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TRAIL GUIDE TO AND DISCUSSION OF THE GEOLOGY OF CARLSBAD CAVERN: MAIN CORRIDOR AND BIG ROOM

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INTRODUCTION

Carlsbad Cavern, located in Carlsbad Caverns National Park in southeastern New Mexico, is one of the most geologically significant and studied caves in the world. Many geologic details may be observed from the main trails of Carlsbad Cavern, which affords a better overview of shelf and shelf edge geology, tectonic history, diagenesis, hydrology, speleogenesis, and speleology than any surface trails of comparable length. This guide is not long enough to consider the stops in detail. It is intended to help cave visitors find sites and relate what they see to the overall geologic and speleological framework. Stop descriptions briefly include where to look, what to look for, which figures in the proceedings are relevant, and the significance of the site. The guide will likely raise as many questions as it answers.

This guide considers five aspects of regional geology and speleogenesis: (***A***) regional geology and sedimentology; (***B***) post-Permian geologic history; (***C***) pre-drainage dissolutional history; (***D***) post-drainage influence of H_2S and thermal convection; and (***E***) post-drainage speleothems and biothems. The icons (e.g., ***A***) accompanying each stop will help users focus on those aspects that are of greatest interest.

Users of this guide should take a flashlight to facilitate examination of the outcrops, a sweater to allow their leisurely study, and wear comfortable, non-skid footwear. Each stop is identified on the accompanying Carlsbad Cavern maps (Fig. 1-6), which are greatly simplified. Interested visitors may wish to purchase the larger, more detailed map in the Visitors Center bookstore.

The trail is steep in places, but handrails are present throughout most of its length. Be sure to stay on the trail. Going off trail may be hazardous, will likely cause irreparable damage to irreplaceable resources in this largely inactive cave, and, of course, is prohibited without specific permission. Any breakage or other impact will likely be permanent. Please respect and help protect this rare and precious environment. As you look at and discuss the geology, please speak softly, avoid obstructing other visitors, and watch where you are going when walking through the cave.

Main Corridor Trail Guide

The Main Corridor Trail starts from the Amphitheater at the surface and descends 230 m through a complete section of shelf crest to slope depositional facies (Fig. 1 and 2). Outcrops along the way reveal details of the post-depositional history of the region, including several generations of paleokarst, pre- and post-drainage cave development, and a spectacular array of speleothems (secondary cave deposits).

A **(MC1) Teepee**: Behind the lectern at the cave entrance (Fig. 2), shelf crest fenestral dolostone beds thin upward into a central disrupted zone, indicating that the common "teepee" structures in the Permian Tansill Formation have syndepositional origins. Gray marine cements and laminated internal sediments may be seen in the disrupted zone (1.2 m right of axis) and in interstratal cracks that thin away from the axis. The bed just above trail level is undisrupted. Did cements fill open pores or did their precipitation open the pores? The jury is out. Can you think of other possible methods to form these features?

A **(MC2) Inclined fracture**: At Audio Guide Stop [5] (small, brown sign), a vertical wall over the trail as one looks into the cave displays several pores 10s of centimeters across that formed along an inclined fracture of, perhaps, Laramide origin.

A **(MC3) Fenestral dolostones**: At the first switchback after [5], a boulder set in the wall to the left of the trail displays laminated carbonate rocks with abundant birds-eye fenestrae, an indicator of intertidal environments. Macrofossils are rare in these environments.

A, B **(MC4) Interstratal pores**: On the left, just beyond the end of the stone wall, several beds have split apart with the lower parts of pores floored by laminated internal sediments locally covered by spar. This general pattern resembles Stromatactis, an important component of some mid-Paleozoic biostromes.

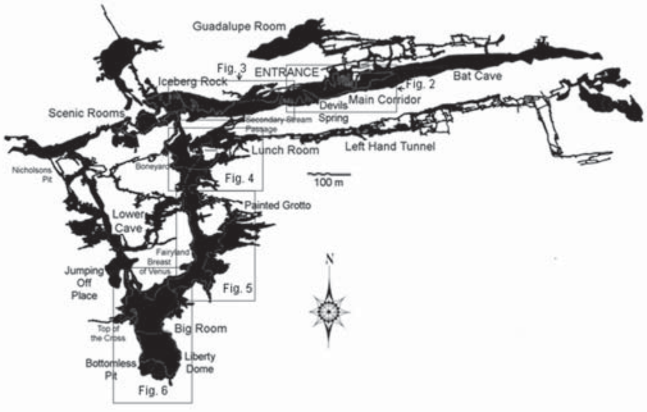

FIGURE 1. Plan view shadow map of Carlsbad Cavern showing location of more detailed maps used to identify field guide stops in the cave.
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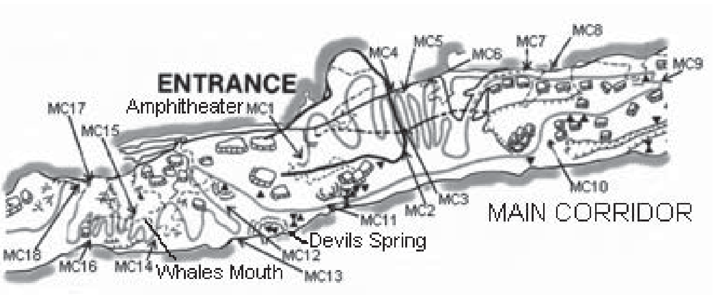

FIGURE 2. Detailed map identifying Main Corridor Stops 1 18.

C, D **(MC5) Angular breccias**: At the next turn to the right, on the left of the trail, is a deposit of angular carbonate debris. No evidence of clast rounding or accompanying sediments suggests deposition by waters flowing in from the draw outside. Nor do significant surface tufas suggest that the entrance has been a spring, at least since the surface was developed following the cessation of Laramide uplift.

