereef facies and occurs as vug fillings and as vein and fracture fillings that are nearly vertical and strike parallel to the reef escarpment. It also fills spaces between breccia, both tectonic (such as can be seen in Walnut Canyon) and solutional (such as is exposed in Carlsbad Cavern and other caves in the Guadalupe Mountains). It occurs along Basin and Range structures, filling fault zones 5 m or more wide, and it lines "spar caves"—small (usually <5 m in diameter), geode-like caves covered with dogtooth spar crystals (some as large as footballs). Because of its occurrence along Basin and Range faults and because of its thermal isotopic signature, this type of spar is believed to be Miocene in age, during which time the geothermal gradient in the Delaware Basin area may have been as high as 50°C/km (Barker and Pawlewicz, 1987).

STOP 4. Down the trail, just beyond the gate and second **tunnel.** Notice how the travertine (dripstone and flowstone) is associated with bedding planes in the Tansill Formation. Solutions descended from the surface along vertical joints until they encountered horizontal bedding planes, whereupon they moved laterally to the cave wall where the travertine was deposited (Fig. 5). This type of bedding plane—controlled travertine is typical of the upper, Tansill level of Carlsbad Cavern, but once the unbedded, Capitan, reef rock is encountered this type of travertine is replaced by travertine developed along vertical joints or by seeping water-type speleothems (e.g., cave popcorn).

STOP 5. To the right of the 4-m-high breakdown block, 13 m after the end of the right-hand stone wall. Note the mudcracks in the flat, bedding-plane ceiling of the Tansill Formation. These mudcracks are evidence of exposure and desiccation of the Tansill Formation during the time of its deposition. This section of the Tansill Formation is part of the "pisolite shoal" or "shelf-crest" facies, which is characterized by pisolite and tepee structures. The shelf crest facies represents a paleotopographic high that occurred as a narrow belt behind and parallel to the reef front (i.e., it was a longshore bar). Abundant evidence (such as these mudcracks) exists for the intermittent exposure of the shelf crest, but the extent, duration and nature of this exposure is highly controversial.

STOP 6. Seating area, looking eastward down Bat Cave. Farther down this passage is where the famous Carlsbad Cavern bats reside during the summer months. Note again the flat planar ceiling that represents a major bedding plane in the Tansill Formation. The original passage was lower than the passage void you see now (it was at the toe of this sloping trail), but over time slabs of bedded Tansill fell from the ceiling to litter the floor with large tabular breakdown pieces so as to create a somewhat higher passage. Also note how the passage wedges up to the left. Originally, the main dissolution of this passage was along



New Mexico Room
The Chocolate Drop
Sulfur
Guadalupe Room
Green Lake Room
Main Corridor
Veiled Statue
Iceberg Rock
Lower Devil's Den
Green Lake
Frozen Waterfall
Bashful Baby Elephant
Queen's Chamber
Devil's Den
Baby Hippo
Appetite Hill
Grape Arbor
Secondary Steam Passage
Smoke Marks
Mystery Room
King's Palace
Lunch Room
687 ft (209 m) below entrance
Elevators
Mabel's Room
Papoose Room
Ice Chamber
Nailhead Spar Lining Room
Cable Slot
Boneyard
Visitor's Center
(surface)
Green Clay Room
Nicholson's Pit
Dome Room
Chinese Theater
Jim White Tunnel
Talcum Passage
Painted Grotto
Lower Cave
The Paintbrush
Billing Dove Tunnel
Longfellow's Bathtub
Sword of Damocles
Nooges Realm
Colonel Boles' Formation
The Rookery
Lion's Tail
Polar Regions
Giant Dome
Twin Domes
Lower Cave
Rock of Ages
Fairyland
Temple of the Sun
Jumping Off Place
93 ft (28 m) to floor of Lower Cave
Breast of Venus
Cave Man
Totem Pole
Crystal Springs Dome
Sulfur
255 ft (78 m) to ceiling
Big Room
Top of the Cross
gypsum
Salt Flats
gypsum
Mirror Lake
Liberty Dome
Liberty Dome to Bottomless Pit is 370 ft (113 m)
Bottomless Pit
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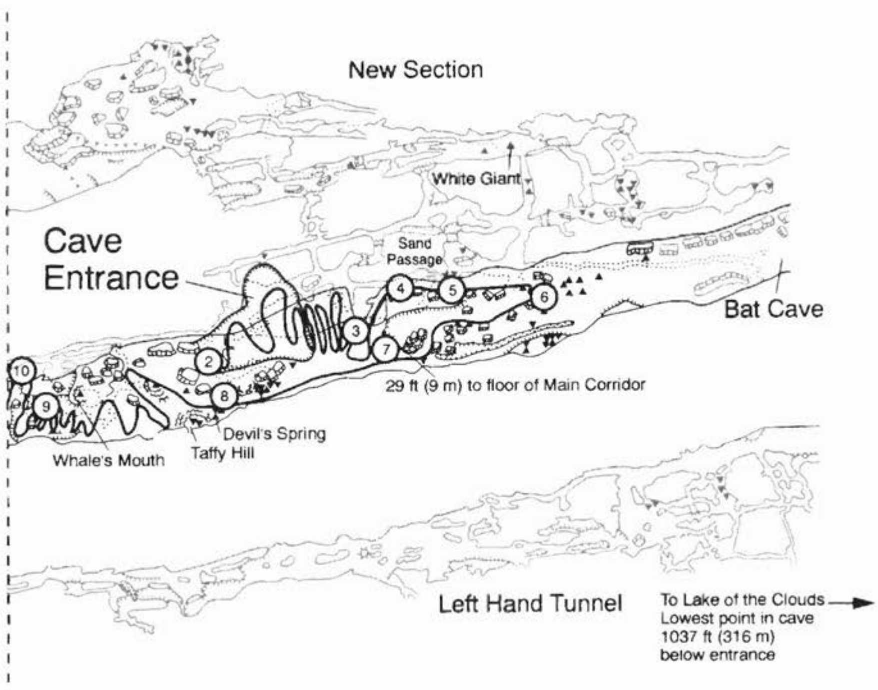

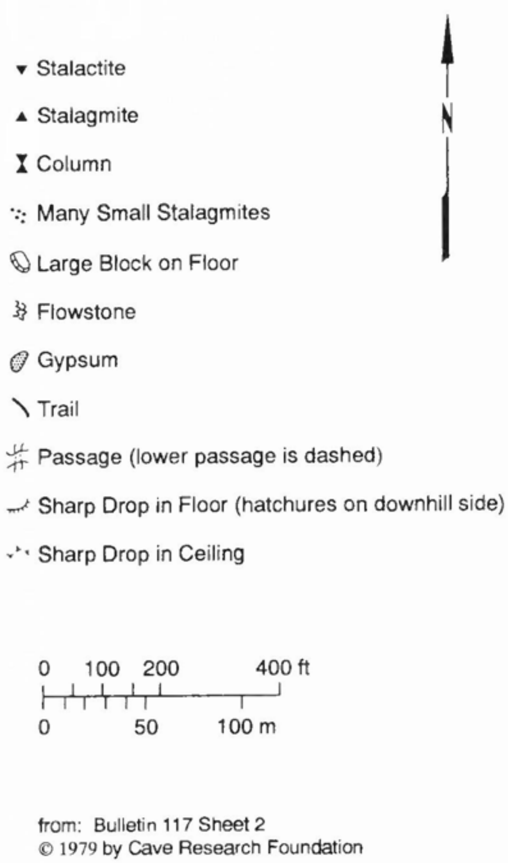

FIGURE 1. Carlsbad Cavern, walking tour route and stop locations.

the right-hand wall. Ceiling breakdown collapsing into the passage had more space to fill on the right than on the left—hence the wedged configuration of the now-present void.

