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DETRITAL ORIGIN OF A SEDIMENTARY FILL, LECHUGUILLA CAVE, GUADALUPE MOUNTAINS, NEW MEXICO

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Abstract—Lechuguilla Cave is a hypogene cave formed by oxidation of ascending hydrogen sulfide from the Delaware Basin. A unique sediment deposit with characteristics suggesting derivation from the land surface, some 285 m above, was investigated. At this location, the observed stratigraphy (oldest to youngest) was: bedrock floor (limestone), cave clouds (secondary calcite), calcite-cemented silstone, finely laminated clay, and calcite rafts. Grain-size analysis indicates that the laminated clay deposits are composed of 59–82% clay-size minerals. The major minerals of the clay were determined by X-ray diffraction analysis and consist of interstratified illite-smectite, kaolinite, illite, goethite, and quartz. Scanning electron microscopy observations show that most of the clay deposit is composed of densely packed irregular-shaped clay-size flakes. One sample from the top of the deposit was detrital, containing well-rounded, silt-size particles.

Surface soils are probably the source of the clay minerals. The small amount of sand- and silt-size particles suggests that detrital particles were transported in suspension. The lack of endellite and alunite is evidence that the clays were emplaced after the sulfuric-acid dissolution stage of cave formation. Fossil evidence also suggests a previously existing link to the surface.

Key Words—Caves, Cave Sediments, Lechuguilla Cave.

INTRODUCTION

Lechuguilla Cave, which is located in Carlsbad Caverns National Park, southeastern New Mexico (Figure 1), is the fifth longest cave in the world and the deepest known cave in North America, with a mapped length of over 160 km, and a vertical range of 475 m. Since its discovery, Lechuguilla Cave has been the focus of numerous geologic and biologic studies, as well as ongoing exploration. The cave is perhaps best known for its mineral decorations, such as the meter-size gypsum crystals referred to as "gypsum chandeliers".

Lechuguilla Cave is situated on the western margin of the Permian Basin, southeast New Mexico, at the eastern edge of the Guadalupe Mountains. The area has a semiarid climate with an annual precipitation of 36 cm (Palmer *et al.*, 1991). The cave occurs mostly within the Permian Capitan Formation, of the Capitan Reef Complex. The elevation of the cave entrance is 1414 m above mean sea level (amsl). The water table occurs at 955 m (Palmer *et al.*, 1991), and the cave is predominantly dry, with most water found in lower levels. The cave is of hypogene origin, formed by the mixing of descending oxygen-rich meteoric groundwaters, with ascending, sulfur-rich basinal waters (Palmer *et al.*, 1991). Apparently numerous phreatic episodes occurred. Polyak *et al.* (1998) determined the timing of speleogenesis at the 1230- and 1180-m elevations to be 5.7 and 5.2 Ma, respectively.

In general, caves are impacted by surface streams and develop by epigene (surface-related) processes. In contrast, hypogene caves rarely show significant effects of surface waters unless erosion exposes the cave to allow surficially derived sediments to enter the cave. In Lechuguilla, as in all of the hypogene caves of the Guadalupe Mountains, large (>1 m) connections to the surface are random and not related to specific recharge points such as sinkholes. Unlike other Guadalupian caves, Lechuguilla has not been extensively invaded by seepage water. A laterally extensive, siltstone caprock has probably diverted water away from the cave (Cunningham and Takahashi, 1992). Lechuguilla is considered a pristine cave system with limited input of allochthonous material (Cunningham *et al.*, 1995)

A deposit within Lechuguilla Cave occurs with characteristics typical of clastic, surface-derived sediment. Several options exist for the source of this material: 1) The sediment was transported into the cave from a surface source; 2) dissolution of limestone during speleogenesis resulted in liberation of trace constituents and accumulation of insoluble residue; 3) the minerals formed during speleogenesis by diagenetic reaction of existing clays with sulfuric groundwater; or 4) the minerals formed by microbiologic alteration of bedrock or other materials. To investigate this material, we considered the texture by size analysis and clay fabric, and mineralogy by X-ray diffraction. We also investigated the deposit in context with the surrounding cave and with surficial features.

