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BIOTHEMS: BIOLOGICALLY INFLUENCED SPELEOTHEMS IN CAVES OF THE GUADALUPE MOUNTAINS, NEW MEXICO, USA

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Abstract.—Biothems are speleothems in which the morphology, internal structure or composition was influenced by organisms. This paper is a first attempt to identify biothems found in modern and fossil pools (former pools, now dry) of the Guadalupe Mountain caves. We have identified several features that suggest biologic involvement including patchy distribution, projecting forms, downwardly pendant forms, active slime (biofilm), mineralized slime, internal micritic or pelmicritic fabric and fossil filaments and/or fossil biofilm seen in the scanning electron microscope. We distinguish between Type 1 biothems, those containing direct evidence of microbial involvement, and Type 2 biothems, those suspected of biologic involvement but lacking obvious direct evidence. Type 1 biothems include bryolites, conical crusts, moonmilk (some varieties), pool fingers, ramose balls, rusticles, u-loops and webulites. Type 2 biothems include blades/chenille spar, drips, hemispheres, pinnacles/conical mounds, scales, radiating flowers, tangential chips and tufted cushions. These terms are preliminary and meant to guide future research.

INTRODUCTION

Despite a long history of study and exploration, caves remain a rich resource for both research and recreation. Popular research topics include speleogenesis, mineralogy of cave precipitates, stalactites and stalagmites (particularly as records of climate change), and micro- and macro-biology (Northup et al., 1997). Surprisingly little work, however, has been done on cave pools and the minerals that line them (González and Lohmann, 1988; González et al., 1992; Melim et al., 2001). Our continuing work in the modern and fossil cave pools of the Guadalupe Mountains has shown that there are complex interactions between inorganic and biologic processes that influence the development of a wide variety of pool speleothems. This report is our preliminary effort at identification of features with possible biologic involvement. This work is mainly based on observation of morphology and should be used to guide future research rather than be considered a definitive description of pool biothems.

FIELD LOCATION

The Guadalupe Mountains are located in southeastern New Mexico and West Texas, in the southwestern United States. They expose a thick stratigraphic sequence of Permian carbonate rocks, including outstanding outcrops of the Capitan Reef Complex of Newell et al. (1953; see also Saller et al., 1999). Approximately three hundred caves are known in the Guadalupe Mountains (DuChene and Martinez, 2000), overseen by Carlsbad Caverns National Park, the National Forest Service, and the Bureau of Land Management. These include Carlsbad Cavern, one of the most popular of the caves managed by the National Park Service, and Lechuguilla Cave, fifth longest cave in the world (Gulden, 1996) and the deepest known in the continental United States.

SPELEOTHEMS: GENERAL CONSIDERATIONS

Mineral precipitates formed in caves are called speleothems and include the commonly encountered cave decorations such as stalactites, stalagmites, etc. (Hill and Forti, 1997). Precipitation is typically attributed to calcite oversaturation resulting from either CO_2 degassing or to evaporation from cave walls or cave pools (Thraikill, 1971; Hill and Forti, 1997). However, the growing recognition that caves contain abundant microorganisms (Northup and Lavoie, 2001) and that these communities can affect mineral precipitation (Melim et al., 2001; Jones, 2001; Cacchio et al., 2004) questions the assumption that speleothems are the result of purely abiologic precipitation.

WHAT ARE BIOTHEMS?

Cunningham et al. (1995) coined the term "biothems" to describe speleothems in Lechuguilla Cave containing evidence of microbial life such as filaments, hyphae, or webs of mineralized biofilm. We extend this definition to any speleothem where the morphology, internal structure or composition was influenced by organisms. Although there are exceptions, most of the purported biothems were apparently formed underwater in cave pools. A few living examples occur in the Guadalupe caves but many more examples are found in the abundant dry paleopools.

CHARACTERISTICS OF ABIOLOGIC CAVE POOL DEPOSITS

Typical pool precipitates include rafts, pool spar and shelfstone (Hill and Forti, 1997). The top of paleopools can be easily recognized by either the presence of shelfstone (if present) or the horizontal waterline marked by the upper limit of pool spar. Rafts and shelfstone form along the surface as evaporation and/or degassing lead to precipitation. Below the water level, rock surfaces are coated by uniform to botryoidal crusts (pool spar; Hill and Forti, 1997) that are similar to the isopachous cements common in phreatic cementation (see James and Choquette, 1990a, b; Choquette and James, 1990; Tucker and Wright, 1990).

