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BEDROCK FEATURES OF LECHUGUILLA CAVE, GUADALUPE MOUNTAINS, NEW MEXICO

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Lechuguilla is a hypogenic cave dissolved in limestones and dolostones of the Capitan Reef Complex by sulfuric acid derived from oil and gas accumulations in the Delaware Basin of southeast New Mexico and west Texas. Most of the cave developed within the Seven Rivers and Capitan Formations, but a few high level passages penetrate the lower Yates Formation. The Queen and possibly Goat Seep formations are exposed only in the northernmost part of the cave below -215 m. Depositional and speleogenetic breccias are common in Lechuguilla. The cave also has many spectacular fossils that are indicators of depositional environments. Primary porosity in the Capitan and Seven Rivers Formations was a reservoir for water containing hydrogen sulfide, and a pathway for oxygenated meteoric water prior to and during sulfuric acid speleogenesis. Many passages at depths >250 m in Lechuguilla are in steeply dipping breccias that have a west-southwest orientation parallel to the strike of the shelf margin. The correlation between passage orientation and depositional strike suggests that stratigraphy controls these passages.

Lechuguilla is a hypogenic cave that has been dissolved out of limestones and dolostones of the Capitan Reef Complex Fig. 1) by sulfuric acid derived from oil and gas accumulations in the Delaware Basin of southeast New Mexico and west Texas (Hill 1987; Palmer & Palmer 2000). Since its discovery in 1986, explorers have mapped more than 170 km of passage containing spectacular speleothems and an extraordinary assortment of other features (DuChene 1997; Hill & Forti 1997; Davis 2000). Jagnow (1989) is the only researcher who has previously written about the bedrock geology. Bedrock outcrops in Lechuguilla are superb because they have not been subjected to the chemical and mechanical weathering processes that affected surface exposures. Therefore, they provide an opportunity to view details of the Capitan Reef not readily seen on the surface.

Since 1991, members of the Lechuguilla Cave Inventory Project have been documenting the geologic, mineralogical and speleogenetic features of Lechuguilla Cave (Jagnow *et al*. 2000). Data have been collected for 159 geologic and mineralogical categories at more than 3500 survey stations spread throughout the cave (DuChene 1996). One of the goals of the Inventory Project is to better understand how Lechuguilla fits into the stratigraphic framework of the Capitan Reef Complex. The purpose of this paper is to summarize data collected on the bedrock features exposed in Lechuguilla Cave.

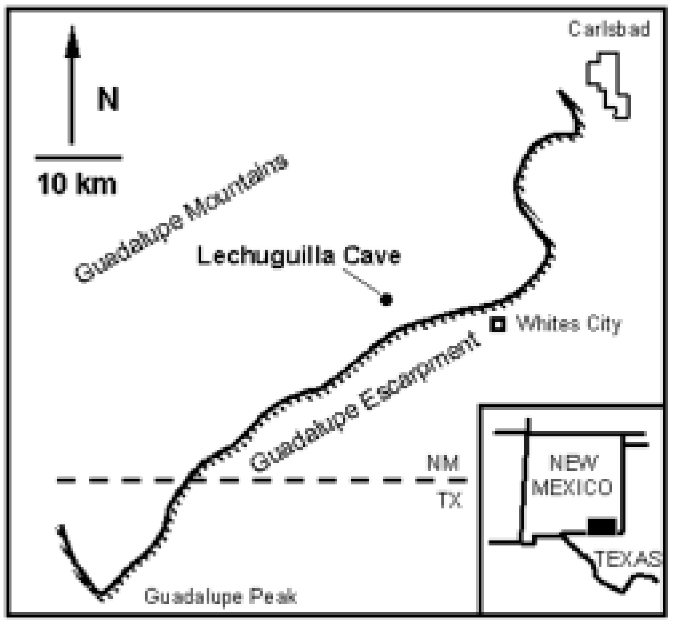

Figure 1. Location map of Lechuguilla Cave in the Guadalupe Mountains, New Mexico (from Palmer & Palmer 2000).

DEPOSITIONAL ENVIRONMENTS

Sediments of the Capitan Reef Complex deposited along a shelf and shelf margin on the periphery of the Delaware Basin in late Guadalupian (Permian) time. Within these broad divisions, Garber *et al*. (1989) recognized seven depositional environments (Fig. 2). The most landward environments are represented by coastal sabkha and playa facies (1) that grade down dip to tidal flat and shallow lagoon deposits (2). Sediments in these environments are interbedded carbonates and siliciclastics that become progressively more anhydritic up dip. The shelf grades down dip into the shelf margin comprised of a pisolite shoal (3), the immediate backreef (4), reef (5), forereef slope (6), and basin margin (7). The pisolite shoal was the highest part of the shelf profile and was located on the basinward side of the lagoon. The pisolite shoal grades into the immediate backreef comprised of bedded, highly fossiliferous packstones, grainstones and algal boundstones. Grains include fragments of mollusks, brachiopods, echinoids, and peloids.

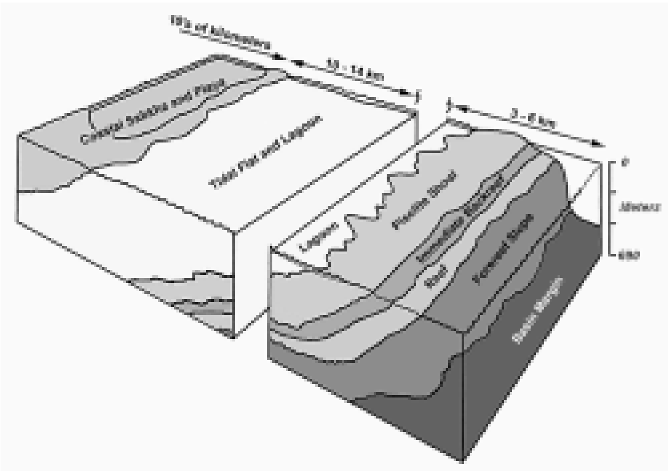

Figure 2. Schematic block diagram showing the seven depositional environments of the Capitan shelf margin: (1) coastal sabkha and playa; (2) tidal flat and lagoon; (3) pisolite shoal; (4) immediate backreef; (5) reef; (6) forereef slope; (7) basin margin. Lechuguilla Cave is developed in the immediate backreef, reef and slope. Modified from Garber *et al.* (1989).