METHODS

Twenty, 8-cm^3 size samples were collected. The relative amounts of sand, silt, and clay were determined

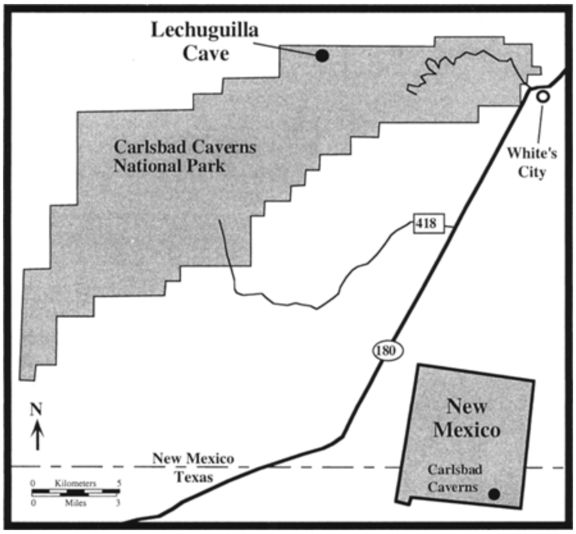

Figure 1. Location of Lechuguilla Cave.

by centrifuge and sieve analysis. Bulk and clay mineralogy were determined with X-ray diffraction (XRD) using CuKα radiation at 40 kV and 35 mA. The samples were suspended in distilled water and the <2-μm fraction was separated, filtered, and transferred onto a glass slide (Foos and Quick, 1988). Samples were air-dried, treated with ethylene-glycol vapor, saturated with K^+, and heated to 100, 300, 400, and 550°C. The texture of the laminated clay deposits was observed by scanning electron microscope (SEM).

RESULTS

Sample sites

The deposits are located in the southern part of the cave in an area called Deliverance Passage. The samples were collected from the Aintry Room, located 2 km into the cave at an elevation of 1115 m amsl and 299 m below the entrance. The land surface elevation is ~1400 m amsl above the site, indicating 285 m of overburden.

The Aintry Room is up to 30 m wide and 7 m high. The cave walls consist of bedrock and secondary calcite coatings. The floor is covered with thin, loose flakes of calcite ("calcite rafts") that formed when the room was partially submerged. Rafts are formed when calcite crystallized on pool surfaces as thin sheets, which then sank to the bottom of the pool when they became too heavy to float.

Sampling site 1 (Table 1) was an excavated trench on the floor. Sampling site 2 (Table 2) was a shelf ~1 m above the floor, attached to the back and side walls of a small alcove, on the eastern side of the room. At site 2, layers of light- and dark-brown laminated clays, capped by calcite rafts, occur on top of a shelf of laminated calcite-silt. The exposure has a relatively fresh face, although it is unclear why this is so. The thick banded calcite-silt (layer 2K) shows a contact relationship with "cave clouds" (mamillarian structures) on the wall at the south end of the shelf. Cave clouds are calcite coatings that form on walls or ceilings in subaqueous conditions. Deposition of the calcified siltstone appears to post-date deposition of the cave clouds. The calcite-silt is similar to deposits described in Carlsbad Caverns (Hill, 1987) as calcified siltstone. In Carlsbad Caverns, these deposits are overlain by calcite rafts, suggesting that the sequence is related to regional shifts in water level within the Guadalupe Mountains. The calcite siltstone is composed of 80% calcite and 20% quartz silt. Hill (1987) noted that the siltstone is found on up-facing surfaces, and at elevations between 1115–1150 m. The 1115-m value matches that of the deposit in Lechuguilla Cave. The interbedded clay, calcite, and calcite rafts at site 2 (layers 2J-2A) appear to represent a semi-continuous depositional series characterized by alternating clastic sediment and calcite raft formation and deposition.

Direct correlation of the two sample sites is not possible. However, the uppermost calcite-raft layer at site 2 (2A) is probably roughly equivalent with the top layer of rafts on the floor near site 2 and site 1 (1A). The thicker deposit of rafts at site 1 is consistent with the geometry of the room, and the effects of a declining water table. Likewise, the relatively thicker clay (and other raft) deposits at site 1 may reflect differences in position relative to the geometry of the room.

Table 1. Detailed description of site 1.