B, C **(MC6) Spar-filled fractures**: On the wall to the left of the trail is an irregular fracture largely filled by dogtooth calcite. At least five generations of dogtooth spar in the mountains may be identified by associated pore geometry, internal sediments, and associated secondary minerals. Thus, researchers must carefully document spar occurrence to properly interpret the significance of crystal chemistry. Which generation is represented here? The limited exposures make an attribution difficult. To the left of the spar, fractures suggest a small fault may have helped localize porosity development.

A, B **(MC7) Nodules and stylolites**: About 30 m past the gate of the manmade tunnel and 12 m before the prominent, tall rock on the right of the trail, on the wall rock that overhangs the left handrail, horizons of nodules at eye level have developed. When? Why? Stylolites are common here as well, indicating considerable burial compaction beneath a thick overburden. Following this the region was lifted by the Laramide Orogeny and then eroded to form a gently rolling surface, which has been subsequently uplifted and tilted towards the northwest by Basin and Range tectonics.

A, B, C **(MC8) Lacy pores and mud crack casts**: To the left of the trail, ~5 m beyond the top of the tallest block on the right, a stratiform horizon of irregular, lacy pores highlight dolomitic mudstones of the Tansill Formation. These pores may have formed after the dissolution of evaporite nodules that formed beneath the sediment surface in a sabkha environment. Note the fracture filled with massive dogtooth spar, so corroded as to resemble the general bedrock, and recall the calcite spar-filled fractures seen earlier at Stop MC6. Yet, calcite spar only lines these lacy pores. Why do the lacy pores remain largely open even though they must have been filled with water at the same time as the cracks? In order for pores to be filled with calcite or other minerals, it is not enough simply to be open: pores must be connected to an open system through which water flows and maintains slight supersaturation. On the roof of the main corridor just to the right of the trail, polygonal mud crack casts show where moist sediment, deposited on the shelf-crest, dried out. Thus, parts of the shelf-crest environments were exposed. Models that call for the shelf crest environments to have been but rarely exposed (Pray, 1977) underplay the significance of these features.

B, C, D **(MC9) Bat Cave and wall pockets**: The passage behind the Bat Cave sign continues straight at this level for 500 m along a fracture parallel to the shelf edge. This trend is associated with paleokarst breccias, which controlled water flow at several stages in the evolution of the region. Massive collapse breccias are common in the linear Bat Cave/Main Corridor sections and parallel Guadalupe Room. Several generations of paleokarst may be present. The nearly flat roof evolved at least in part by collapse up to the apparently stable roof. Sediments that entered the cave through entrance(s) at the end of Bat Cave were transported downwards to the level of the Lower Cave through only partially known passages. The wall on the far side shows large, shallow scoops that resemble scallops. Scallops form from turbulent water flow increasing the diffusion of solutes away from the surface, with scallop length an inverse function of current velocity (Curl, 1974). These much larger scoops may reflect bigger eddies resulting from the lower viscosity of air. Consequential heat transfer to the walls caused condensation and corrosion. The lack of associated sediments or small-scale scallops argues against subaqueous origins for these features.

E **(MC10) Guano**: As you peer up at the Entrance, brown deposits of cave swallow and bat guano cover the rocks in front of you. Swallow nests line the walls overhead and towards the cave's entrance. Bats roost in the Bat Cave passage, where their guano was mined for fertilizer in the early 20th Century. Mining operations were never very profitable, perhaps because only about a meter of bat guano overlay ~20 m of clay and silt. All of the material was mixed up and marketed, increasing production but decreasing the quality.

A, B, D, E **(MC11) Yates contact and oriented popcorn**: At the Devils Spring sign, a prominent horizon of stalactites and flowstones marks the top of the Permian Yates Formation at the top of the large flowstone mound. Vadose seepage collects above an impermeable sandstone layer at the top of the Yates and flows down-dip, emerging along the wall. However, the morphology of the cave hardly reflects these lithic differences. Stalagmites to the right of the trail ~10 m ahead have small, irregular lumps of carbonate precipitates called popcorn. Most popcorn forms in the vadose zone from evaporation of thin films of water. Water films thin over substrate protrusions enhancing rates of evaporation and degassing, which causes enhanced mineral precipitation rates. Note how the popcorn is not evenly distributed but is more common and better developed on surfaces facing the entrance. Downward flowing cool air warms and facilitates evaporation, effecting this asymmetry.

D, E **(MC12) Inflowing air**: At the Cavern Climate sign near the base of the flowstone slope, downward air flow is felt all year long. The flow is stronger in the winter, when convective exchange with the outside air draws cold air into the cave. In the summer, convective exchange with the exterior is minimal, but airflow is still felt, representing Rayleigh-Benard convection in the cave. Rising air cools along the passage ceiling. On exposed surfaces and in the atmosphere, condensing moisture dissolves CO_2 and becomes a weak acid. This moisture dissolves bedrock and flowstone, such as the corroded flowstone overhead.

A **(MC13) Pisoliths**: At the first turn beyond the Cave Climate sign, on the left wall ~1.6 m above the floor, is a bed of pisoliths, pea-to-marble sized concentrically laminated carbonate precipitates that formed from supersaturated waters in restricted ponds on the shelf-crest (Dunham, 1972; Esteban and Pray, 1977).

C **(MC14) Mn and alunite (?)**: Just to the left of the trail and ~1 m beyond the bench, a thin black and white crust covers the limestone. The black, immediately next to the bedrock, is a manganese oxide. The white may be gypsum, alunite, or several other acidophilic minerals (Polyak and Guven, 2000). Alunite has been dated in several of the Guadalupe caves using $^{40}Ar/^{39}Ar$ (Polyak et al., 1998). Alunite is associated with gypsum and endellite, which are stable in low-pH conditions (Deer et al., 1967). A phreatic environment would not have maintained these acidic conditions. Carbonate dissolution would have buffered the pH. Consequently, dates derived by this method (4-6 Ma; Polyak and Provencio, 2000) represent minimum ages of drainage when the caves were last flooded. These coatings are most common below sediments covered by a carbonate crust. Why? When did these coatings form?