Look across the passage to the south wall and notice the large (1.55 m long), scallop-like marks. Since the distance between scallop crests is inversely proportional to the flow velocity (Curl, 1974), for a passage cross section of 30 x 20 m, a past flow rate of 3-12 m/sec can be calculated (i.e., the water that carved these scallops flowed with this velocity down the passage). The skewness of the scallops indicates that past flow was eastward, along Bat Cave; this flow probably exited from a second paleospring after the entrance spring had become defunct. The presence of scallop marks is quite unusual for Guadalupe caves. Usually these caves do not display scalloping or the scallops are not developed well enough to determine the direction and velocity of past flow. The size of these scallop marks suggests that they are of phreatic origin. No vadose (small-scale) scallops are known in any Guadalupe cave. These caves have an entirely nonvadose, phreatic (bathyphreatic to shallow-phreatic water table) origin, unlike most other caves in the world.

STOP 7. At the bottom of the slope, below the cave entrance, where the trail flattens out. The floor bedding plane represents the base of the Tansill Formation and the top of the Yates Formation (where the Yates interfingers into the massive reef). Note the ceiling bedding plane; this plane defines the ceiling of the Main Corridor Passage almost all the way to Iceberg Rock (Stop 14).

STOP 8. Devil's Spring–Taffy Hill. Again, notice the association of travertine with a bedding plane. Devil's Spring is fed by water that has flowed out along the bedding plane, down the Taffy Hill flowstone cascade and then into the pool. The tannish color of Taffy Hill is most probably due to iron derived from the Yates Formation. Observe the cauliflower-like crust coating the sides of the Devil's Spring pool. This is an example of a subaqueous coralloid ("underwater popcorn" as cavers call it). However, most cave popcorn in Carlsbad Cavern and other caves in the Guadalupe Mountains is subaerially formed. Subaerial popcorn will be pointed out at later stops.

At the apex of the Taffy Hill flowstone cascade is some old-looking, white travertine that has been corroded flush with the limestone wall

FIGURE 2. The Guadalupe Mountains and Gypsum Plain near Carlsbad, New Mexico. The Capitan Reef Escarpment rises along the edge of what was once the Delaware Basin. The headquarters of Carlsbad Caverns National Park sits atop the remains of the reef. Guadalupe Peak can be seen at the extreme upper left, Slaughter Canyon is in middle distance and Walnut Canyon is a snake-like feature on the right. Backreef beds (on the right) can be seen merging into the unbedded reef and forereef beds (between the reef and Gypsum Plain) can be seen dipping toward the basin. Photo by Jeep Hardinge.

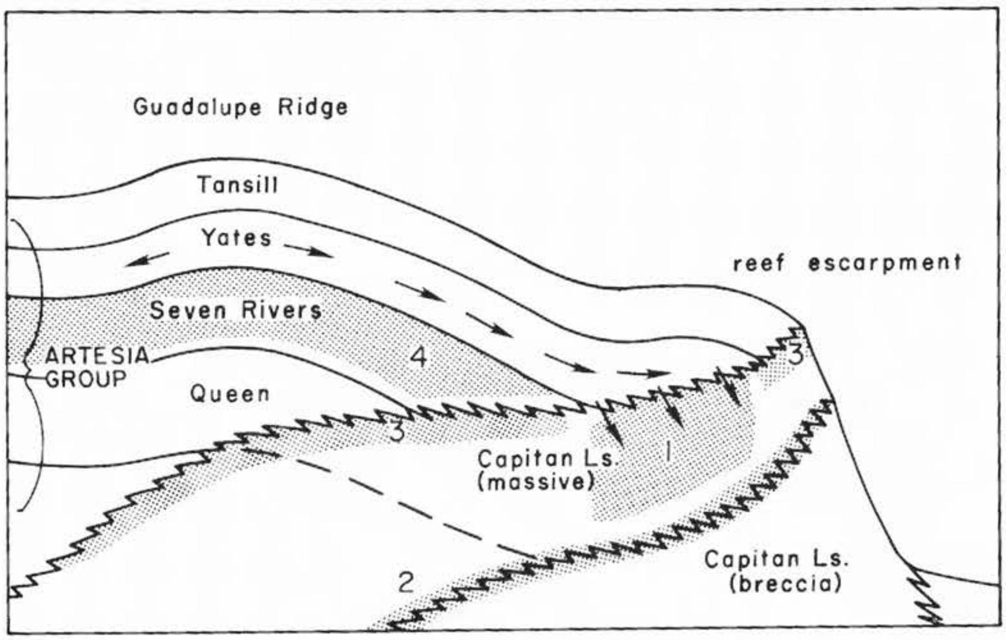

FIGURE 3. Four zones of preferential solution (shaded areas): (1) below the Yates transition into the massive Capitan Limestone, (2) at the contact between the massive and breccia members of the Capitan Limestone, (3) at the transition between the Artesia Group members and the Capitan Limestone and (4) immediately beneath the Yates Formation in the Seven Rivers. Arrows indicate movement of ground water along impermeable siltstone in the Yates Formation. After Jagnow (1977).

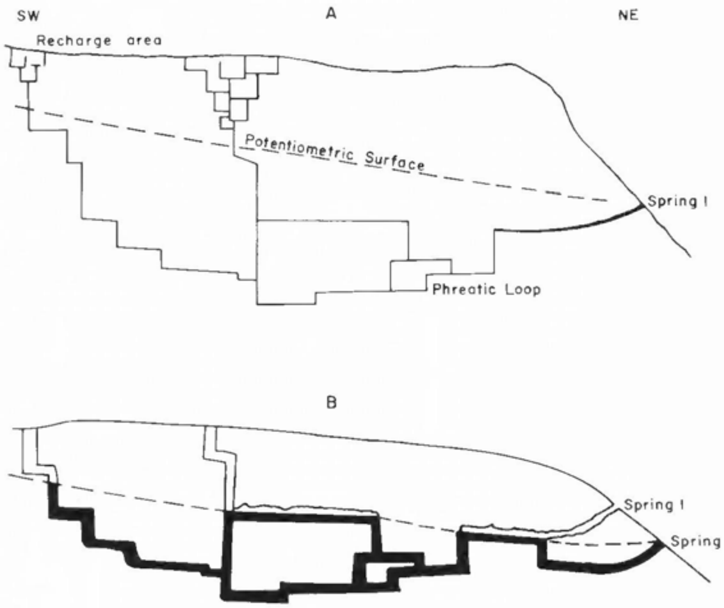

FIGURE 4. A. Model of bathyphreatic flow in the Guadalupe Mountains. Since the massive Capitan reef has a low fissure frequency and a relatively low permeability, water takes a deep course through the limestone. The water ascends under hydrostatic pressure along joints, bedding planes and at the contact of the reef with forereef and backreef facies and eventually exits at a spring downgradient from the recharge area. Since the reservoir capacity of the limestone is low and the minimum flow path to the spring is long, the potentiometric surface remains high in the rock and is steeply inclined. The future course of integrated passages in the Guadalupe Mountains is highly influenced by the development of these early bathyphreatic flow routes, even though, initially, these routes may be inaccessibly small. B. Caves with a mixture of phreatic and water-table components. As the caves enlarge and water discharges primarily along developing trunk passages, the potentiometric surface "lowers" into sections of these passages which become ideal water-table caves. Spring shafts or joint chimneys constitute phreatic loops between horizontal levels. Spring positions shifted down and northeastward as the Gypsum Plain and regional base level (now at Carlsbad Springs, Carlsbad) lowered. After Ford and Ewers (1978).