Unit	Thickness (cm)	Description
TOP		dusting of gray silty material
1A	7.7	calcite rafts
1B	0.3	gray clay
1C	74.4	massive to slightly laminated, dense, hard, medium-brown clay; with "boxwork-like" calcite deposits that appeared to be infilling cracks within the clay (Samples IDS 293, 294, 295, 296, 297, 298, 299, 300)
1D	10.0	extremely friable medium-brown clay (Samples IDS 301, 302)
1E	>25	weathered calcite rafts
BOTTOM		excavation became impractical; bedrock was not reached

Table 2. Detailed description of site 2.

Unit	Thickness (cm)	Description
TOP		dusting of gray silty material
2A	2.6	loose calcite rafts (white and red)
2B	1.3	calcite layer
2C	2.6	red and silty calcite rafts
2D	0.3	white clay
2E	0.6	red rafts
2F	0.3	red calcite rafts
2G	0.3	red/silty calcite
2H	0.3	white clay
2I	10.3	variably laminated, light to dark-brown, dry cracked clay (Samples IDS 303, 304)
2J	2.6	punky clay/silt
2K	20 to 51	thick-banded calcite/silt
	92	air
BOTTOM		cave floor (rubble and rafts)

Grain-size analysis

The deposits are dominantly composed of clay with minor amounts of fine sand and silt. These sediments (Table 3) contain an average of 9 wt. % sand, 21 wt. % silt, and 70 wt. % clay. The shelf deposit (site 2, IDS304) contained the greatest amount of clay (82 wt. %). The fine-grained nature of these deposits and small amount of sand-size particles suggest that the sediment was transported in suspension.

X-ray mineralogy

XRD analysis indicated that the samples consist of interstratified illite-smectite (I-S), kaolinite, illite, goethite, and quartz (Figures 2, 3, and 4). The swelling clay (I-S) had a 0.142-nm reflection that increased to 0.170 nm after treatment with ethylene glycol, and collapsed to 0.100 nm after saturation with K^+ and heating to 300°C. The 00*l* reflections are irrational indicating interstratifications. This clay was identified as illite-smectite with 30–40% illite based on reflections at 0.552 and 0.88 nm (Moore and Reynolds, 1997). The *d*(060) of 0.1507 nm indicates the smectite component is dioctahedral and the I-S has a relatively low concentration of Mg and Fe. The occurrence of kaolinite was determined from basal reflections at 0.713 and 0.356 nm that were not affected by ethylene-glycol treatment or by heating to 400°C, but these peaks disappeared after heating to 550°C. Discrete illite was identified from the presence of periodic 00*l* reflections at 1.00, 0.50, and 0.33 nm, which did not change after treatment with ethylene glycol or heating to 550°C. Characteristic peaks for goethite occurred at 0.418 and 0.269 nm. Quartz was observed in the bulk samples. The minerals alunite, hydrated halloysite (endellite), montmorillonite, and palygorskite, which were observed in Lechuguilla by previous workers (DuChene, 1986; Cunningham *et al.*, 1995; Polyak and Güven, 1996), were not observed in these samples.

Table 3. Grain size analysis (wt. %).

Sample #	Sand >50 μm	Silt 50–2 μm	Clay <2 μm
IDS294	8	25	67
IDS298	11	30	59
IDS302	10	17	73
IDS304	8	10	82

Scanning electron microscopy

SEM analysis indicates that the samples have the characteristics of detrital sediment (Figure 5). Sample IDS 294, collected at the top of a thick sequence of laminated clays, was clearly detrital, being composed of randomly oriented silt- and clay-size particles (Figure 5a). Most of the finely laminated deposits are clay-size material consisting of densely packed irregular-shaped flakes with a random fabric. Random fabrics in clay deposits form either by bioturbation or deposition by flocculation (O'Brien and Slatt, 1990). Bioturbation is unlikely in this setting. Thus, the clays

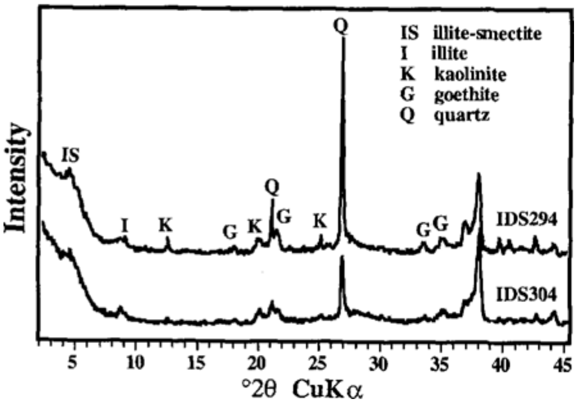

Figure 2. Whole-rock XRD pattern of laminated clay deposits from site 1 (IDS294) and site 2 (IDS304).