Beds of the immediate backreef end abruptly against the massive reef.

The massive reef, 90-180 m thick, consists of sponge-algal boundstones, wackestones, packstones and grainstones. Reef-building organisms include ecologically zoned phylloid and dasycladacian algae, sponges, bryozoa, crinoids, and brachiopods. Basinward from the reef, bedded forereef slope deposits are 366-457 m thick with dips ranging from > 30° in the upper forereef to 5-10° in the lower forereef. Slope sediments include matrix-poor debris flows, grain-flows, and a minor amount of rock-fall debris (Melim & Scholle 1995). The lower slope grades into and intertongues with siliciclastic silt, sand, and carbonate debris at the basin margin.

STRATIGRAPHY

PREVIOUS WORK

Field geologists divide the rocks of the Guadalupe Mountains into formations with easily recognized characteristics that extend over wide geographic areas. (*e.g.*, King 1948; Newell *et al.* 1953). Stratigraphic studies show that backreef formations are equivalent to specific parts of the Capitan reef and to formations in the Delaware Basin, even though the lithologies change across the shelf margin (Newell *et al.* 1953; Tyrrell 1964, 1969). More recent work has focused on the specifics of deposition and diagenesis, using sequence stratigraphy to unravel the detailed geology of the Capitan Reef Complex (e.g., Fitchen *et al.* 1992; Melim & Scholle 1995; Tinker 1998; Kerans & Tinker 1999). These studies document a complex depositional history influenced by fluctuations in sea level. When sea level was high, carbonate deposition and reef building was at a maximum. When sea level was low, the upper part of the Capitan Reef Complex was emergent and subject to karst development and erosion. Wind blown siliciclastics deposition was also greater during times of low sea level (Tinker 1998).

The lithologies of the formations that crop out in Lechuguilla Cave are described briefly in this report. Formations are discussed in the order that they are encountered during a traverse of the cave from the entrance to any of the three lower level branches (Fig. 3).

BEDDED CARBONATES AND SILICICLASTICS

Carbonate and siliciclastic beds within the lower Yates, Seven Rivers and upper Queen Formations crop out throughout the upper part of Lechuguilla. Most of these outcrops are in the upper levels between the entrance and a depth of 244 m.

Yates Formation. Outside of the cave, the Yates Formation is very pale-orange to yellowish-gray, fine-grained, laminated, commonly pisolitic dolomite in beds 10-60 cm thick, alternating with grayish-orange to pale-yellowish orange, calcareous, quartz siltstone or very fine-grained sandstone, in beds 2.5-15 cm thick (Hayes & Koogle 1958). The Yates Formation conformably overlies the Seven Rivers Formation and is equivalent to the lower part of the upper Capitan Formation. Dolomite beds of the Tansill Formation conformably overlie the Yates (Fig. 3).

The Yates Formation is exposed at the entrance of Lechuguilla, in the PHD Room above the Chandelier Graveyard and in Tower Place (Figs. 3 & 4), as well as in other high level passages. The PHD Room is located at the top of a

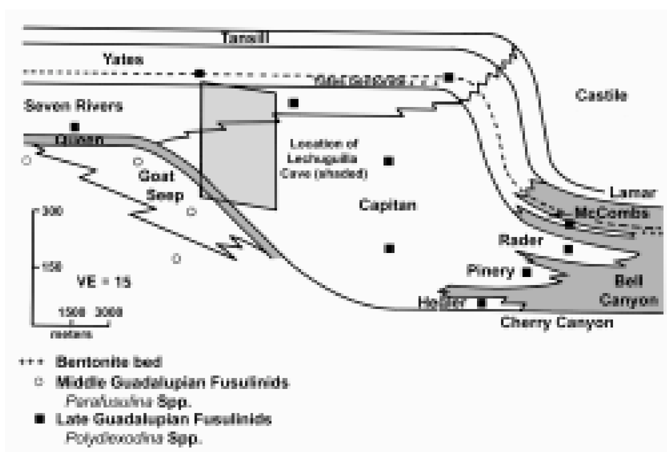

Figure 3. Schematic cross section showing location of Lechuguilla Cave within stratigraphic framework of the Guadalupe Mountains, New Mexico and Texas. Middle Guadalupian beds are characterized by *Parafusulina*; Upper Guadalupian beds by *Polydiexodina.* Note dashed correlation line within Yates, Capitan and Bell Canyon formations and position of Yates bentonite on shelf margin and in toe of slope. Shaded units are composed mostly of siliciclastics. Modified from Garber *et al.* (1989).