(Fig. 6). This is a prime example of a speleothem that has been subjected to condensation-corrosion—a process that has occurred (and is occurring) throughout Carlsbad Cavern and many other Guadalupe caves. Condensation-corrosion (also sometimes called "gas-weathering") is the process by which water charged with a high level of carbon dioxide condenses out on bedrock or speleothem surfaces and corrodes them. Three atmospheric conditions are needed in a cave before condensation-corrosion can occur: (1) a high CO_2 level in the air, (2) a high amount of moisture (humidity) in the air and (3) a temperature gradient between air in different passages. In the case of Taffy Hill, a temperature gradient between cave and entrance air is causing denser, cooler, drier air to flow from the entrance into the cave along the floor of the Main Corridor, whereas less dense, warmer, more moist, higher-CO_2 air is flowing out of the cave along the ceiling. This more acidic air causes the ceiling travertine to be corroded. At certain times of the year (especially in the winter) a "cloud" of moisture hangs over Taffy Hill due to the mixture of dry outside air and moist cave air.

STOP 9. Whale's Mouth. Inside the lighted "Whale's Mouth" is a beautiful display of drapery speleothems. "Speleothems" are secondary mineral deposits in caves ("cave formations") that are usually named after objects they look like (e.g., a cave drapery looks like a curtain or drapery). Five basic hydrologic mechanisms influence the shape of speleothems: dripping, flowing, seeping, pool and condensation water (Hill and Forti, 1986). Draperies are a composite flowstonedripstone speleothem. At first, rivulets of water flow down an inclined surface, building up narrow flowstone bands of minerals. Small undulations in the bedrock cause the flowstone to become slightly curved, with preferential deposition of travertine on the outside edge of each curved segment. With time, these curves can become more and more accentuated so that the drapery becomes highly folded or furled along its lower edge. Finally, dripstone forms at the bottom of the drapery where the furls are steep enough for water droplets to fall to the floor. Cavers call this type of drapery at the Whale's Mouth "bacon" because it is colorfully streaked in parallel bands like strips of bacon. The colored bands are caused by iron or other impurities.

Also note the lighted stalagmite on the south wall of the cave passage. The stalagmite looks like it is surrounded by a "halo" of popcorn. This is an example of "subaerial popcorn." Subaerial coralloids assume popcorn, coral, grape or knobstone shapes (rather than cauliflower shapes, as was seen under water at Devil's Spring) and they form in a variety of ways: (I) by water seeping through bedrock, (2) by thin films of condensation water moving down over wall irregularities, (3) by splash from dripping water and (4) by water moving upward from pools onto walls by capillary wicking. All four mechanisms are similar in that they link coralloid growth to the presence of thin films of water (how or where these thin films originate is less important). The popcorn on the far wall was formed by mechanism (3): water drips from the ceiling onto the stalagmite and splashes onto the wall, forming a "halo" of popcorn there.

STOP 10. South wall of cave, where trail cuts through the short tunnel. Note the maze of passages in the wall. One must crawl through this maze in order to get into the "New Section" of the cave (Sand Passage, Guadalupe Room). The New Section represents a horizontal level 120 m down from the surface, intermediate between the Bat Cave level (-60 m) and Big Room level (-230 m). The New Section is off limits to all but cave researchers.

Go through the short tunnel to the hand railing on the other side of the tunnel. This area of the cave is called Devil's Den. The passage you see below the large breakdown block in the floor connects (via a handline and lots of down-climbing) with Lower Devil's Den and Secondary Stream Passage (at the Big Room level). Now, look along the right wall, just beyond (2 m) the railing and note the rounded "cobbles" in a solution alcove. This is the first occurrence of the mysterious cobbles that can be found in the Secondary Stream Passage at the Big Room level (-230 m) and even lower at the Lower Cave level (-260 m).

STOP 11. Upper Devil's Den. The highest occurrence of massive gypsum in Carlsbad Cavern can be seen in the protected alcove of Upper Devil's Den. Massive (nonspeleothemic) gypsum in Guadalupe caves is the result of a sulfuric acid dissolution mechanism:

$$2H^{+} + SO_4^{-2} + CaCO_3(ls) + 2H_20 = CaSO_4.2H_20\ (gyp) + H_20 + CO_2 \quad (1)$$

All large passages in Carlsbad Cavern were dissolved by sulfuric acid, but in passages such as the Main Corridor, where water flowed vigorously upward toward a paleospring outlet, any gypsum that did precipitate by this reaction was redissolved and carried out of the cave. Only in places of relatively slack current or disconnected flow (e.g., Upper Devil's Den, Big Room) did gypsum precipitate and remain on cave floors.

Note the laminations in the cave gypsum where the trail narrows at the beginning of the tunnel. These laminations represent a two-component system of colorless selenite alternating with opaque gypsum. Despite the resemblance to laminations in the anhydrite of the basinal Castile Formation, the cave-gypsum laminations do not contain any calcite. But, like the Castile laminations, these cave-gypsum laminations may represent varves (annual accumulations of material) caused by seasonal variations in volume or rate of water flow, evaporation or temperature.

STOP 12. Up steps and along tunnel, overlook to Lower Devil's Den. From this vantage point you can look down into Lower Devil's Den, about 90 m below. Bones of the extinct ground sloth *Nothrotheriops shastensis* have been found in Lower Devil's Den not far from