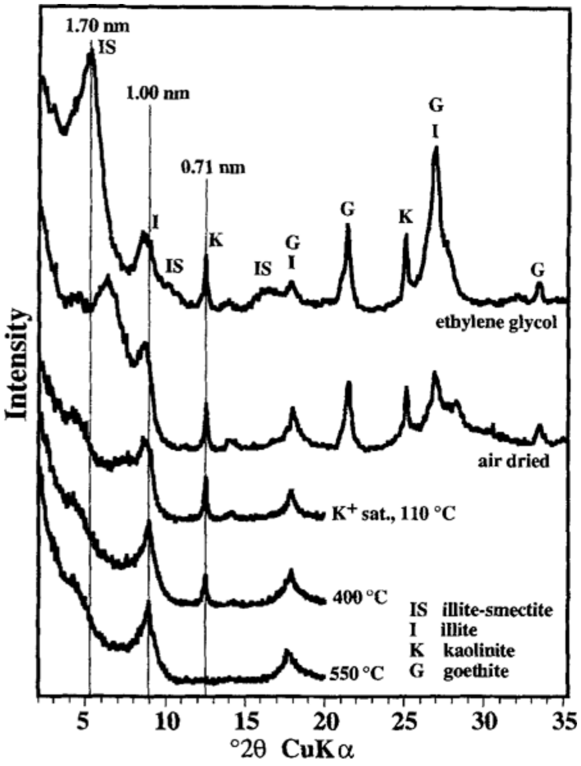

Figure 3. XRD patterns of oriented clay from site 1 (IDS294).

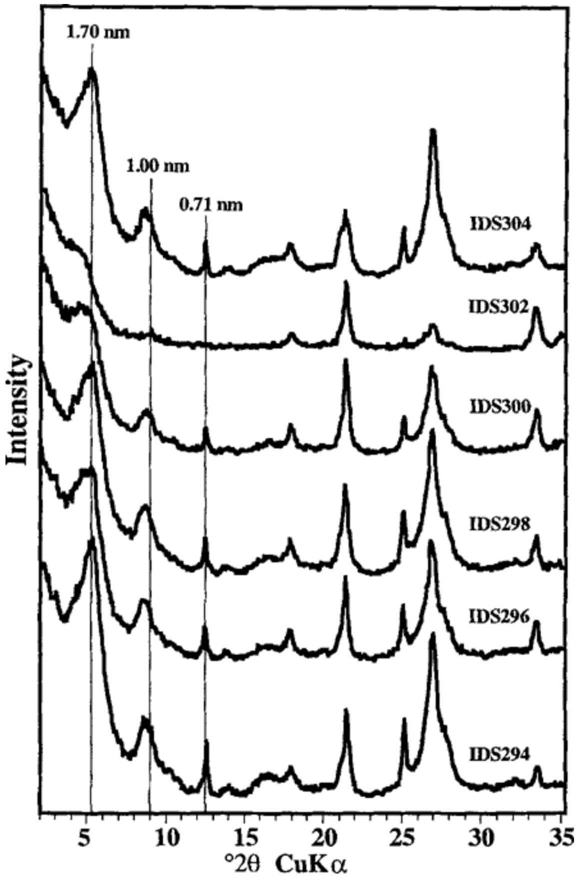

Figure 4. XRD patterns of ethylene-glycol treated, oriented-clay aggregates from sites 1 and 2.

were deposited from suspension by flocculation. Flocculation may have been promoted by the mixing of surface waters with standing water of a cave pool.