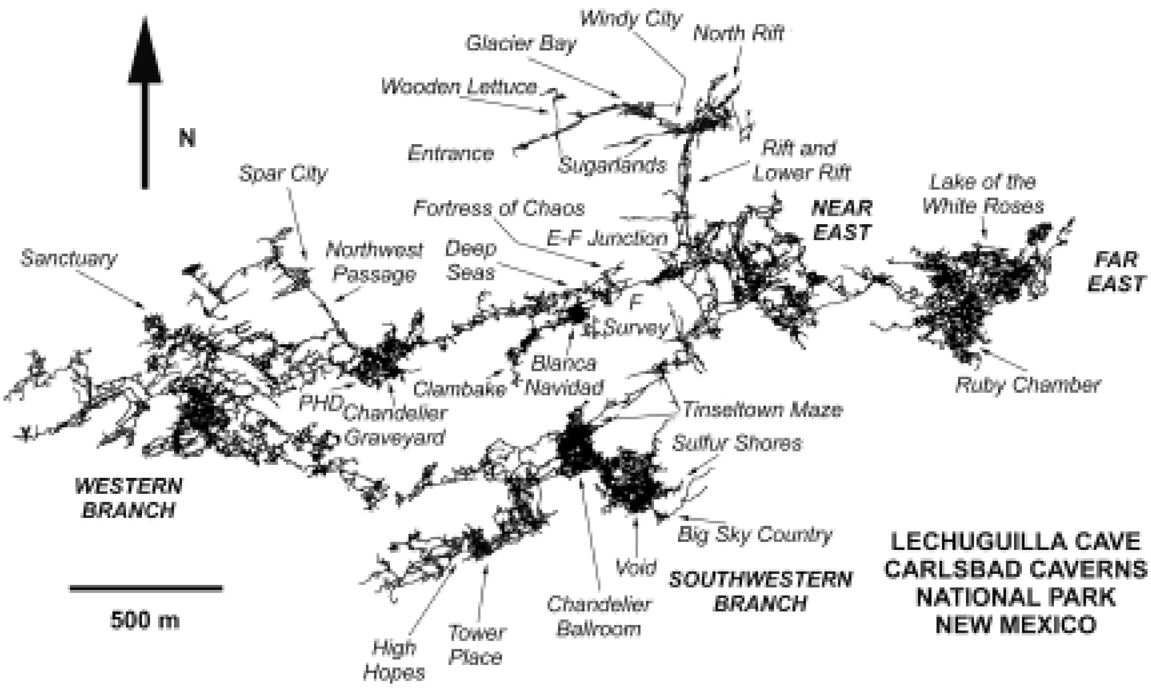

Figure 4. Map of Lechuguilla Cave showing localities discussed in text.

prominent, southeast-trending solution-enlarged joint that intersects a 3 m thick, pink, siltstone bed at the base of the Yates. The floor of the room is covered with siltstone breakdown blocks up to 6 m across. In Tower Place, a pinkish-orange siltstone bed ~1.5 m thick crops out on the southeast side of the room.

Seven Rivers Formation. In outcrop, the Seven Rivers Formation consists of yellowish-gray, fine-grained, commonly pisolitic dolomite in beds 30 cm to 1 m thick with rare beds of very pale-orange quartz siltstone (Hayes & Koogle 1958). These rocks grade into fossiliferous grainstones and rudstones toward the Capitan Reef. The Seven Rivers rests on the Queen Formation and is overlain by siltstone and carbonate beds of the Yates. The Seven Rivers is equivalent to the lower part of the Capitan Formation (Yurewicz 1977)(Fig. 3).

The Seven Rivers is the backreef formation that crops out throughout most of the upper part of Lechuguilla Cave. It is exposed at numerous sites between the entrance and Glacier Bay where beds stand out in relief due to differential solution. Parts of the Seven Rivers are highly fossiliferous, particularly near its contact with the massive reef. At EF Junction, which is probably less than 15 m above the massive Capitan Formation (Jagnow 1989), outcrops are composed of rudstone and consist mostly of sand-size fragments of shells and algal debris with scattered intact fossils.

Queen Formation. The Queen Formation is composed of very pale orange to yellowish-gray, fine-grained, laminated, dolomite in beds 10 cm to 1.2 m thick, interbedded with very pale-orange, silty dolomite, calcareous quartz siltstone, and very fine-grained sandstone in beds 10 cm to 1 m thick (Hayes & Koogle 1958). The Queen Formation lies conformably beneath the Seven Rivers Formation (Fig. 3). Jagnow (1989) believed that the Queen Formation is exposed in lower Windy City, Sugarlands, the North Rift, and Lower Rift. The contact between the Seven Rivers and Queen is best seen in the north part of the Rift where the Shattuck Member, a siltstone bed ~1.5 m thick, marks the contact between the Seven Rivers and Queen formations.

Capitan Formation. Field geologists in the Guadalupe Mountains traditionally divide the Capitan Formation into massive and breccia members (Hayes & Gale 1957; Hayes & Koogle 1958; Motts 1962; Hayes 1964). The massive part of the Capitan typically lacks bedding planes and is composed of light-gray, cream or white, calcitic, fossiliferous limestone with minor dolomitic limestone. The breccia member is composed mostly of fragments of reef limestone mixed with lenses and pods of siliciclastic material that were deposited in the forereef slope (Figs. 2 & 3). The contact between the massive and breccia members is gradational and indistinct at depths of 250-275 m.

Reef limestones of the massive Capitan crop out at depths of 175–275 m throughout Lechuguilla. Parts of the upper level of the Far East are developed in tan to gray, dense limestone with areas of moderate to intense fracturing (Fig. 4). In areas where the limestone is not covered with speleothemic crusts and coatings, sponge, crinoid, bryozoan, and brachiopod fossils can be seen. Locally, the reef rock contains fractures filled with calcite-cemented breccia as well as pods of fine-grained sandstone, some with ripple marks.

Breccias of the Capitan forereef slope crop out in passages and galleries below 250 m throughout the cave. Slope deposits are exposed throughout the Western Branch with particularly good examples in the Fortress of Chaos and Chandelier Graveyard. Dipping forereef beds are exposed about 30 m west of the Deep Seas Room.

Goat Seep Formation. The upper 150 m of the Goat Seep Formation is exposed on the western, faulted face of the Guadalupe Mountains (King 1948) and in North McKittrick Canyon, where it consists of light gray massive fine-crystalline to saccharoidal dolomite that is very porous in places (Hayes 1964). The formation consists of massive reef and forereef talus deposited along the shelf margin (Newell *et al.* 1953), and is mostly composed of dolomite (Hill 2000). The Goat Seep and Capitan were deposited along a prograding shelf margin that advanced as much as 6 km (King 1948). The Goat Seep shelf margin lies north of the Capitan margin in the Guadalupe Mountains, and the Goat Seep Formation is mostly adjacent to, rather than beneath, the Capitan (Fig. 3). Debris flows derived from the Goat Seep Formation intertongue with the Cherry Canyon Formation and may lie beneath part of the Capitan breccia member (Fitchen *et al.* 1992).

The Goat Seep Formation, if present at all in Lechuguilla, is likely restricted to the northernmost part of the cave. However, carbonate debris flows derived from the Goat Seep may underlie the Capitan in the area of Lechuguilla and could crop out elsewhere in the cave. No rocks similar to the Goat Seep Formation described by Hayes (1964) were observed during this study.