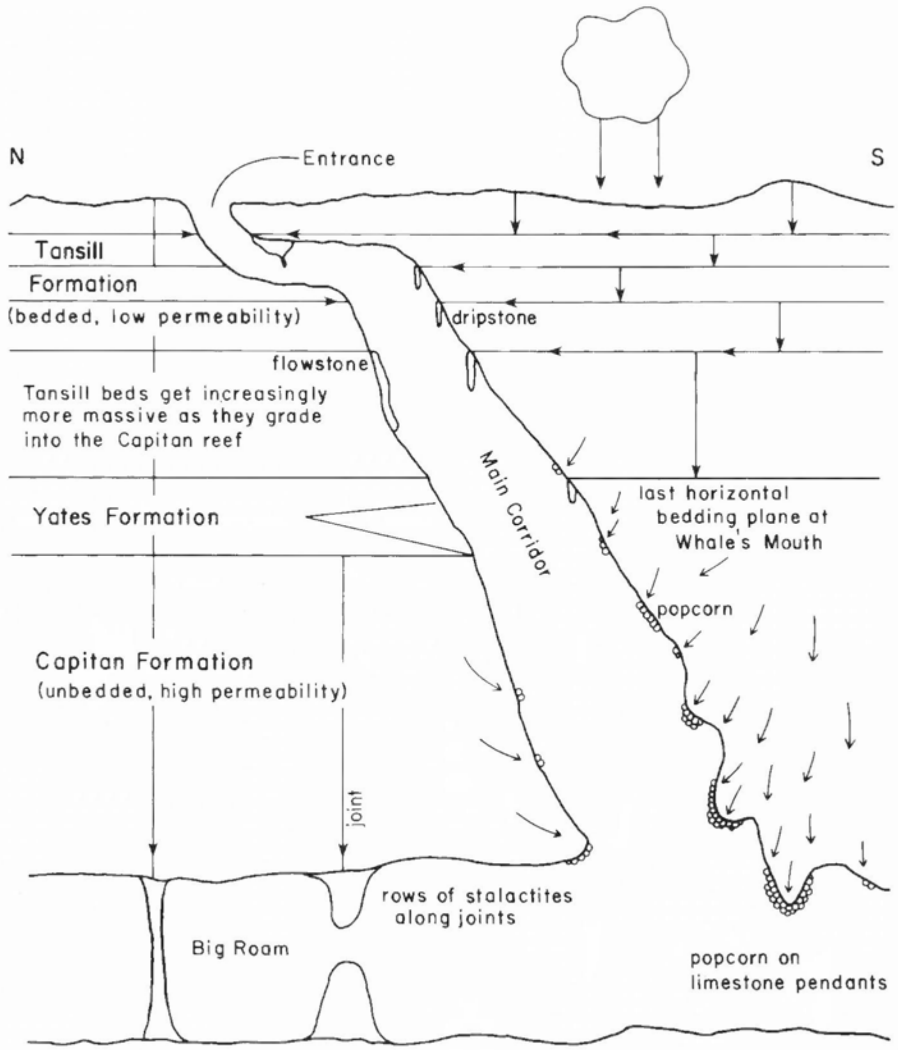

FIGURE 5. Influence of bedding and permeability on the type of speleothem deposited, Carlsbad Cavern. From Hill (1987).

this spot on the cave floor. These bones were dated at 111,900 years before present (ybp) (U-series on bone; Hill and Gillette, 1987). This age implies that the entrance to Carlsbad Cavern has been open for at least 112,000 years. The sloth probably wandered into the cave entrance and fell from Upper Devil's Den to Lower Devil's Den, where it died.

STOP 13. Seating area, after emerging from the Devil's Den tunnel and before the Baby Hippo. Note the high ceiling in this section of the Main Corridor. This is the same bedding plane in the Tansill Formation that was pointed out at Stop 7. Follow the high bedrock ledge in front of you all the way (-60 m up) to the top: can you see a stalagmite perched on the top of the ledge? This stalagmite was tied off curing a "balloon ascent" in order to explore the passageway near the ceiling. Unfortunately, the passage "doesn't go" (as cavers like to say).

Downhill from this seating area are a number of tall, narrow stalagmites, among which is the "Witches Finger" (Fig. 7). Massive stalagmites (like the Rock of Ages) form where dripping is rapid and there is not enough time for a ceiling droplet to reach equilibrium with its surroundings so as to form a large stalactite. If dripping is very fast, then water flow and precipitation takes place down along the sides of the stalagmite and it increases in width. If dripping is slower, then most of the material deposits on the apex of the stalagmite and a tall, thin, "broomstick" stalagmite like the Witches Finger forms. A stalagmite such as the Witches Finger, which is uniform in diameter, may also be evidence for the constancy of dripping over time.

STOP 14. Tip of Iceberg Rock. The large rock in front of you is the upper tip of Iceberg Rock, the largest breakdown block in Carlsbad Cavern. Iceberg Rock was estimated by Bullington (1968, p. 22) to be "170 feet in length and to weigh over 200,000 tons." Note the area of rock unadorned with travertine directly above Iceberg Rock: this is the area from which the rock fell. Tilted stalactites on the base of Iceberg Rock (which grew before the rock fell and which we will see at Stop 19) have an Electron Spin Resonance (ESR) date of 513,000 ybp and vertically oriented stalagmites on the top of Iceberg Rock (which grew after the rock fell) have a U-series date of 180,000 ybp or younger (Ford and Hill, 1989). Therefore, we know that Iceberg Rock fell sometime between about 500,000 ybp and 200,000 ybp. (Nothing to get worried about!)

STOP 15. Green Lake Room. Green Lake is another cave pool fed by drip water. The narrow passage seen high above the Green Lake connects to the New Mexico Room. Native sulfur has been found in the New Mexico Room along siliciclastic bedding planes dipping toward the basin, and in the Chocolate High, a new area of the cave discovered in 1992. Hill (1987) speculated that the siliciclastic beds may be an extension of the Bell Canyon Formation, along which hydrogen sulfide migrated from the basin into the reef (Fig. 8).

STOP 16. King's Palace. As one enters the region of the King's Palace more and more "cave formations" (speleothems) can be seen. An unusual type of speleothem readily observed along the trail as one

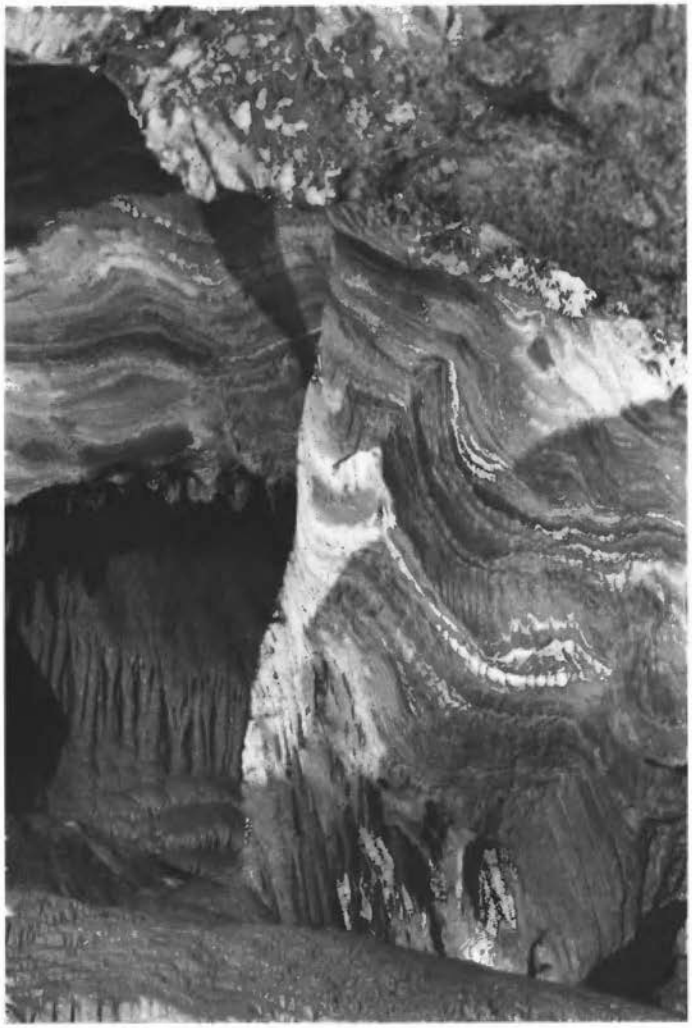

FIGURE 6. Photo of Taffy Hill flowstone, showing travertine that has been condensated-corroded flush with the bedrock limestone wall. At the upper right is corroded bedrock wall. In the middle of the photo is corroded flowstone and on the bottom is the uncorroded, still-growing flowstone of Taffy Hill. Photo by National Park Service.

FIGURE 7. Photo of Witches Finger, a "totem-pole" or "broomstick" type of stalagmite. Photo by National Park Service.

enters the King's Palace is the "deflected stalactite" (Fig. 9). Deflected stalactites start out their growth as curved soda straws and continue growing in this curved mode. The precise cause of deflection is not known. One hypothesis is that the curvature is related to the direction of air-flow; however, even adjoining stalactites (within tens of centimeters of each other) can have different directions of curvature or be perfectly vertical.