Dense structureless clay was the most common feature observed (Figure 5c). The dense packing and lack of structure may be related to reorientation of the swelling illite-smectite that resulted from repeated wetting and drying. The lack of euhedral crystals and fine structures suggest the clay has undergone transport and was not precipitated *in situ*. Notably absent are tubular or rhombic structures, characteristic of halloysite or alunite. Minor post-depositional alteration of the deposits was observed. Rare detrital grains were replaced by iron hydroxides and a fibrous mineral, possibly illite. Fibrous material, similar to some of the features described by Cunningham *et al.* (1995) was also observed (Figure 5f). Cunningham *et al.* (1995) interpreted these features as representing bacterial or fungal filaments.

DISCUSSION AND CONCLUSIONS

Mixtures of clay, silt, and sand, and the SEM observations indicate the sediments are detrital. However, the sediments may have been transported to this site from elsewhere in the cave or accumulated from insoluble residue. The mineral assemblage (illite-smectite, kaolinite, illite, goethite, and quartz) is typical of detrital sediments. The clay minerals probably did not accumulate as insoluble residue during cave formation or from condensation-corrosion residues, because the insoluble residue of the dolostone bedrock and condensation-corrosion residues are composed of illite and dickite (Polyak and Güven, 2000). Surface soils are the most likely source of the clay minerals. The eolian-dust component of soils in the region is composed of kaolinite, illite, and smectite (Gile and Grossman, 1979). The illite-smectite may be formed by the pedogenic alteration of smectite in the surface soil horizons of arid regions (Allen and Hajek, 1989). Detrital cave-mud deposits have been observed in other caves of the Guadalupe Mountains and their mineral assemblage (kaolinite, illite, and montmorillonite) is similar to this deposit in Lechuguilla (Polyak and Güven, 2000). Because cave-authigenic clay minerals, including endellite, trioctahedral smectite, and palygorskite were not observed in this deposit, and cave-forming sulfuric acid-bearing waters convert clay minerals to endellite and alunite (Polyak and Güven, 1996) the clays were probably emplaced after the sulfuric-acid dissolution stage of cave formation.