BEDROCK FEATURES OF LECHUGUILLA CAVE

BRECCIA DEPOSITS

Breccia is a coarse-grained rock composed of angular broken rock fragments held together by mineral cement or in a fine-grained matrix. In the Capitan Reef Complex, it resulted from both talus accumulation and solution collapse.

Breccias can be classified as crackle, mosaic and chaotic based on the amount individual clasts have been rotated and the distance they have been transported (Loucks 1999) (Table 1). Crackle breccia clasts are sharply angular, unrotated, and have not been transported from their place of origin. Mosaic breccia has poorly sorted, sharply angular clasts that are slightly rotated and have been transported no more than a few centimeters. Chaotic breccia has angular to subrounded, poorly sorted clasts of mixed lithology transported many meters.

In Lechuguilla Cave, breccias were formed by both depositional and speleogenetic processes. Depositional breccias were deposited during the growth of the Permian

Table 1. Classification of breccias in Lechuguilla Cave.

Type	Characteristics	Matrix	Occurrence	Depositional Environment	Example
			Depositional breccias		
Mosaic	Clasts sharply angular with no rounding of corners; very slight or no rotation of clasts; unsorted; well-cemented.	Calcite (predominant), silt (minor)	Fracture fill (fractures open and sub-vertical)	Tension fractures in massive reef and backreef limestone	Far East
			Collapsed beds (deposits sub-horizontal)	Bedding collapse and fragmentation due to dissolution of underlying beds	
Chaotic	Clasts angular to subrounded, poorly sorted, mixed lithologies		Large masses parallel to dip of forereef slope	Forereef slope	Fortress of Chaos
	Clasts angular to subrounded, poorly to moderately sorted, mixed lithologies including bedded pisolitic limestone and siltstone; moderately imbricate; well cemented.	Calcite (predominant), silt (minor)	Channel fill	Passes and channels through reef	Approach to Chandelier Graveyard
			Speleogenetic breccias		
	Characteristics	**Matrix**	**Occurrence**	**Depositional Environment**	**Example**
Crackle	Clasts sharply angular and unrotated; surfaces not chemically altered; lithology identical to surrounding bedrock	Calcite, gypsum, or may be uncemented	Ceilings and walls of passages and galleries	Ceilings and walls of passages and galleries	Passage walls and ceilings of Tinseltown Maze
Mosaic	Clasts sharply angular with no rounding of corners; very slight or no rotation of clasts; unsorted; uncemented to well-cemented	Gypsum	Wedging where gypsum is crystallizing in compression fractures	Compression fractures where dissolved gypsum is migrating downward through bedrock	Void
		Uncemented	Collapse of compression-fractured rock into passage	Open passages currently in the process of stabilization or collapse	Void
Chaotic	Clasts sharply angular; surfaces chemically unaltered except where facing original passage; unsorted; clasts show evidence of rotation due to falling from ceiling or wall; lithology identical to surrounding bedrock.	Uncemented	Passage and gallery floors. Clasts may be isolated or in large piles	Secondary fill (“breakdown”) in passages and galleries.	Fortress of Chaos

Figure 5. Chaotic breccia near Blanca Navidad Hall, Lechuguilla Cave. Photo by Dan Legnini.

Figure 6. Fissure filled with breccia cemented with sparry calcite, Far East, Lechuguilla Cave. Photo by Kathy Sisson-DuChene.

(Guadalupian) Capitan Reef Complex and are part of the bedrock. Speleogenetic breccias, also known as breakdown, form during the air-filled, vadose stage of cave formation due to the following factors: (1) removal of buoyant support when the water level lowers below a passage horizon; (2) base level back flooding; (3) undercutting by free-surface streams; (4) crystal wedging processes, and (5) earthquake activity (Ford & Williams 1989). In Lechuguilla, (1) and (4) were the foremost factors. Davies (1949) was the first to classify breakdown in caves, and more recently, Loucks (1999) presented a classification for recognizing speleogenetic breakdown in paleokarst.

Chaotic breccia is the most common type of depositional breccia in Lechuguilla Cave. It crops out in passages below 250 m in the Capitan forereef slope where it consists of poorly sorted clasts up to a meter or more in diameter cemented together by gray or brown, coarsely crystalline calcite. Typical examples crop out in the Fortress of Chaos, Chandelier Graveyard and the approach to Blanca Navidad Hall (Fig. 5). Chaotic breccia with smaller clasts fills many fractures in massive reef limestone. Most fracture filling breccia is cemented by gray calcite (Fig. 6), but some has a matrix of reddish-brown fine-grained sandstone.

Depositional mosaic breccia is rare in Lechuguilla, occurring in backreef beds where non-speleogenetic dissolution of evaporites in Guadalupian time caused overlying beds to collapse. It also occurs in massive reef limestone where rocks are broken when they fall into fractures and depositional voids. In Spar City and the northern end of Wooden Lettuce Passage, “ghost breccia” is formed where clasts of chaotic breccia have been completely dissolved, leaving only the coarsely crystalline calcite matrix.

The most common type of speleogenetic breccia in Lechuguilla is breakdown, found throughout the cave. Breakdown fragments range from a few millimeters to several meters in diameter and litter the floors of most large passages and galleries. Most breakdown accumulations are uncemented, but in some areas, calcite flowstone binds the clasts together. Speleogenetic crackle breccia is common in the Chandelier Ballroom and the Void where the massive reef limestone is shattered, but where many fragments remain in place. A good example of speleogenetic mosaic breccia crops out at the east end of the Tinseltown Maze where the bedrock is shattered and clasts have been rotated by gypsum crystal wedging.

FRACTURES AND FRACTURE FILL

Many vertical fractures in Lechuguilla are filled with siliciclastic sediment ranging from coarse silt to very fine-grained sand. Hayes (1964) described fractures of this type as “Type 1 sandstone dikes” that formed when tension cracks caused by settling of the reef were filled with sand.

Type 1 sandstone dikes exposed in Lechuguilla Cave occur at depths ranging from 125-345 m, but they are concentrated between 200 and 250 m in the lower part of the Seven Rivers Formation (Fig. 7). Most of the sandstone in the dikes is stained pink or pinkish-orange, but in some fractures it is colorless to white. Regardless of color, the sandstone is friable and disaggregates at the slightest touch. It is common for sand to fall from fractures and accumulate in piles along walls or on passage floors.