STOP 17. Queen's Chamber. Look up at the ceiling at the profuse and tangled mass of helictites. A helictite is a speleothem that formed by seeping water rather than by dripping water. In the center of each helictite is a tiny capillary tube through which water moves under hydrostatic pressure to the outer growth tip. Helictite growth is therefore not controlled by gravity and can proceed in any direction. The helictites seen here in the Queen's Chamber are the "vermiform" (worm-like) variety and the "antler" (twig-like) variety. Antler helictites are those that have straight stems and bifurcating branches. More often than not the branches take off in an almost horizontal or vertical direction. Other types of helictites in Carlsbad Cavern (but which do not occur here in the Queen's Chamber) are a "filiform" (thread-like) variety consisting of tiny, hair-like filaments and a "beaded" variety composed of aragonite (instead of calcite) and shaped like a string of rosary beads.

As you walk along the trail, just before it turns back on itself, look up and see the overhead metal ladder. This is the way into Mabel's Room, another off-trail chamber in Carlsbad Cavern.

STOP 18. Papoose Room, just before the short tunnel. Here, adjacent "spongework"-like holes in the rock are filled with green clay and dogtooth spar crystals. "Spongework" is a three-dimensional, honeycombed, "Swiss cheese" network of cavities a few centimeters to a few meters or so in diameter and depth. Spongework is the result of diffuse circulation of water within pore spaces in bedrock. Every cave in the Guadalupe Mountains is surrounded by bedrock that exhibits a matrix or framework of spongework. Hill (1987) called these caves "Solution Stage II caves." Solution Stage II cavities and small caves predate and are cut across by the large, Solution Stage III, sulfuric acid cave passages (like the one you are walking in).

The green clay in one of the holes is montmorillonite, a type of clay that often derives from limestone. This montmorillonite clay has been dated by the K-Ar dating method at 188 ± 7 Ma (early Jurassic). While highly speculative, this date makes sense geologically because the Jurassic was a time of uplift and exposure of rock to karst-forming meteoric water. If this clay is really Jurassic in age, then it is one of only a few Jurassic deposits known to exist in the Delaware Basin area. The dogtooth spar is part of the Miocene thermal spar episode discussed at Stop 3.

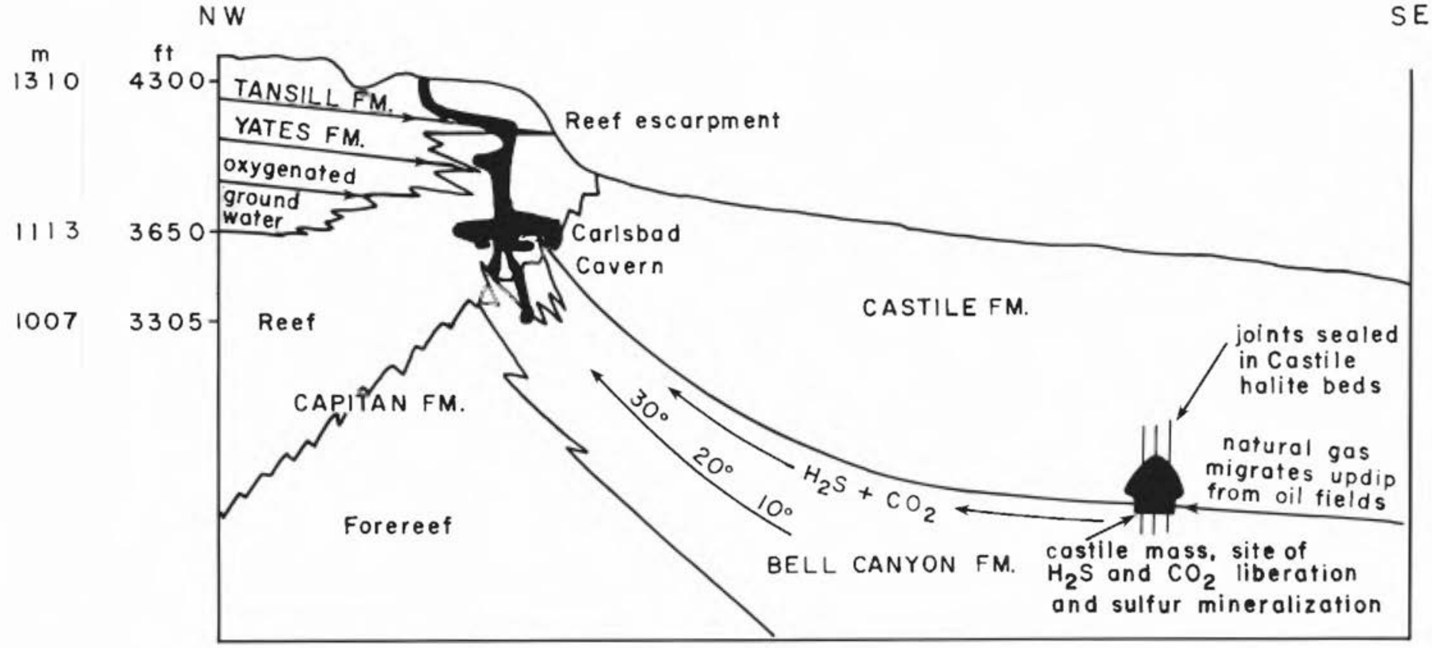

FIGURE 8. Model of gas ascension from the basin into the reef along the Bell Canyon Formation. Natural gas migrated updip from the oil fields to the east and encountered anhydrite at the base of the Castile Formation. Reactions between the gas and the anhydrite solutions produced hydrogen sulfide, carbon dioxide and the replacement-limestone of the "castile" masses and buttes. Hydrogen sulfide moved updip along interfingerings of the Bell Canyon Formation and where this gas mixed with oxygenated ground water moving downdip along backreef beds, sulfuric acid formed, which dissolved out the large cave passages in the Guadalupe Mountains. From Hill (1987).

STOP 19. Base of Iceberg Rock, Appetite Hill. Look up at the base of Iceberg Rock. These are the tilted stalactites that grew on the bottom of Iceberg Rock before it fell and which have been dated at —513,000 ybp (as discussed at Stop 14). Turn off onto the Cutoff Trail. About **5** m in from the main trail, breccia pieces cemented in a mudstone matrix can be observed in the cave wall about 3-4 m up from the floor. Hill (1987) called this breccia-filled paleokarst "Solution Stage I caves" and speculated they were Late Permian in age. Back on the main trail and up farther along Appetite Hill, mudstone clasts (similar in texture and composition to this mudstone matrix) can be seen as isolated, angular pieces within the rock. Since these mudstone clasts appear to be penecontemporaneous with sedimentation, the mudstone matrix-filled breccia caves must also be very early, perhaps dating from the Ochoan when the Guadalupe Mountains may have begun uplifting and when a freshwater lens first became established in the reef (Mruk, 1985).

FIGURE 9. Photo of a deflected stalactite, Kings Palace. The direction of deflection is not consistent, even between deflected stalactites that are close to each other (i.e., notice that the stalactite on the left is vertically oriented). Photo by National Park Service.

STOP 20. The Boneyard. "Boneyard" is a large form of spongework separated by stretches of unaffected wall. Boneyard is so named because it looks like a jumble of bones (Fig. 10). This integration of space and rock may be a few meters deep and wide, or it may continue for a distance of many meters. A boneyard type of passage form is evidence of nondifferential phreatic attack where cave ceilings are subjected to as much solution as cave walls. Boneyard is often found at the base of large rooms or passages and is believed to represent contemporary enlargement of spongework in rock surrounding passages being dissolved by a sulfuric-acid mechanism, especially in slack current places (Hill, 1987).