E **(MC15) Whales Mouth -** Above and right of the trail is an array of thin speleothems called bacon rind. Individual growth layers are commonly well preserved and displayed, and may reflect climatic variations at the time they grew. On the opposite wall above the ledge is a prominent stalagmite with an associated halo of popcorn. This popcorn formed where a thin film of water, derived from drips that splattered on impact with the stalagmite, was evaporated by the downward flow of warming air.

A **(MC16) Shallow marine**: Just left of the trail, beds are thicker and less distinct than the shelf-crest beds in the section above. Several macrofossils seen here include part of a large bellerophont snail. These sediments were deposited in normal marine water between a few meters to ~25 m deep. Fauna here were adapted to life in an occasionally energetic environment of shifting sediments.

B, C, D **(MC17) Pores with silt and cobbles, boneyard**: On the right of the trail, ~8 m before walking under the wedged rockfall, are numerous small, interconnected pores. Rounded carbonate clasts with a clastic silt matrix and covered by brown silts with scattered bat bones fill the pores. Similar pore-filling sediments are also in other scattered locales: below Bat Cave entrance, Sand Passage, Secondary Stream Passage, Lower Cave, and Nicholsons Pit. This distribution indicates downward transport from the Bat Cave entrance. When the Bat Cave entrance was first opened, it was just above the surface arroyo and captured floodwaters with traction load that flowed downward to the lowest drained cave levels. Later, erosion deepened the wash and only floodwater with suspended silts was captured. The Guadalupe Room and approximately one-third of the known cave are reached through the larger pores (passages) above. Exposed on the block to the left, fenestral nodules have been displaced prior to final deposition. Similar features have been interpreted in McKittrick Canyon as caused by high wave energy (Bebout and Kerans, 1993).

A **(MC18) Deeper marine, ammonoids, nodules**: On the left side of the trail just ~20 cm above the metal post and below the overhanging block (Fig. 3), small ammonoid cephalopods are common, as well as indistinct nodules that have been displaced after they formed. Cephalopods are characteristic of well-oxygenated normal marine water. They are commonly thought of as nektonic (swimmers); their abundance here suggests either slow sedimentation rates that allowed the nektonic organisms to form a significant portion of the accumulated sediment or some other concentrating mechanism (e.g. winnowing or local mass mortality); alternatively they could have lived and died in this benthic environment. The dark crystalline material is marine cement, which occurs as botryoidal crusts in early open pores with laminated internal sediments on the bottom. Where were these materials deposited? Are they reefal? A marine hardground?

A, *C, D* **(MC19) Deeper marine, large diverse fossils and later gypsum**: The right wall of massively bedded rock 3 m beyond the wide place displays common shelly macrofauna, including bivalves, cephalopods, and snails. These organisms are all adapted to living on a shifting sea floor. No sessile forms typical of living attached to a hard substrate (reef) are seen. The partly filled snail (1.3 m above trail, 3 m before red phone box) exhibits a geopetal structure, which indicates the original attitude of the strata. The blocks to the left of the trail and ahead are the first massive gypsum deposits seen from the trail, although higher examples are known off-trail. Gypsum blocks comprise several distinct textures (Buck et al., 1994). Ten meters past the red telephone and above the end of the left-hand rail, the block has low porosity gypsum clasts with sub-horizontal laminae unlike any fabric seen in the nearby wall rock. A sugary, porous, lumpy crust coats these blocks and has formed by the re-crystallization of the underlying material. Massive selenite crystals make up some blocks further along. Gypsum blocks in areas with limestone bedrock are commonly massive, laminated, or brecciated, but generally lack evidence of bedrock replacement.

A, D, E **(MC20) Reef and popcorn**: On the right of the trail where the right hand rail begins is a small exposure of bedrock without any secondary coating. Several brachiopods that lived on a hard substrate as part of the framework structure of the Capitan Reef are exposed. Although this community would have included unattached, mobile forms, none are apparent here. The Massive Capitan Formation is large and laterally continuous, but only parts display the organic framework builders, trappers, encrusters and binders, topographic relief, and potential wave resistance that

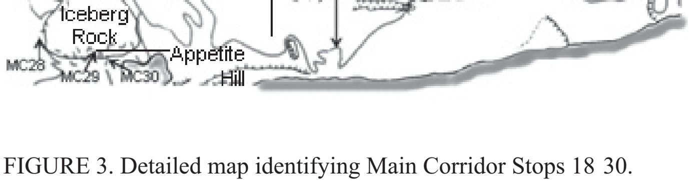

FIGURE 3. Detailed map identifying Main Corridor Stops 18 30.

characterize true reefs (Dunham, 1972). Were the sediments in this exposure part of a large reef or a small patch reef?

The ceiling of this passage is encrusted with rounded, robust lumps of popcorn. Even though this popcorn is significantly different from most of the deposits in the cave, it exhibits the preferred orientation towards the upper parts of the cave, as described at Stop MC11. The large popcorn lumps probably reflect a high, relatively constant supply of seepage water in thick films.

***A* (MC21) Early pores and internal sediments**: On the right, ~2 m above the 4th step, primary pores are floored by laminated and cross laminated, coarse carbonate sediment. Finer-grained, gray, laminated internal sediments, which occur in early pores through much of the shelf edge, locally overlie the laminae.

***A* (MC22) Balloon Ballroom**: As the trail begins to descend towards the lower part of the cave it passes beneath a prow of thick bedded and fractured shelf crest sandstone high above. Explorers long wondered if the cave might continue at the higher level. Eventually, in the early 1980s, cavers used helium balloons and parachute cord to place a climbing rope over the stalagmite on the very edge of the prow and climbed 65 m aloft. The passage ended after only ~10 m! Why does the cave passage end at that level and start its steep descent here? Rocks above include shelf crest pisoliths, which are found in breakdown >150 m below, giving an idea of the original scale of this passage.