Type 1 sandstone dikes are common in the F Survey and in Big Sky Country above the Void. One dike in Big Sky Country is 2 m-wide and filled with sandstone that ranges from colorless to beige and displays liesegang banding (nested bands caused by rhythmic precipitation within a fluid-saturated rock). A sample of the siliciclastic material from this fracture

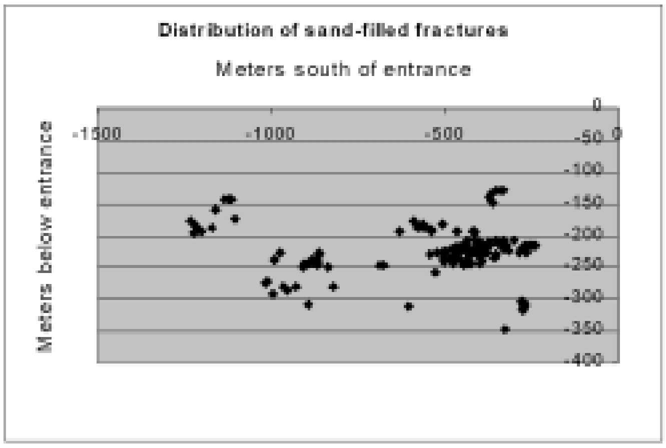

Figure 7. Distribution of sand-filled fractures in Lechuguilla Cave. Y-axis is depth below entrance; X-axis is distance south (or north) of entrance.

is composed of uncemented, colorless to white, subangular to subrounded, non-calcareous, coarse silt to very fine-grained sand (W. B. Hanson, pers. comm. 1989).

Fractures filled with breccia are also common in the massive Capitan reef limestone in Lechuguilla. Most of this fracture-filling breccia is cemented with sparry calcite (Fig. 6), but there are a few places where breccia clasts are mixed with sand.

PALEONTOLOGY

The Capitan reef was built by marine organisms that had skeletons composed of minerals, predominantly calcium carbonate. Principal frame-building organisms include calcareous sponges, encrusting calcareous algae, and bryozoans (Newell *et al.* 1953; Cronoble 1974; Wood 1999). Fossils of many of these organisms are common in the bedrock of Lechuguilla Cave. They lived where environmental conditions were best suited to their needs for food, clean water, and oxygen. Consequently, when these organisms are found in place, they are excellent indicators of the environment at the time they were alive.

Most fossils in Lechuguilla have been broken into sand-size fragments that accumulated in voids in the Capitan Reef and in the backreef lagoon. However, many intact fossils are exposed where the bedrock is not covered by mineral coatings and crusts. Common fossils include brachiopods, bryozoans, crinoid columnals, echinoid spines, gastropods, pelecypods, scaphopods, cephalopods and porifera. table 2 summarizes the habitats of the more common fossil groups observed in Lechuguilla Cave. For discussions of the paleontology and paleoecology of the Capitan Reef Complex, see Newell *et al.* (1953), Cronoble (1974), Babcock (1977), Wood *et al.* (1994) and Wood (1999).

Table 2. Distribution of biota in the Capitan Reef Complex (after Newell *et al.* 1953).

Category	Most common habitat
Algae	reef
Brachiopoda	immediate backreef, reef and proximal slope
Bryozoa	reef and proximal slope
Porifera	reef
Fusulinidae	reef
Cephalopoda	all
Gastropoda	backreef
Pelecypoda	backreef, reef and proximal slope

ALGAE

Calcareous algae are sediment-binding and encrusting organisms that were important to the stabilization of sediment within the massive reef facies of the Capitan Formation. The upper Capitan Formation contains an abundant and diverse calcareous algal flora, including skeletal phylloid algae. In contrast, the lower Capitan, which is equivalent (at least in part) to the Seven Rivers Formation (Fig. 3), contains only a hemispherical form of alga (Babcock's form C) and a problematic alga *Archeolithoporella* in any abundance (Babcock 1977). *Archeolithoporella* is an encrusting skeletal alga(?) that played an important role in binding and stabilizing sediment within the reef (Newell *et al.* 1953; Achauer 1969; Cronoble 1974; Babcock 1977; Wood 1999).

BRACHIOPODA

Brachiopods are solitary marine invertebrates that may be attached or unattached to the substrate. They are characterized by two bilaterally symmetrical calcareous or chitinophosphatic valves. In the Capitan, brachiopods are most common in the immediate backreef, reef and proximal slope, but they are found in most marine environments. Most of the brachiopods in the reef are cemented to the substrate, but pedunculate types are also represented, particularly along the seaward margin (Newell *et al.* 1953).

Many brachiopod shells in Lechuguilla are composed of crystalline calcite that is less soluble than the surrounding bedrock, and dissolution has caused the fossils to stand out in relief on passage walls and ceilings. In some cases, the shells are broken, revealing the internal spiral structures of the brachiopod. Particularly fine specimens up to 5 cm across and similar to *Neospirifer* sp. are exposed in Spar City where they are associated with crinoid columns, sponges, bryozoans, and a straight-coned nautiloid. An excellent example of a rare, complete *Leptodus* sp. is exposed in the Sanctuary (B. Luke, pers. comm. 1997; Fig. 8). Because of their fragility, and because the ventral valve of *Leptodus* was securely attached to the reef substrate, the shells tend to break up after the animal dies, and the ventral valve is more likely to be preserved (Newell *et al.* 1953: 66 & 194). Other brachiopod fossils, some with internal structures exposed, are present in the Clambake Room (L. Doran, pers. comm. 1999).