STOP 21. Crossing trails, Big Room. Turn around and look up at the lighted hill on which there are "spires" or "spikes" sticking up from floor breakdown blocks (Fig. 11). These geomorphic karren forms are called "spitzkarren" and are carved in bedrock. The spitzkarren was formed by "acid rain" dripping off the cave ceiling, much as

FIGURE 10. Photo of The Boneyard, Carlsbad Cavern. Photo by National Park Service.

FIGURE 11. Photo of spitzkarren, Big Room, Carlsbad Cavern. Photo by National Park Service.

similar-looking spitzkarren is formed in the limestone terranes of Yugoslavia and elsewhere—that is, by water charged with carbon dioxide (Sweeting, 1973).

STOP 22. Lunch Room. This is the end of the geologic scenic tour. For those of you who do not want to go on the Big Room geologic tour, you can exit to the surface via the elevators here in the Lunch Room.

STOP 23. Big Room Geologic Tour, Lunch Room. Look up at the ceiling of the Lunch Room and note the solution pockets. "Solution pockets" are spherical cavities in cave walls and ceilings that are tens of centimeters to tens of meters wide and deep. Ceiling solution pockets can be approximately equidimensional, or they can be linearly developed along joints. Solution pockets are prime indicators of phreatic dissolution. Bretz (1949) was the first to propose a phreatic origin for Carlsbad Cavern and his classic paper brought to the attention of the world the importance of phreatic dissolution of caves. These solution pockets have been modified—rounded and scoured by condensation-corrosion (see discussion, Stop 8).

STOP 24. Cross-trails, Big Room. On the hill to your right are sharply spiked geomorphic forms in bedrock called "spitzkarren." (These forms were described at Stop 21.)

Turn around toward the opposite wall in order to see "flat-bottomed" popcorn. Flat-bottomed popcorn is a type of subaerial coralloidal speleothem formed by condensation water (type 2 popcorn, Stop 9). It forms in areas of condensation-corrosion (mechanism described at Stop 8) and is the type of popcorn associated with the so-called "popcorn line" in the Big Room (Stop 25). Martini (1986) attributed the growth of flat-bottomed popcorn ("trays" as they are called in South Africa) to evaporation and undersaturated solutions where growth is possible only upward and laterally along a rock pendant. In Carlsbad Cavern the undersaturated solutions are supplied by condensation.

STOP 25. Lion's Tail. Here, a definite "line" can be seen on both speleothems and wall rock (Fig. 12), where popcorn occurs below the "line" and bare, corroded bedrock occurs above the "line" (e.g., the corroded upper part of the "Lion's Tail"). Some geologists have speculated that this popcorn line represents a water line made when the Big Room was filled with water, but Hill (1987) showed that the line resulted from an air-flow, condensation-corrosion phenomena. Hill's interpretation was supported by CO_2 measurements made along Left Hand Tunnel (the cave passage at the other end of the Lunch Room where the line continues) and by U-series dates on popcorn which varied from 33,000 ybp to >350,000 ybp. Dates on popcorn and on travertine beneath the popcorn (collected from the base of the Twin Domes stalagmite on your left) show a gradual change from a moist, travertine-depositing environment to a more evaporative, popcorn-depositing environment.

The popcorn line in the Big Room and Left Hand Tunnel can be related to the process of condensation-corrosion and also to patterns of air flow. Where cold, dry, denser air moves into a cave room along a passage floor, it deposits popcorn; where warmer, moister, less dense, CO_2-rich air flows out of the room along the ceiling it corrodes the bedrock and speleothems. The main mass of air flowing into the Big Room moves from the Lion's Tail straight across the room to the area of Crystal Springs Dome; it does not "turn the corner" at the Temple of the Sun. Hence, the popcorn line dies out around the "corner" before reaching the Breast of Venus but is well developed in the Crystal Springs Dome area across the passage (Stop 32).

STOP 26. To the right of the trail, along the wall, just beyond the Breast of Venus. Note the conically shaped mass of travertine that appears to cover a light-colored mass of detrital material. These are the "half cones" of Good (1957) and the light-colored material is a mixture of coarse-grained silt and fine-grained sand (Hill, 1987). This quartz-sand half-cone and others like it along the west wall of the Big Room are most perplexing because it is not at all clear where this siliciclastic material came from. The conical masses of sand have gradational, rather than dike-like, contacts and appear to be sand lenses in the limestone wall that slumped into conical piles as the cave walls receded by dissolution.

FIGURE 12. Popcorn line along trail near the Lion's Tail stalactite, Big Room, Carlsbad Cavern. Note that the popcorn covers the wall and speleothems below the line, but not above it. Photo by Alan Hill.

STOP 27. Jumping Off Place. Bend over the railing (not too far!) and look down at the cave floor below. This is the floor of Lower Cave, a passage which is off limits except to cave researchers and other authorized persons. Look farther beyond, where a high passage is lighted—this is the Talcum Passage, a remnant passage at the Big Room level.

Turn around and note the massive gypsum block overlying the bedrock floor. The gypsum block has a number of vertical holes in it—these are "drip tubes" created by water dripping off the ceiling and into the soluble gypsum. This massive gypsum formed according to the chemical equation described at Stop 11 (Upper Devil's Den). Essentially, when sulfuric acid dissolves limestone, gypsum is produced as **a** by-product of the reaction. A sulfur isotope analysis on these particular gypsum blocks had a value of $\delta^{34}S$ = —19 per mil (CDT). The enrichment in the light isotope of sulfur in this (and other) gypsum blocks in the caves of the Guadalupe Mountains was what led Hill (1987, 1990) to propose a genetic connection between the caves in the Guadalupe Mountains and hydrocarbons in the Delaware Basin. As you go through the tunnel look for laminations in the gypsum as were seen at Stop 11.

STOP 28. Second tunnel in gypsum block; native sulfur, —2.5 m above the floor, located along a drip tube. Look closely for the native sulfur in this occurrence but *please do not touch it!* The pale-yellow sulfur covers an area —0.6 m high and 0.3 m wide. It occurs in gypsum, but did not form by the reduction of the gypsum—it formed by the oxidation of hydrogen sulfide. Drip tubes in gypsum are formed under subaerial (dripping) conditions and the sulfur has formed subaerially (rather than subaqueously) according to the following equation:

$$2H_2S + O_2 = 2S + 2H_2O \qquad (2)$$

Native sulfur has been found in other parts of Carlsbad Cavern (off of the Lunch Room, in the Left Hand Fork of Left Hand Tunnel and in the New Mexico Room below the Balcony and up in the Chocolate High). It is also present in Lechuguilla Cave, Cottonwood Cave and Spider Cave. In Lechuguilla Cave massive amounts (tons) of sulfur have been found in a number of cave passages.