***A, B* (MC23) Gray geopetal sediments:** To the left of the trail, 25 cm above the handrail and on the blasted surface of Iceberg Rock, is an early pore filled with internal sediments that indicate the angular displacement of this massive rock.

***A* (MC24) Fusilinids**: The large block to the right of the trail, ~5 m before the small tunnel, is largely composed of pale colored grains that look like large grains of rice. These are fusilinid foraminifera, which were common in the upper Paleozoic. Fusilinids became extinct during the end of the Permian mass extinction episode. The abundance of fusilinids suggests they either lived in this environment with little input of other sediments, or were hydraulically winnowed and sorted. How does this facies relate to the rest of the shelf-edge sedimentary complex? Geopetal structures are common in this rock and indicate that the fallen block has rotated 90^o.

***A, B* (MC25) Depositional breccia**: Eight to 15 m after the end of the first left hand rail in the tunnel following (24), the left wall of the passage is developed in a carbonate breccia, the first and highest outcrop of this facies visible from the trail. The breccia is inter-bedded with reefal rocks. Rounded clasts differ from those associated with breakdown and result from the failure and down slope movement of weakly cemented sediments.

***C, D* (MC26) Calcite rafts and internal sediments**: Three meters before [16], on the right side of the trail, beneath a canopy of flowstone, a deposit of calcite rafts lies on an inclined, laminated, granular, rather brightly colored crust. The laminated sediments are cemented sands of uncertain origin. Examination of thin sections reveals the sands have been thoroughly cemented by calcite cement, which has partially replaced the quartz sand grains. Color banding reflects the composition of the cements, not the sands themselves, and probably resulted from chemical variations in the early cave environment. Examine the edge and underside of the laminated sands carefully. Round, parallel holes ~1 cm across perpendicularly pierce the steeply dipping laminae. These holes were probably vertical when they formed and indicate that the deposits have shifted *en masse* to the present position. Curiously, the holes are not filled with the rafts that cover the laminated deposit. Cave rafts form at the surface of pools due to evaporation and degassing. They float because of the surface tension of the water. Rafts may eventually become too big and sink, especially where drips from the ceiling disrupt the calm water. Accumulations of rafts are widely distributed in the cavern but the geometry and association of these deposits stands out. They appear to have formed in a paleo-cave during an earlier period of speleogenesis. The site was fortuitously exposed by trail building in the current cavern.

***B, C, D, E* (MC27) Iceberg Rock**: The enormous rock to the left of the trail is still part of Iceberg Rock. Collapse in caves is commonly associated with the initial drainage and the loss of the buoyant support of the water. Here, however, the pre-collapse surfaces were clearly covered with massive vadose speleothems. On the broken surfaces, speleothems have formed in places. One has been radiometrically dated at ~180 ka, which gives a minimum age for collapse (Hill, 1987; Ford and Hill, 1989). Collapse may have resulted from seismic activity associated with the continuing uplift in the Basin and Range Orogeny. Tectonic activity continues in recent time. Small local earthquakes have occurred as recently as 2005.

***B, C* (MC28) Paleobreccia**: About 4 m above the trail, ~25 m after the turnoff to the Scenic Rooms, is an exposure of paleo-collapse breccia. Large, angular blocks of carbonate bedrock have collapsed into a solutional void floored by gray laminated sediments like those examined earlier. The matrix between the blocks is most similar to upper Permian and lower Mesozoic clastics and unlike younger sediments described from the surface. Similar paleokarst discontinuously crops out along two trends parallel to the shelf edge that were apparently part of a massive cave system in late Permo-Triassic times. The host bedrock is a depositional (foreslope) breccia.

***D, E* (MC29) Displaced stalactites covered with popcorn**: Above the gate where the trail from the Scenic Rooms rejoins the Main Corridor trail, stalactites hang at a pronounced angle from vertical off the bottom of Iceberg Rock. They clearly formed before the collapse of this massive block. Although the rock has fallen ~10 m, the delicate stalactites have not broken. Broken stalactites elsewhere in the cave have commonly been ascribed to past tectonic activity, but we should not discount human impact. Pre-breakdown material has been dated at ~500 ka and post-breakdown overgrowths at $\leq$180 ka (Hill, 1987; Ford and Hill, 1989).

***D, E* (MC30) Broken surface without popcorn**: Looking back at Iceberg Rock from the top of Appetite Hill, you can see how the Iceberg Rock fit into the ceiling before collapse. The broken surface on the ceiling is only minimally decorated with stalactites or popcorn. The processes that created the popcorn before collapse have been largely inactive since collapse. The convection associated with the popcorn is still active, so why has the precipitation of popcorn declined? It seems likely that condensation has decreased due to the progressive development of entrances allowing the drying of the caves and the spatial limitation of condensation.

A **(MC31) Sponge reef** –The small blasted tunnel's left wall (Fig. 4) exposes a cemented sponge lump, a cyclic shelf edge facies reflecting alternating episodes of sedimentation, encrustation, and cementation.

D, E **(MC32) Macrocrystalline popcorn**: On the right wall ~15 m beyond the tunnel is a spectacular exposure of popcorn displaying length-slow calcite rhombs, saddle-shaped rhombs, twinned lumps, and aragonite prisms, which formed from the seepage solutions as they were progressively evaporated from thinner and thinner water films.

A, C, D **(MC33) Boneyard sign**: Large Guadalupian cave rooms commonly terminate in fractures that exhibit a complex style of porosity called "boneyard" or "spongework." Some researchers believed that boneyard represents an earlier stage of secondary porosity development that controlled the subsequent speleogenesis (Hill, 1987, 1996). However, details of boneyard structure suggest that much of it resulted from the enlargement of fractures by condensation of water from convecting, cooling air. This process was most aggressive after the cave initially developed entrances, allowing barometric differences in the air outside the cave to pump air in and out, and before the entrances were so big as to reduce the relative humidity of the cave and, hence, condensation. Where the condensate seeps away from the surface before it can be evaporated, enlargement and integration of pore systems may result. Most of the sediments in this area were skeletal sands with few reefal elements.