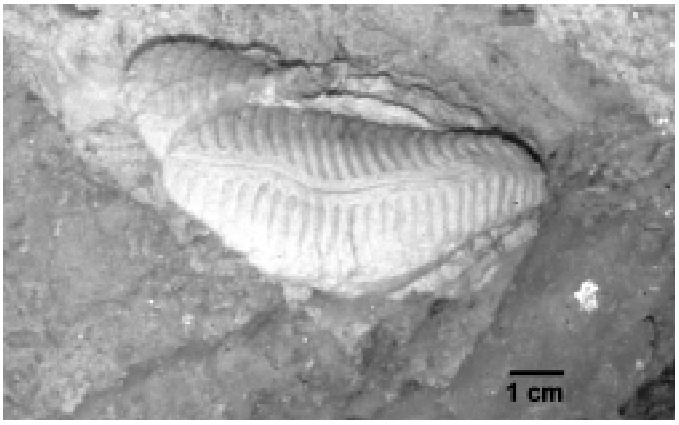

Figure 8. *Leptodus* sp. in Sanctuary, Lechuguilla Cave. Photo by John Lyles.

BRYOZOA

Bryozoans are attached colonial invertebrates with calcareous skeletons. They occur in branching forms that superficially resemble modern branching corals, and as fenestrate varieties that have small window-like openings between branches arranged in a reticulate pattern. Fragments of fenestrate bryozoans are common in the massive Capitan as well as in debris flows within the forereef slope. Good examples of bryozoans are present in the Void and numerous other sites in Lechuguilla Cave. For a discussion of the role of fan shaped and branching bryozoa as frame builders of the Capitan Reef, see Wood *et al.* (1994, 1999)

ECHINODERMATA

Echinoderms are solitary, bottom-dwelling marine organisms characterized by an endoskeleton formed of plates or ossicles composed of crystalline calcite and having bilateral-radial symmetry. Crinoidea (crinoids) and Echinoidea (echinoids), subphyla of Echinodermata, are common in the Capitan Reef Complex.

Crinoids are attached or unattached echinoderms characterized by five-fold symmetry, a body that is enclosed by calcareous plates, and a stem (or column) composed of individual, button-like segments. The most common crinoid fossils in Lechuguilla are individual columnals and 1-3 cm long segments of the column. However, longer branched segments are present in Spar City and in the Clambake Room (Linda Doran, pers. comm. 1999).

Echinoids, or sea urchins, are characterized by subspherical shape, interlocking calcareous plates, and movable appendages or spines. Because they are composed of plates, echinoid skeletons break apart after the death of the animal so that complete fossils are rare. Echinoid spines are bulbous with a convex indentation at the attached (proximal) end, tapering to a blunt or pointed tip. Excellent echinoid spines 4-5 cm long have been found in the Clambake Room (Fig. 10). Echinoid spines are commonly associated with gastropods, suggesting that they occupied the same ecological niche (Newell *et al.* 1953).

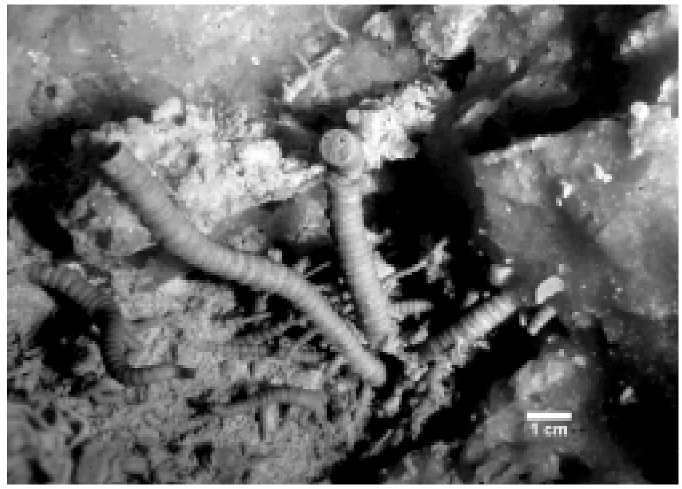

Figure 9. Crinoid column segments, Clambake Room, Lechuguilla Cave. Photo by Dave Bunnell.

FUSULINIDAE

Fusulinids are foraminifers belonging to the suborder Fusulinina, family Fusulinidae, and are characterized by a multichambered elongate calcareous microgranular test typically having the shape of a grain of wheat. They are common in reef and slope sediments and are used by paleontologists to date and correlate Paleozoic strata.

Fusulinids are widely distributed in the bedrock of Lechuguilla Cave, but most have been recrystallized so that they are useless for age correlation. One usable sample was collected at a depth of 331 m on the route from the Ruby Chamber to Lake of the White Roses. The bedrock in this area dips of 20°-25° and is comprised of highly fossiliferous and brecciated limestone. These fusulinids are all an advanced species of *Parafusulina*, having all of the characteristics of *Polydiexodina* except the multiple tunnels. They have been transported and abraded, which is consistent with their position within forereef slope deposits. The *Parafusulina* fossils are probably of lower Capitan age indicating that these slope deposits are equivalent to the Queen or Seven Rivers formations.

GASTROPODA

Gastropods (snails) are mollusks in which most species have an asymmetric, helically coiled shell with the apex pointed away from the aperture (Fig. 11). Bellerophontid gastropods, however, have a planispirally coiled shell. Gastropods are most common in sediments of the immediate backreef but are found throughout the shelf margin.

Some of the most spectacular fossils in Lechuguilla are large bellerophontid gastropods found at numerous sites in the Seven Rivers Formation. The most "famous" of these is "The Flying Potato," in the F Survey near the E-F Junction (Fig. 12). This specimen has a width of 190 mm and a height of 115 mm. It is one of many bellerophontid gastropods in the lower part of the Seven Rivers Formation exposed in the walls and ceiling

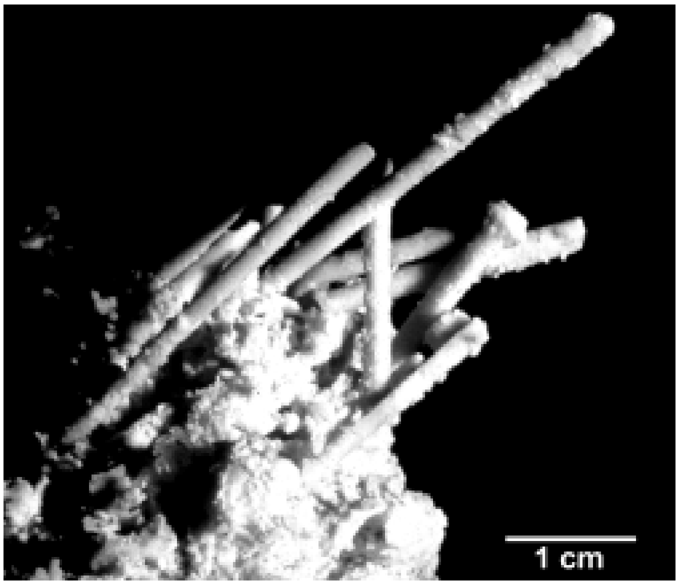

Figure 10. Echinoid spines, Clambake Room, Lechuguilla Cave. Photo by Dave Bunnell.