BIOTHEM INDICATORS

While no single feature is diagnostic, a number of features can suggest biologic involvement in formation of a speleothem. These include:

Patchy distribution: While pool spar typically coats all pool surfaces (Hill and Forti, 1997), biothems are patchy, often occurring in only one area of a pool or one pool in a room with several pools. Patchy distribution is difficult to explain chemically as it is hard to maintain closely spaced, chemically distinct, subaqueous microenvironments without invoking biologic controls.

Projecting form: The morphology of biothems is varied, but all of the forms recognized so far share the characteristic that they stick up, jut out or hang down from the surface they coat. This characteristic separates them from the uniform or botryoidal crusts of pool spar they often cover. There is no reason a biothem couldn't also form a uniform coating but then it would be difficult to distinguish from abiologic crusts.

Downwardly pendant forms: Some biothems exhibit a vertical, pendant orientation, something unexpected in the subaqueous pool environment (unlike the subaerial environment where dripping water commonly creates vertical features such as soda straws and stalactites).

Active slime: In several caves, some biothems have been observed with threads of clear mucous hanging off the ends. This has not been observed on bare rock surfaces, nor on surfaces that lack other biothem indicators. However, biofilms are likely present on additional surfaces (Northup et al., 1997).

Mineralized slime: Many biothem locales are associated with drapes, loops, strings, drips and veils of what appears to be mineralized slime. These are very similar to snottites, subaerial microbial strings that occur in a sulfuric acid-dominated Mexican cave (Hose et al., 2000) and microbial slime drapes in deep sea vents, except that they are mineralized.

Internal fabric: Unlike the usually clear pool spar, many biothems are composed of dense brown calcite. Thin sections of selected biothems show this to be micrite, often with clotted pelmicritic texture (Melim et al., 2001; Melim et al., 2004). Micrite is increasingly perceived by carbonate scientists as a microbial precipitate, resulting either from the calcification of biofilms (Riding, 2002) or direct precipitation by microbial activity (Yates and Robbins, 1998, 1999). Clotted textures, in particular, suggest microbes (Chafetz, 1986; Burne and Moore, 1987; Buczynski and Chafetz, 1993; Arp et al., 1998; Riding, 2002).

Fossil filaments and/or biofilm: Fossil filaments and biofilm have been found in several biothems using the scanning electron microscope (SEM) (Melim et al., 2001, unpublished data). These features are found by etching the sample and are therefore not surface contaminants but integral to the rock. The mere presence of microbial remnants is not proof of biogenicity but does support the idea (Jones, 2001).

TYPES OF BIOTHEMS AND BIOTHEM-RELATED FEATURES

Degrees of potential biologic involvement

Biothems can be divided into two groups: those in which the influence of microbes seems obvious and those in which the relationships are less apparent. Distinguishing between forms with strong presumptive evidence of biologic involvement and those with only inferred involvement is important as this serves as preliminary structure to which the growing body of field and laboratory observations may be related. As more observations are made, particular features may either be demonstrated to have organic associations or be recognized as abiotic.

Type I (demonstrated biologic associations): speleothems containing direct evidence of microbes such as fossilized filaments or other cellular material, mineralized slime, or microbial fabrics in thin section. This does not mean that the microbes actively precipitated the speleothem (Jones, 2001), but does indicate the presence of microbes; and their activity may have influenced the environment in which the speleothem formed.

Type II (suspected biologic associations): speleothems with one or more of the biothem indicators, but without observed direct evidence of microbes. Additional study of Type II speleothems not yet examined in detail may reveal such evidence.

Type I

Bryolites

Massive composite forms including drips, small pool fingers, webulites and u-loops. These are commonly found covering much of the wall space and speleothems below the waterline in unusually large pools but may also occur in smaller pools. Commonly, bryolites are composed of a dense micritic crust, which may be light-to-medium brown in color, over massive-to-crudely laminated white micrite.

Guadalupe Localities: Carlsbad Cavern, Endless Cave, Cottonwood Cave, Dragon Cave, Lechuguilla Cave, Madonna Cave.