D, E **(MC34) Subterranean spitzkarren**: The massive blocks of breakdown near the junction of the Main Corridor trail and the Big Room are covered with tall spires that may be misidentified as stalagmites. Observe how the spires are pointed on top, unlike most stalagmites that are blunt on top. Additionally, the spires are located on the upper edges and corners of the collapse blocks. Why is this? Acidic condensates fell from the ceiling causing dissolution of the upper surface of the blocks. As the condensate films seeped down the upper surface of the block and more drips added to the flow, the films became thicker and, with more solvent, the effect of dissolution increased. At the upper edges and corners, no concentration of flow occurred and less dissolution took place. These tower-like features resemble alpine surface karst called "spitzkarren," a German term. Karst studies essentially began in Europe and many of the terms reflect Slovenian, German, and French origins.

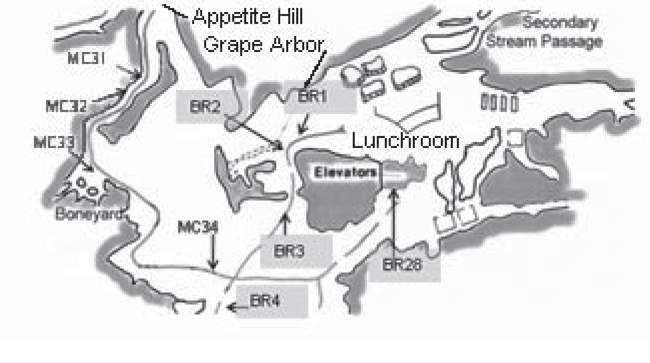

FIGURE 4. Detailed map identifying Main Corridor Stops 31 34 and Big Room Stops 1 4 and 28.

Big Room Trail Guide

The Big Room is one of the largest cave rooms in North America, and the largest in the U.S. It is developed near the -225 m level, from which some pits descend 30-45 m, and some ceiling domes extend upwards >70 m. The Big Room is entirely developed in the Capitan Formation. Significant aspects of Permian sedimentology as well as pre- and post-drainage speleogenesis may be viewed from the trail. Additionally, some of the largest and most spectacular speleothems in the cavern are found here, which allow valuable insights into the complex interaction of bedrock geology, water chemistry, and physics in cave environments. The guide begins and ends at the elevators by the Underground Lunchroom (Fig. 4).

D, E **(BR1) Grape Arbor:** The passage connecting the Underground Lunchroom to Big Room is profusely decorated by diverse speleothems, including (1) stalactites, stalagmites, and other forms associated with the concentrated recharge of seepage water, (2) deposits formed at and beneath the surface of pools, and (3) popcorn resulting from the evaporation of diffuse seepage. The first two associations were clearly coeval, but the popcorn has covered almost all of the first group. Did the pattern of water supply change from concentrated to diffuse seepage? Why? Most prolific deposits of popcorn are associated with overlying voids where condensation and bedrock etching take place, which provide the source of solutes that are precipitated below. But this area seems to be missing an upper source area.

D, E **(BR2) Rimstone dams**: The irregular dry pools on the right of the trail formed from the upward growth of rimstone dams. Mineral precipitation was focused at the dam-water contact due to increased degassing rates and the proximity of nucleation sites. In deep pools, precipitation is concentrated on the dams and cave rafts.

A, C, E **(BR3) Base-level control and debris:** The Big Room, entered at Audio Guide station [22], is clearly developed at a prominent level (-225 m), although numerous pits lead downward to the level of Lower Cave. Only the Main Corridor leads upwards to other known areas. There is no evidence of horizontally flowing water, but several researchers have hypothesized flow rising through pits along the outer limb of fresh water lenses, mixing with reduced basinal brines on which the fresh water floated (Palmer, 1991; Palmer and Palmer, 2000). The floor to the left of the trail is littered with thick deposits of angular clasts. This debris was derived from the blasting of the several elevator shafts, which were made to facilitate access. The debris is being gradually removed from the cave in order to restore a more original state. Early cave management practices were less focused on preservation and protection than today's Park policies. One early park superintendent considered blasting a tunnel to the surface to allow cars to drive into the cave and around the Big Room.

C, D, E **(BR4) Gypsum**: The large blocks to the left of the trail, just 25 m past the Main Corridor Trail junction (Fig. 5), are composed of gypsum. Gypsum is rare in most limestone caves but common in Guadalupian caves (Davis, 1980). Gypsum deposits in the Big Room are some of the largest in any cave in the world, reaching 8 m thick. Bretz (1949) suggested that the gypsum formed after the cave formed, drained, and re-flooded with waters carrying gypsum dissolved from surface outcrops. This explanation has been abandoned in favor of models involving the production of H_2SO_4 by oxidation of H_2S in the caves (Egemeier, 1973, 1987; Hill, 1987, 2000; Palmer and Palmer, 2000; Queen, 1981, 1994a; Queen et al., 1977). Gypsum is locally associated with other accessory minerals considered indicative of precipitation in acidic, sulfate-rich environments (Hill, 2000), including endellite, alunite, and natroalunite (Polyak and Guven, 2000). What evidence of early gypsum depositional environments do we see?

D, E **(BR5) Oriented popcorn**: Two meters past the Speleothem sign: Many of the massive speleothems along the sides of the trail have popcorn developed over protrusions on the lower surfaces. This finely crystalline popcorn shows a general orientation towards the Main Corridor. It grew preferentially into the flow of air descending from upper parts of the cave, as described earlier at Stop BR11 on the Main Corridor. What do variations in crystal size from one locale to another mean?