Figure 11. Helically coiled gastropods near station F5, F survey, Lechuguilla Cave. Photo by David Jagnow.

of the F Survey. At the time of its discovery, the "Flying Potato" was the largest known bellerophontid gastropod in the world (Kues & DuChene 1990).

PELECYPODA

Pelecypods (clams) are mollusks with symmetrical mirror-image valves. They are found in the backreef, reef and forereef slope of the Capitan Reef Complex but are most common in the proximal lagoon and nearby reef. Newell *et al.* (1953) identified 24 varieties of pelecypod from the Capitan Formation.

Pelecypods have been reported from numerous stations in the Void in Lechuguilla Cave.

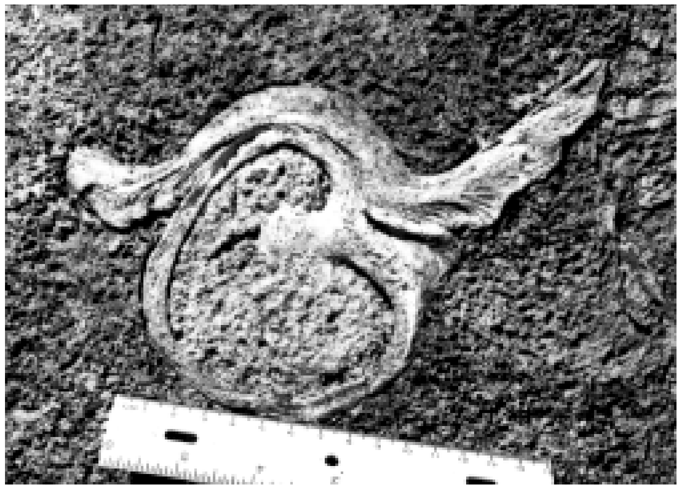

Figure 12. Bellerophontid gastropod at station F5, F survey, Lechuguilla Cave. Photo by David Jagnow.

CEPHALOPODA

Cephalopod shells are the straight, curved or coiled skeletons of marine mollusks that are divided into chambers connected by a siphuncle. Modern cephalopods include octopi, squid, cuttlefish and *Nautilus*.

Most of the cephalopod fossils found in Lechuguilla are coiled ammonoids ranging up to 15 cm across. Typical examples are found in the Rift, in High Hopes, and in a fissure in Clambake Room (Fig. 13). One example of a straight-coned nautiloid has been found in Spar City (Fig. 14). This specimen is 16 cm long with an aperture ~1.5 cm across. It is associated with branching crinoid columnals, sponges and large neospiriferid brachiopods, all of which are coated black.

PORIFERA

Sponges belong to the phylum Porifera, which consist of many-celled aquatic invertebrates characterized by an internal skeleton of silica or calcium carbonate. Sponges are most commonly found in growth position in the massive reef, but they are also found in transported blocks within the forereef slope and in patch reefs in the backreef lagoon.

Common varieties seen the Capitan Formation in Lechuguilla are *Lemonia*, *Amblysiphonella*, *Cystaulites*, *Guadalupia*, and *Girtycoela.* They are illustrated in Newell *et al.* (1953) and Bebout and Kerans (1993).

DISCUSSION

In the limestones of the Guadalupe Mountains, the mixing of connate water rich in hydrogen sulfide with oxygenated meteoric water is essential for sulfuric acid speleogenesis (Davis 1980; Hill 1987; Palmer & Palmer 2000). Aside from geochemical processes, major factors that controlled the location, development and morphology of cave passages were the location of porous and permeable rock along the Capitan shelf margin, structure and stratigraphy, and the depth of the water

Figure 13. Ammonoid, Clambake Room, Lechuguilla Cave. Photo by Dave Bunnell.

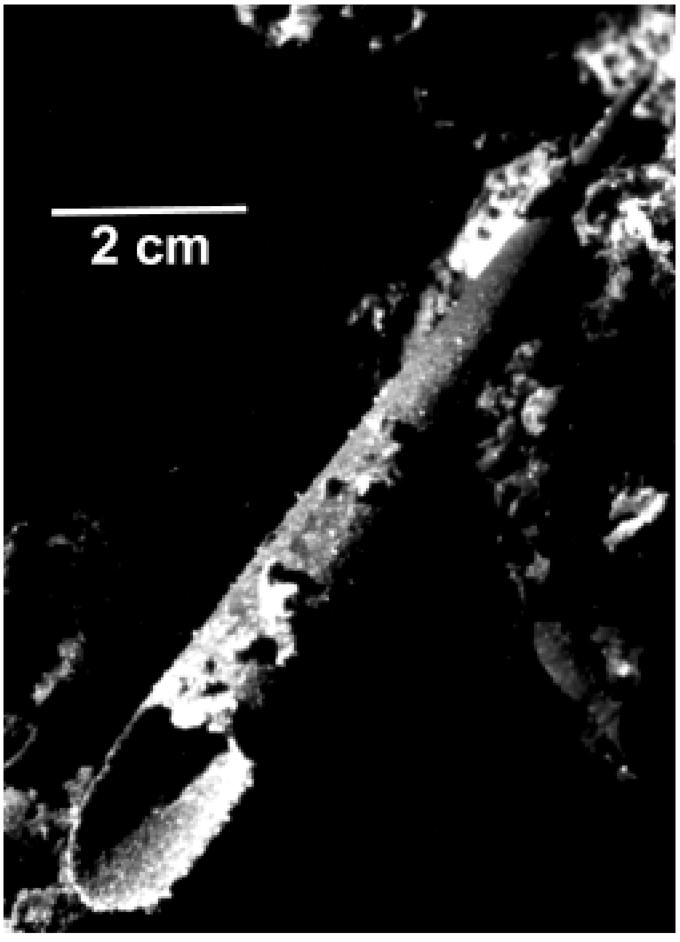

Figure 14. Straight-coned nautiloid, Spar City, Lechuguilla Cave. Photo by Tim Stone.

table during speleogenesis.