Conical crusts

Conical-to-ridge-like encrustations covering pool floors and walls that may reach 3 cm in height, and are generally perpendicular to the underlying growth surface. In some examples, the ridges align perpendicular to apparent water flow. Elsewhere, they radiate from the center of small pools. There are several variations of this form based on the morphology of the cones. **Pool meringue** has 1-2 cm sharp peaks coating pool spar knobs and can grade into webulite (Figure 1; Rust et al., 2004). Other examples are smooth and rounded calcite displaying only pointy tips, or sharp ridges of aragonite. Active examples of these features have been identified by visible trails of slime off the apexes of cones and ridges in several caves. Fossil filaments have been found in pool meringue but they are very rare (Melim et al., unpublished data).

Guadalupe Localities: Carlsbad Cavern, Cottonwood Cave, Endless Cave, Hell Below Cave, Hidden Cave, Virgin Cave.

Moonmilk:

Masses of white, microcrystalline carbonate of uniform mineralogy that at a given site may contain calcite, gypsum, or hydromagnesite, among others (Geze, 1976; Hill and Forti, 1997). Fresh moonmilk is plastic to slightly crunchy, water saturated and often contains living microbes (Figure 2; Williams, 1959; Ohde and Takii, 1978; Gradziñski,et al., 1997, Boston et al., 2001). It is

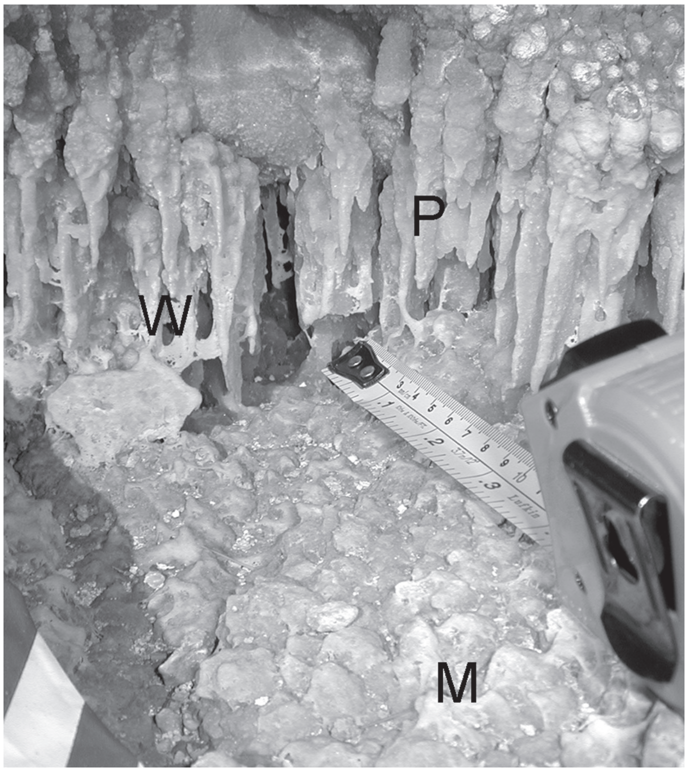

FIGURE 1. Webulite (W) and u-loops connecting pool fingers (P, to chenille spar) in Lower Cave, Carlsbad Cavern. The foreground pool spar is coated in peaks of pool meringue (M). The coating of pool meringue is continuous with the webulite. Metric tape for scale. Photograph by K. Ingham.

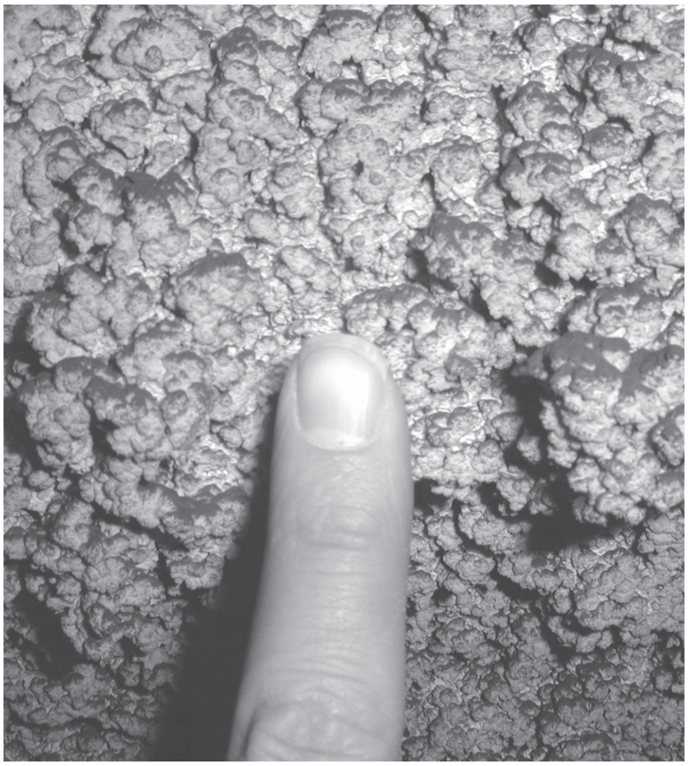

FIGURE 2. Moonmilk coating the wall of Spider Cave. This material is soft and has a Crisco-like texture (Boston et al., 2001). Photograph by K. Ingham.