D, E **(BR6) Popcorn line**: Near the blade-shaped stalactite called Sword of Damocles and around much of the Big Room, popcorn developed just beneath a well defined level ~6 m above the floor. Wall rocks and speleothems are etched above the line. The popcorn line was long interpreted as representing an old flood line developed after the cave had drained, dripstone formed, and the room re-flooded (Bretz, 1949; Jagnow, 1977) as the popcorn line is nearly flat from the end of the Left Hand Tunnel to the Bottomless Pit, a distance of ~1500 m. Although the southwestern part of the line is ~2 m higher than the northeastern part, this slight incline was interpreted as a result of the Guadalupian block tilting after the caves had formed (Jagnow, 1977). Similar features are observed in various parts of this and other caves in the area, at different elevations. However, the lack of rafts and shelfstones, the consistent orientation of certain popcorn accumulations, and the lack of continuity of the popcorn line in areas associated with through-going pits in the cave floor suggest a more interesting origin.

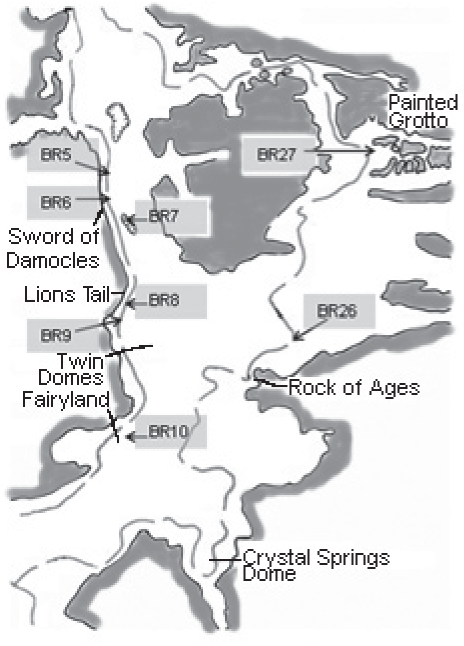

FIGURE 5. Detailed map identifying Big Room Stops 5 10 and 26 27.

C **(BR7) Floor slots**: Many Guadalupian caves have sections that were developed at discrete levels, connected by pits, fissures, and boneyard complexes to lower levels. Individual levels show little correlation with levels in other caves. The Big Room - Left Hand Tunnel is one of the best examples of base level control. Many of the passages developed at this horizon exhibit deep floor slots (such as the one to the left), some descending to the lower level. Did slots and pits serve as conduits for the upward flow of water to upper active areas? This concept is discussed more at Stop BR23. The vertical slots found in the passage floors exhibit base level control resembling spring-slots observed in several active caves associated with the input of H_2S to the cave atmosphere from hypogenic waters (Hose and Macalady, 2006). In southeast New Mexico, sulfidic springs might have been associated with past periods of igneous intrusion (Calzia and Hiss, 1978).

D, E **(BR8) Lions Tail**: This stalactite and the adjacent one are among the most dramatic examples of the popcorn line. At first glance, it seems obvious that the lines had formed like a bathtub ring around a large pool. However, a closer examination reveals that the popcorn formed sub-aerially by precipitation from condensates. Air moving up in the cave and cooling resulted in condensation charged with CO_2. The carbonic acid corrodes the higher bedrock and saturates the condensate with calcite. As condensates seeped down the wall into the lower, downward flowing air mass, evaporation occurred and popcorn was precipitated (Queen, 1981, 1994b) Stalagmites had a reduced supply of seepage water to provide dissolved minerals and thus have less, if any, popcorn.

D, E **(BR9) Hall of Giants:** These massive "Twin Domes" are some of the largest in Carlsbad Cavern. Clearly they formed from dripping water, but why are there no stalactites associated with the drip sites above? This seeming anomaly is common in many of the Guadalupian caves associated with popcorn lines. It is likely that the rates of degassing and evaporation are less in the upper parts of the passage, where air rising up from the deeper, warmer cave is water-saturated and CO_2-rich.

D, E **(BR10) Fairyland**: The floor of the Big Room near Audio Guide Stop [26] is characterized by numerous ancient pools, which now are mostly dry. Pool levels are defined by shelfstones and lily pads, below which cauliflower-like lumpy precipitates and rafts accumulated. Above the pool levels, small stalagmites formed, commonly covered by lumpy popcorn showing preferred orientation. The morphology of lumpy precipitates above and below the old water levels is distinct. If the popcorn lines had formed at old pool levels, they would have resembled these pool-related features.

D **(BR11) Sediment mounds**: On the right of the trail, the Breast of Venus is one of several conical mounds of flowstone in the area. Trail builders broke into the largest of the mounds, located on the right of the trail, ~12 m beyond the Breast of Venus, and found that the mound developed over a conical pile of weakly cemented sediments (Good, 1957). The excavated sediments were used to make the trail, a practice that would not be allowed today for conservation reasons. But we should make the most of past mistakes and we can learn much from this one. The sediments beneath the crust are weakly cemented white or pale gray sands, which may have entered the room from the ledge above. If the sands had remained cemented as they fell into the cave, they would have formed a pile of sandstone clasts, not loose sands. Thus, the sandstone cements dissolved as the cavern formed. Gray sands are now weakly cemented by syntaxial quartz overgrowths.

C, D **(BR12) The ceiling domes**: Behind the trail junction sign and, also, to the left, domes have developed along fractures in the cave roof (Fig. 6). These may have formed as descending fresh waters mixed with groundwater in the cave (i.e., mischungskorrosion domes of Bogli, 1964, 1980), or as vadose seepage entered the cave before significant entrances had developed, dissolved CO_2 and H_2S from the groundwater dominated cave atmosphere, and became more aggressive.

D, E **(BR13) Pools with lily pads**: These dry pools to the left of Audio Guide sign [29] were contained within constructional dams, but instead of growing upwards like the irregular rimstone dams discussed at Stop BR2, lily pads are defined by structures that grew horizontally in regular arcs. In most of these pools, subaqueous precipitates form botryoidal or mammillary crusts, and usually lack features influenced by gravity. This association typifies inorganic precipitation in subaqueous environments.