STRATIGRAPHY AND RESERVOIR CHARACTERSTICS

Most of Lechuguilla Cave developed in the immediate backreef facies of the lower part of the Seven Rivers Formation, and in the massive reef and forereef slope environments of the Capitan Formation. Immediate backreef sediments are porous rudstones and packstones that become progressively more abundant toward the reef. These rocks have high interstitial porosity where pores have not been filled with calcite or anhydrite cement. Porosity tends to increase toward the shelf margin where water circulation winnowed finer grained material from the sediment.

The massive Capitan is composed of carbonate precipitated by reef flora and fauna and held together by encrusting organisms such as *Archeolithoporella*. Irregular voids, fractures, and cavities are common, resulting from random growth and collapse of reef structures in a dynamic environment. Massive reef limestones have excellent porosity and permeability where not filled with post-depositional cements.

Much of the sediment that was deposited in the forereef slope of the Capitan was produced in the massive reef. Slope detritus is coarsest near the top of the slope, and becomes progressively finer toward the toe of the slope. Large fragments of reef material have the same porosity and permeability as the massive reef. Finer grained material near the top of the slope can also have excellent porosity.

Together, the immediate backreef, massive reef and forereef slope deposits of the Seven Rivers and Capitan Formations form an elongate, tabular lithosome as much as 6 km wide, hundreds of kilometers long, and 600 m thick. This body of rock is the most seaward part of the Capitan shelf margin and is where primary porosity and permeability are best developed. It comprises a significant part of the Capitan aquifer of Hiss (1980) and contains Lechuguilla and most of the other caves in the Guadalupe Mountains. To the east in the Delaware Basin, the Capitan aquifer is both a reservoir for groundwater and a path for hydrodynamic flow. In the past, prior to the erosion events that exhumed and dissected the Guadalupe Mountains, it is likely that the Capitan-Seven Rivers lithosome was continuous to the western escarpment of the uplift (DuChene & Martinez 2000).

Primary matrix porosity in the Capitan-Seven Rivers lithosome is important to speleogenesis because it provided the reservoir in which water with dissolved hydrogen sulfide was stored; i.e., if the lithosome did not have well-developed primary porosity, sulfuric acid speleogenesis could not have taken place. The permeability of the lithosome allowed oxygenated meteoric water to move freely through the reservoir to sites where caves were being formed. Reservoirs with intergranular or intercrystalline porosity have more surface area than those with fracture porosity. This means that there is more surface area where sulfuric acid can react with bedrock, implying that dissolution could occur at a faster rate and in a larger volume of bedrock. Passages and galleries developed where the reservoir has intergranular porosity should have wider cross sections than passage developed along fractures. Examples of galleries formed in porous bedrock are the large, mostly tubular, northeast-trending passages in the Western and Southwestern branches of Lechuguilla Cave. Passages developed along fractures include the Rift and the Northwest Passage.

STRUCTURAL AND STRATIGRAPHIC CONTROL OF CAVE PASSAGES

The map of Lechuguilla Cave (Fig. 4) shows two major passage orientations with a primary west-southwest trend parallel to the shelf margin and a secondary trend more or less perpendicular to it. These trends can be correlated with joint patterns mapped by King (1948: Plate 21) for the Guadalupe Mountains. Many north- and northwest-trending passages such as the Rift and the Northwest Passage, and some northeast-trending passages such as the route to Sulfur Shores, are clearly controlled by joints. These passages are narrow compared to their height, have >150 m of vertical relief, and die out with depth. They extend across formation boundaries and connect upper and lower levels of the cave.

In contrast, many northeast-trending passages and galleries are developed at depths of 250–300 m in south-dipping breccias and debris flows of the Capitan forereef slope. These passages parallel depositional strike of the slope and do not cross formation boundaries. Passages are roughly tubular in cross section with floors covered by breakdown blocks composed of depositional breccia. Some galleries, such as the Deep Seas Room, have elliptical cross sections with the long axis sloping to the south. These factors strongly suggest that bedding within the forereef slope controls the shape and orientation of many passages in the lower level of Lechuguilla.

Stratigraphy was not the only control on passage formation. The position of the water table and the porosity of the bedrock were other critical factors that determined where speleogenesis took place. Major levels occur at depths of 150-220 m and 250-300 m, indicating that there were at least two speleogenetic episodes. During the first, the water table was probably located at a depth near 150 m, above the contact between the Seven Rivers and Capitan formations. Bedding, joints, fractures and sandstone dikes in the lower Seven Rivers and Upper Capitan controlled passage morphology and orientation at that level. During the second episode, the water table was probably at a depth of 210 m near the transition between the massive and forereef slope members of the Capitan. Speleogenesis took place along the upper part of the water table in south-dipping beds of the slope (Palmer & Palmer 2000).

CONCLUSIONS

Based on paleontologic and stratigraphic data from outcrops in Lechuguilla, most of the cave is developed in the immediate backreef facies of the Seven Rivers Formation and the reef and forereef slope facies of the Capitan Formation. This porous lithosome parallels the Capitan shelf margin and extends from the western escarpment of the Guadalupes northeast to the border between New Mexico and Texas. The Capitan-Seven Rivers lithosome was the original reservoir where water containing hydrogen sulfide was stored prior to and during sulfuric acid speleogenesis, and it was the avenue for eastward migration of oxygenated meteoric water. Because mixing of hydrogen-sulfide water with oxygenated water occurred within the lithosome, it was the site of the major speleogenetic events that formed Lechuguilla Cave.

The strike, dip, porosity, and stratigraphic character of beds in the Capitan forereef slope control the orientation and morphology of many passages below -250 m in Lechuguilla. These passages trend northeast, parallel to the shelf margin, and were formed when the water table was near the transitional contact between massive reef limestones and beds of the forereef slope.

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