STOP 29. Top of the Cross. The Top of the Cross is 87 m high from floor to ceiling. This passage was also explored by "balloon

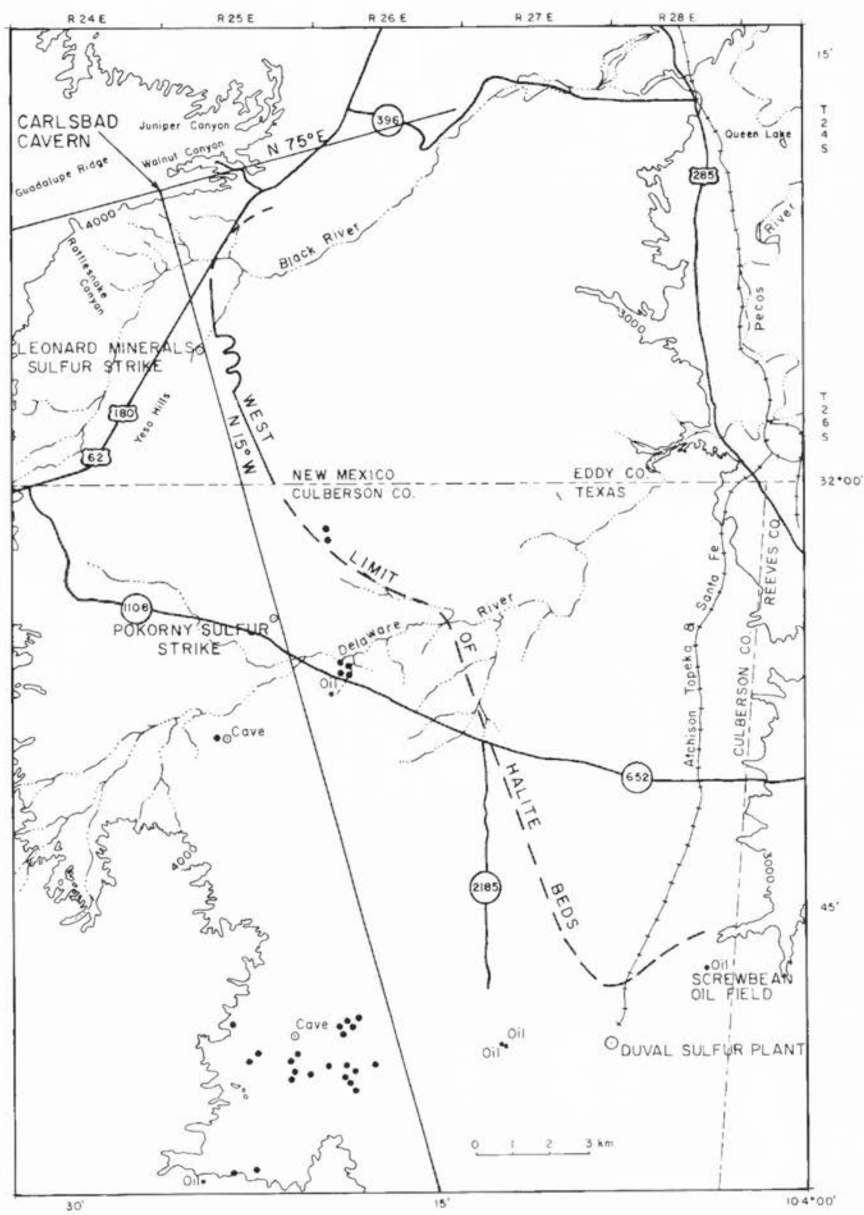

FIGURE 13. Location of Carlsbad Cavern in relation to oil, sulfur and the castile buttes (circular black dots) of the Gypsum Plain. The straight line is an extension of the trend of the Big Room, Bottomless Pit set of joints (N15°W). Dashed and solid line is the west margin of Halite I beds of the Castile Formation. Caves in the Gypsum Plain are tubular and have degassing H_2S and native sulfur.

ascent" (the upper passage goes over the Bottomless Pit and then stops). Note the well-preserved fossils in the Capitan reef rock just east of the seating area.

Just beyond the Top of the Cross, along the right wall, a pure white clay (endellite) can be seen within a surrounding red-brick clay matrix (montmorillonite). Endellite ($Al_2Si_2O_5(OH)_4{\bullet}2H_2O$) is a waxy, colorful (blue, blue-green, pure white and lavender) clay mineral. This mineral is another important indicator that Carlsbad Cavern and other caves in the Guadalupe Mountains had a sulfuric acid genesis. Endellite is known to form only under low pH (<6), sulfuric acid conditions (Hill, 1987).

STOP 30. Bottomless Pit. Bottomless Pit is a tubular-shaped pit called a spring shaft. A "spring shaft" is distinct from a "collapse shaft" or "dome pit," in that it forms by ascending water rather than by descending water. Spring shafts may constitute a "phreatic loop" between two cave levels (Fig. 4) or they may lead to the surface (e.g., the tubular-pit entrance of Deep Cave, Guadalupe Mountains).

Bottomless Pit may have also been an injection site for H_2S gas ascending from the basin. The N15°W series of joints along which this section of the Big Room is developed extends out into the basin and is the site of a sulfur strike at CP Hill ("Leonard Minerals sulfur strike"; Fig. 13). Where gas is injected into the reef along a joint, the H_2S oxidizes to sulfuric acid, the acid dissolves the limestone bedrock, the silt released from the limestone settles to the floor and then the gypsum (from equation 1) precipitates over the silt (Fig. 14). In addition, the clay mineral montmorillonite changes to endellite under low pH, sulfuric acid conditions and the CO_2 released in equation (1) causes passages to enlarge or stope upward by the process of condensation-corrosion. Fissures or tubular conduits (e.g., Bottomless Pit) connect with lower levels (e.g., the Lower Cave level) or "die with depth" (Fig. 14). Passages end abruptly away from gas injection sites and have no clear-cut relationship to recharge or resurgence points, either ancient or modern. The Big Room terminates at the Bottomless Pit without even a minor passage extension or area of breakdown collapse.

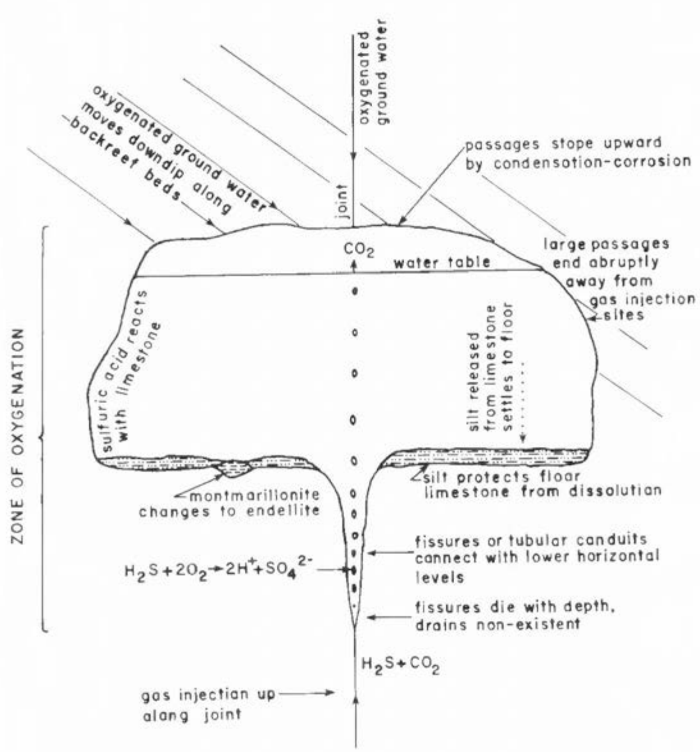

FIGURE 14. Model of hydrogen-sulfide reaction with dissolved oxygen near the water table. Hydrogen sulfide from the basin ascended into the reef along injection points and reacted with oxygen in the zone of oxygenation at or near the water table to form sulfuric acid. Sulfuric acid was neutralized by the limestone away from the injection points and, therefore, horizontal rooms end abruptly. The sulfuric-acid reaction did not occur below the zone of oxygenation and hence vertical passages die with depth below large, horizontal rooms. With successive lowering of base level, new horizontal levels became connected with older horizontal levels by spring shafts and joint chimneys. From Hill (1987).