A, D **(BR14) Jumping Off Place**: To the right and below the trail is Lower Cave. Looking up from Lower Cave to here, the contact between the massive and bedded members of the Capitan Formation can be seen at trail level. The popcorn line, which has been visible along most of the side of the room from the junction of the Main Corridor and Big Room trails, is lacking across the walls away from the Jumping Off Place, providing more evidence for subaerial origins, and at odds with the old pool level hypothesis.

C, D, E **(BR15) Gypsum**: These blocks are amongst the largest of any gypsum deposits in Guadalupian caves. Notice the holes drilled in the deposits by dripping water. The environment in which this gypsum was deposited is not well understood. Most of the gypsum apparently formed by sulfuric acid attacking carbonate rock. Hill (1987, 1996, 2000) believed that H_2S derived as a gas in the deep basin oxidized to form sulfuric acid, which dissolved limestone and produced gypsum. However, mixing saturated sulfidic brines and oxidized fresh (i.e., non-gypsiferous) water will never result in carbonate undersaturation and gypsum supersaturation. Thus, most (or all) of Carlsbad's gypsum formed in the vadose zone. If they did develop in the vadose zone, did the drip holes form at the same time the gypsum beds accumulated? How can we tell? These gypsum deposits, like the deposit seen in the Main Corridor, are commonly massive, or more rarely laminated. Scattered clasts of limestone rock from the ceiling have rarely been incorporated in the gypsum. These limestone clasts do not appear to be heavily corroded, suggesting that although the environment of gypsum formation was acidic, the environment of deposition was near neutral. An outer porous crust of gypsum over the massive gypsum blocks has resulted from the recrystallization.

D **(BR16) Breccia and sulfur**: In the roof of the second tunnel a breccia fabric is clearly preserved in the gypsum. Did this material fall as pieces of gypsum from the ceiling, or has it replaced the bedrock, which is largely foreslope breccia? Compare these fabrics with foreslope sediments that will be visible at Stop BR24. Just beyond the tunnel on the right, ~2 m above the trail, gypsum crusts are covered by a dull yellow dusting of elemental sulfur formed by bacterial oxidation of H_2S (Davis, 1980; Hill, 1987, 2000).

C, D **(BR17) Cemented sands**: On the right of the trail, 15 m beyond Audio Guide Stop [32], a flowstone cap was removed to expose the pale gray, weakly-cemented quartz sands beneath, like those seen in Stop 11. These abut orange-brown, sand filled fractures in the bedrock wall. These gray sands resemble common Permian fracture-filling sands found on the surface. The sediments at this site appear to have been chemically scrubbed of the clay and rust coatings, giving them their current color before quartz cementation. Removing the rust coatings is difficult in an oxidizing environment because iron oxides are nearly insoluble. Bleaching of grains probably took place in a reducing environment, in which iron is soluble. These sands, like those at Stop

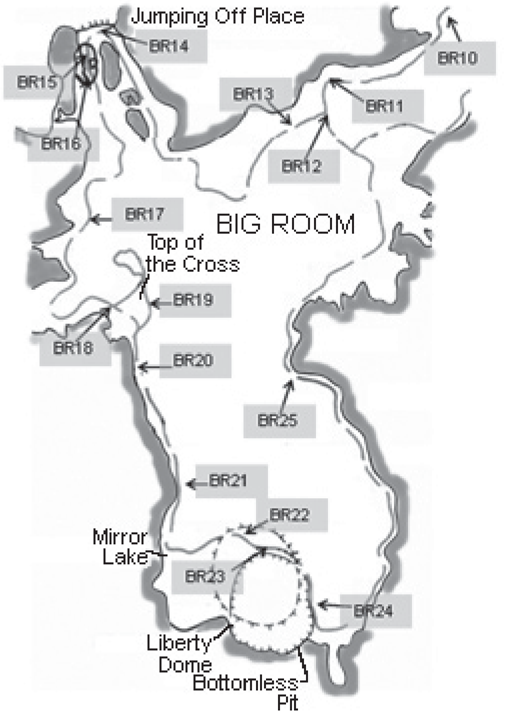

FIGURE 6. Detailed map identifying Big Room Stops 10 25.

11, have been weakly cemented by syntaxial quartz overgrowths. Chert covers some sediment mounds (e.g., Stop 25). Where did the silica come from and why did it precipitate in the cave environment? Quartz precipitation is generally rare in caves. This alcove is associated with several fractures parallel to the shelf edge, which have localized cave development elsewhere in Carlsbad Cavern. These fractures are associated with the principal structural features of the shelf edge – the Reef and Guadalupe Ridge Anticlines and Walnut Canyon Syncline, which formed during the Laramide Orogeny (McKnight, 1986), and help localize cave formation (Jagnow, 1977).

E **(BR18) Chenille spar**: In the small dry pool to the left of the trail as it enters the seating area, shelfstones are decorated on their underside by thin, vertical blades of carbonate called chenille spar. These speleothems are called "biothems," a term applied to speleothems with shape, structure, or mineralogy influenced by organic processes (Queen and Melim, 2006). In subaqueous settings, cave precipitates rarely exhibit vertical orientations (as this chenille spar does) or form perpendicular to a surface. Such characteristics in a subaqueous setting are commonly associated with mineralized mucous (=biofilms) and bacteria. The bacteria and the slime they produce may serve as nucleation sites for carbonate precipitation. By sticking out from the surface in still pools, it is possible that bacteria were surrounded by water with a saturation index very slightly greater than near the pool sides, speeding mineral precipitation.