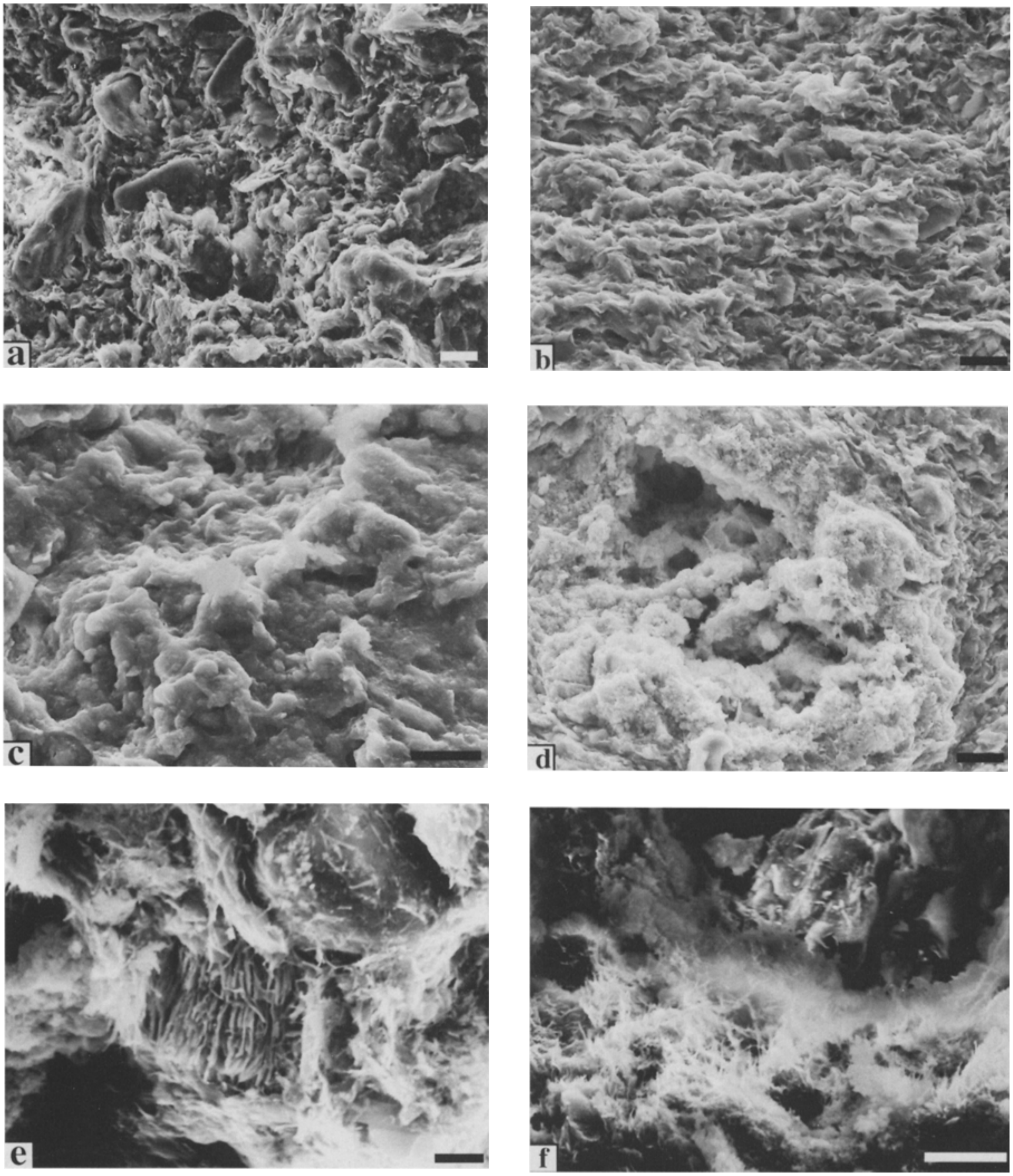

Figure 5. SEM images of laminated clay deposits. a) Site 1, layer 1C, showing a random orientation of clay-size and well-rounded, silt-size particles (IDS294, scale bar = 10 μm); b) site 2, layer 2I, showing a random orientation of clay-size particles and lack of silt-size material (IDS304, scale bar = 10 μm); c) dense structureless sediment from site 1, layer 1C (IDS300; scale bar = 10 μm); d) an accumulation of iron hydroxides within the laminated clay from site 2, layer 2I (IDS304; scale bar = 10 μm); e) a detrital grain (possibly feldspar) replaced by a fibrous clay mineral (IDS298; scale bar = 2 μm); f) either a fibrous clay mineral that was precipitated *in situ* or a bacterial/fungal filament (IDS300; scale bar = 5 μm).

In addition to the sediment characteristics, other data suggest a surface source for the clastic deposits found in the Aintry Room. This portion of the cave is overlain by Walnut Canyon, suggesting downward water seepage and transport of sediments from the surface. However, the vertical distance (280 m) is substantial. Apparent clastic deposits occur beneath surface canyons in other areas in the cave. Such areas include the Over the Rainbow section at the end of the Western Borehole. In the Outback Area of the Far Eastern Maze, there is a subtle sheet of moisture with a thin veneer of sediment that is apparently being carried down a rift.

A semi-articulated skeleton of a fossil ringtail cat (Bassariscus astutus) was found nearby within the cave (Cunningham and LaRock, 1991). Although, the only entrance to the cave is 2 km from the site, this indicates that another connection to the surface was likely. If not, the cat traversed (in the dark) 2 km and survived several vertical drops (≤50 m) to reach this portion of the cave via the present entrance. Evidence of another entrance is supported by radon levels (Cunningham and LaRock, 1991) that are consistently low in a nearby area of the cave. Temperature and CO_2 concentrations are 0.5°C and 0.08% lower than calculated means for other parts of the Southwest Branch of the cave, indicating fresh-air dilution nearby.

These results suggest a surface source for the laminated clay deposits. However, the data do not clearly prove or disprove the existence of a large-scale connection with the surface during the recent past. The bulk of the material was probably transported in suspension by ground water. Connections to the surface allowing the introduction of clay- to silt-size materials may be more prevalent than previously thought. The possible introduction of organic material and other contaminants to the microbiological ecosystem of Lechuguilla Cave may indicate that the cave is not a closed or pristine system.

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