STOP 31. Salt Flats, gypsum and chert. To your left (off the trail) is an exposure of chert that occurs in brick-red to ocher-yellow silt deposits on the floor. The chert displays a layered structure consisting of micritic chert and more porous, granular chert (Fig. 15). The rhythmic layers in the chert may have been produced by a liesegang-ring type of phenomena where silica was periodically precipitated from solutions diffusing through the porous silt medium. The chert is believed to be related to the alteration of montmorillonite to endellite and silica by the action of sulfuric acid solutions (Fig. 16).

Just beyond the chert is an extensive section of massive gypsum blocks. Dissolution features in these blocks include drip tubes and splash undercuts. Drip tubes are caused by water dripping from the ceiling and dissolving vertical tubes in the soluble gypsum. Splash undercuts are formed where dripping water has cut all the way through a gypsum block to the limestone floor rock beneath the block. Dripping water falls through the vertical drip tube, splashes off the bedrock floor and undercuts the base of the gypsum block in a semicircular splash pattern.

FIGURE 15. Porous and micritic layers in a displaced chert lens, Salt Flats, Big Room, Carlsbad Cavern. The porous layers contain grains of quartz sand in a chert matrix, whereas the micritic layers are free of sand. Note the very fine laminations in the micritic layer where the ruler is resting. Photo by Alan Hill.

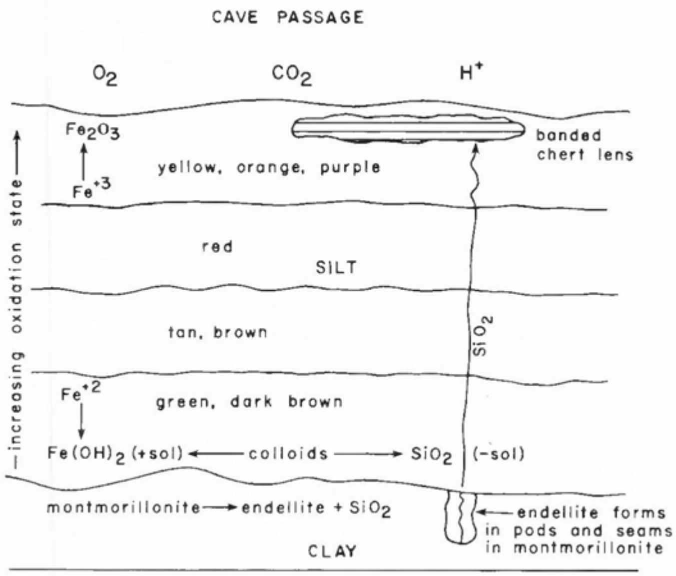

FIGURE 16. Diagrammatic presentation of montmorillonite-endellite clay, color-banded silt and chert deposits of the Big Room, Carlsbad Cavern. Silica and ferric hydrates acted as colloidal "sols" which moved to positively or negatively charged sites to be neutralized. Colloidal behavior produced the color banding of the silt and the rhythmic banding of the chert. From Hill (1987).

STOP 32. Crystal Springs Dome. Notice that the popcorn line is beginning to appear along the wall again. Air flow moves straight across the Big Room from the Lion's Tail area to Crystal Springs Dome area; thus, the line continues here.

Crystal Springs Dome is called an active speleothem because it is still growing from water dripping from the ceiling. Probably less than 5% of all the speleothems in Carlsbad Cavern are active. You can tell active speleothems from inactive ones because the active ones are wet and glistening and the inactive ones are dull and opaque. Note the canopy-like deposit at the base of Crystal Springs Dome, just above the pool level. This type of speleothem is called a baldacchino canopy, after similar ones first described in Italy. A baldacchino canopy is formed when downward-growing flowstone intersects a cave pool. The flat bottom of the canopy corresponds to the flat surface of the pool.

STOP 33. The trail leading down into Lower Cave. This is the way down into Lower Cave. One of the classic cave-pearl localities in the world is located in "The Rookery" of Lower Cave. The Rookery used to be lined with hundreds of cave pearl "nests" before the guides in the 1920s and 1930s handed most of the pearls out to visitors as souvenirs. Cave pearls are banded, pearl-like, speleothemic concretions that form in shallow cave pools or in floor depressions where water is dripping in from above. Cave pearls are usually polished to a high glow and their appearance is nearly identical to that of real pearls.

STOP 34. Lunch Room. We are at the end of our Big Room Tour. Lunch is available here in the Lunch Room or in the cafeteria on the surface. I hope that you have enjoyed your geological tour of Carlsbad Cavern.

REFERENCES

Assereto, R. and Kendall, C. G., 1977, Nature, origin and classification of peritidal tepee structures and related breccias: Sedimentology, v. 24, p. 153-210.

Barker, C. E. and Pawlewicz, M. J., 1987, The effects of igneous intrusions and higher heat flow on the thermal maturity of Leonardian and younger rocks, western Delaware Basin, Texas; *in* Cromwell, D. W., ed., Society of Economic Paleontologists and Mineralogists, Glass Mountains Guidebook, p. 69-83.

Bretz, J. H., 1949, Carlsbad Caverns and other caves of the Guadalupe block, New Mexico: Journal of Geology, v. 57, p. 447-463.

Bullington, N. R., 1968, Geology of the Carlsbad Caverns; *in* Delaware Basin exploration, West Texas Geological Society, Guidebook 68-55, p. 20-23.

Curl, R. L., 1974, Deducing flow velocity in cave conduits from scallops: National Speleological Society Bulletin, v. 26, p. 74.

Ford, D. C. and Ewers, R. 0., 1978, The development of limestone cave systems in the dimensions of length and depth: Canadian Journal of Earth Sciences, v. 15, p. 1783-1798.

Ford, D. C. and Hill, C. A., 1989, Dating results from Carlsbad Cavern and other caves in the Guadalupe Mountains, New Mexico: Isochron/West, v. 54, p. 3-7.

Good, J. M., 1957, Non-carbonate deposits of Carlsbad Caverns: National Speleological Society Bulletin, v. 19, p. 11-23.

Hill, C. A., 1987, Geology of Carlsbad Cavern and other caves in the Guadalupe Mountains, New Mexico and Texas: New Mexico Bureau of Mines and Mineral Resources, Bulletin 117, 150 p.

Hill, C. A., 1990, Sulfuric acid speleogenesis of Carlsbad Cavern and its relationship to hydrocarbons, Delaware Basin, New Mexico and Texas: American Association of Petroleum Geologists Bulletin, v. 74, p. 1685-1694.

Hill, C. A., 1992, Isotopic values of native sulfur, barite, celestite and calcite: their relationship to sulfur deposits and to the evolution of the Delaware Basin (preliminary results); *in* Wessel, G. R. and Wimberly, B. H., eds., Native sulfur—developments in geology and exploration: Society for Mining, Metallurgy and Exploration, Proceedings, Phoenix, Arizona Meeting, February 26, p. 147-157.

Hill, C. A. and Gillette, D. D., 1987, A uranium-series date for the Shasta ground sloth, *Nothrotheriops shastensis* from Carlsbad Cavern, New Mexico: Journal of Mammalogy, v. 68, p. 718-719.

Jagnow, D. H., 1977, Geologic factors influencing speleogenesis in the Capitan Reef Complex, New Mexico and Texas [M.S. thesis]: Albuquerque, University of New Mexico, 197 p.

Martini, J., 1986, The trays; an excellent example of evaporation-controlled speleothems: South African Speleological Association Bulletin, v. 27, p. 4651.

Mruk, D. H., 1985, Cementation and dolomitization of the Capitan Limestone (Permian), McKittrick Canyon, West Texas [M.S. thesis]: Boulder, University of Colorado, 155 p.

Sweeting, M. M., 1973, Karst landforms: Columbia University Press, New York, 362 p.