A **(BR19) Fossils**: The small blocks along the far wall of the seating area were placed there and cemented in place. They display macrofossils that were collected from this part of the cave and once lived in a shelf margin, normal marine environment. The display includes nautiloid cephalopods and brachiopods, which were not reef builders but may have been part of an integrated reef community. About 30 m above the floor, where the arching ceiling meets the walls of the vertical dome above, massive reefal sediments overlie bedded foreslope sediments. Exposed between the Jumping Off Place and the ceiling above, the depositional shelf prograded upward and seaward influenced by rates of sedimentation and subsidence. Lower production rates of detrital skeletal sediments promote the growth of reefs on the shelf edge, whereas faster sedimentation rates result in sand shoals and scattered reefal lumps. How do we know what makes up the ceiling? Explorers used helium balloons to place a parachute cord over a stalagmite >65 m above, then used the cord to pull a climbing rope over it. The dome leads to a long gallery with a fissure. Although it is impassible, winds commonly blow upwards in the fissure, which has been corroded by atmospheric condensation.

D, E **(BR20) Backwards popcorn**: To the right of the trail, stalagmites are encrusted by popcorn that is thickest toward the Jumping Off Place (Stop 14), not toward the natural entrance and the shallower parts of the known cave. Does this locale reflect a large atmospheric circulation loop around the Big Room, or circulation through the Liberty Dome (Stop 23) or elsewhere?

A, B, C **(BR21) Foreslope beds and collapse breccia**: The walls on both sides of the passage approaching the Bottomless Pit are developed in the bedded Capitan, which was deposited in front of the shelf edge as steeply inclined beds composed of originally loose shelf margin sediments and clasts. The contact between the fore-slope and massive shelf margin is near the ceiling. Large clasts of breccia are generally rare in this environment, but may result from failure of the bank edge. In the highest part of the ceiling, a massive breccia crops out above the contact of the massive and bedded Capitan. Probably a collapse breccia, its age is not clear. But, once again, it seems that the present cave is associated with earlier generations of caves and may have been localized by them.

E **(BR22) Coral pipes**: Two meters before the Bottomless Pit sign, the surface immediately left of the trail displays small, lithified spires at about chest level. These "coral pipes" formed as subterranean versions of hoodoos that were later coated with calcite in a manner similar to stalagmites (Hose and Strong, 1983).

C, E **(BR23) Bottomless Pit and bat guano:** To the right of the trail is the ~40 m deep Bottomless Pit, the deepest part of this section of the cave. The pit is interpreted as a conduit formed and utilized by fresh water that rose along the margin of the Capitan Aquifer and mixed with the brines that surrounded the aquifer (Palmer and Palmer, 2000). Major flow would have required an outflow point, which has not been identified. The present water table in this area is ~150 m below this level and discharges at Carlsbad Springs, ~40 km to the northeast. Hydrologic data suggests that most of the flow between Whites City and Carlsbad Springs is through conduit porosity (Hiss, 1980). When the water table was at the level of the Big Room, the associated springs might also have been tens of kilometers away. Would these springs have been coupled with water rising from the Bottomless Pit? No one knows for sure. The guano deposits throughout this area suggested to explorers that the Liberty Dome, above, might lead to another entrance. Explorers climbed the dome in 1976 but only found a small fissure too tight for humans to follow. Does it continue? Could air circulation through the dome have resulted in the unusual popcorn orientations seen at Stop 20?

A, B **(BR24) Foreslope breccia**: On the surface of the large block immediately left of the trail and ~7 m past the Bottomless Pit sign, details of the textures and composition of the bedded Capitan may be seen. Clasts may have formed by the breakup of weakly cemented sediments overlying less well cemented sediments near the top of the foreslope.

D, E **(BR25) Internal sediments**: About 17 m past the wide spot in the trail and 12 m to the left is a bed of clay, with endellite on the bottom covered with convex upwards beds of montmorillonite, that has been exposed by trail builders. A strong flashlight is necessary to see the material well. A thick bed of authigenic chert overlies the sediments. These deposits seem to predate the cave's gypsum deposits, but post-date draining of the cave to this level (Queen, 1981). Hill (1987, 2000) believes the chert was derived by the alteration of montmorillonite clays to chert and endellite. But, chert is not often associated with endellite, which may underlie the montmorillonites or may occur in apparently authigenic masses unassociated with sedimentary montmorillonites elsewhere in the cave. More likely, both the chert and quartz cements of Stops 11 and 17 derived from vadose seepage entering an acidic cave environment with PCO_2 and PH_2S greater than seepage waters.

E **(BR26) Gypsum with flat lower surface**: The alcove on the right of the trail and ~22 m beyond the Draperies sign displays a large mass of gypsum with an unusual flat lower surface. Gypsum blocks and flowstone-like deposits commonly occupy the lower parts of passages. Water carrying dissolved gypsum from the dissolution of the limestone by sulfuric acid in the upper parts of the passage was evaporated by warming air as it flowed into the lower passage. The flat lower surface is more unusual. Was it dissolved by a later pool, after it first formed? Or was the pool there at the time of gypsum precipitation? In active caves enlarging by the input of H_2S, observed gypsum occurs only above pool and stream levels, nowhere below (Hose and Macalady, 2006). Also, note that the top of the gypsum matches the top of popcorn deposits to the right. Might these similarities tell us something significant about the environment of deposition?

E **(BR27) Pool Fingers**: Behind the Painted Grotto sign (Fig. 5), in a dry pool, biothems called "pool fingers" hang beneath the shelfstone. Microbes influenced the growth of these rare speleothems. The nature of control is not known (Queen and Melim, 2006).

A **(BR28) Trilobite**: Three meters to the left of the doors into the elevator complex, ~2 m above the floor, is the well-exposed pygidium of a Dalmanitid trilobite. Trilobites, like most other marine invertebrates, became extinct at the end of the Permian Period. In the Guadalupian shelf margin, trilobites are extremely rare. However, many other invertebrates characteristic of normal marine environments are present and trilobites were common in other upper normal marine Permian settings. Why are trilobites so rare here? The shelf margin environments may have been subject to episodic events with restricted chemistries. Might trilobites have had eggs/larvae that were benthic and, consequently, less widely distributed than forms with pelagic early stages, resulting in slower re-colonization rates?

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