unclear what role these microbes play in forming the moonmilk. Moonmilk is found in both subaerial and subaqueous environments but in currently dry pools it can be hard to tell if it formed subaqueously or formed later in a subaerial setting.

Guadalupe Localities: Nearly all caves have at least small deposits of subaerial moonmilk; subaqueous in Carlsbad Cavern, Cave Tree Cavern, Cottonwood Cave, Dam Cave, Dragon Cave, Endless Cave, Lechuguilla Cave, Madonna Cave; Oso Cave, Panther Cave, Sand Cave, Spider Cave, Virgin Cave.

Pool fingers

Vertically oriented, elongate cylinders pendant from overhanging surfaces in cave pools (Figures 1 and 3; Davis et al., 1990; Melim et al., 2001). Most pool fingers are uniform in diameter with blunt, rounded terminations but some taper to a point (Figure 1). Size is highly variable from <0.5 cm (Figure 4) to > 50 cm (Figure 3) Pool fingers almost always occur in groups with the upper portions growing laterally together. They can grow down from either shelfstone or submerged cave walls or ceiling. In some areas they all are about the same length; in other areas they form in tiers (Figure 3). Internally, pool fingers consist of clear spar and/or clotted micrite laminations (Melim et al., 2001). Fossil microbes have been found in most samples studied thus far, especially in micritic layers (Melim et al., 2001; unpublished results).

Guadalupe Localities: Carlsbad Cavern, Cottonwood Cave, Hidden Cave, Dragon Cave, Madonna Cave, Endless Cave, Lechuguilla Cave, Pink Dam Cave, Sand Cave.

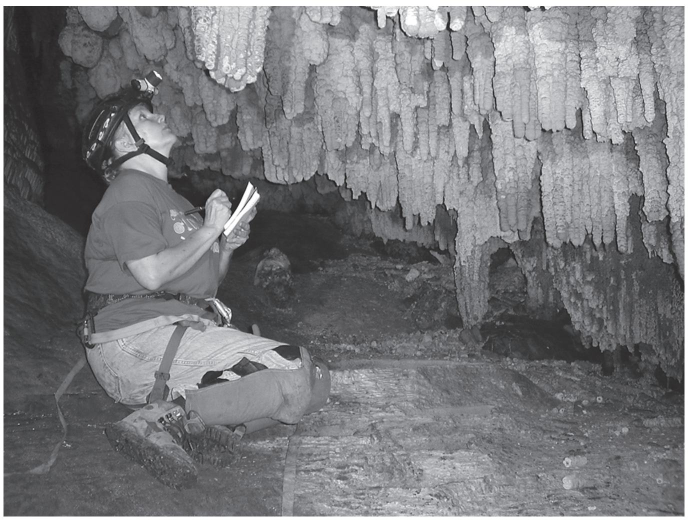

FIGURE 3. Giant pool fingers in Hidden Cave, NM. The pool fingers formed in tiers and taper slightly down. At the top, the pool fingers merge together. Diana Northup for scale. Photograph by K. Ingham.

Ramose balls

Ramose balls are 3-5 cm clumps of randomly oriented, outwardly branched twigs of calcite mixed with 1-2 cm flakes of cave rafts (Figure 7). They have only been found in a single small paleo-pool in Hidden Cave where they are closely associated with abundant drips and u-loops. The individual twigs are ≈1-2 mm in diameter up to 5 mm in length, and appear segmented. Internally, the twigs have central axial zones of micrite and/or clotted micrite and the surface of each twig is calcite pool spar. Each tiny segment has its own clotted micrite core, suggesting individual bacterial colonies (Chaftez, 1986). Other twigs are cored by elongate crystals partly replaced by micrite.

Guadalupe Localities: Hidden Cave.

Rusticles

Rusticles are irregularly curved iron-rich "stalactites", that hang in masses over a meter long in a single paleopool in Lechuguilla Cave (Davis et al., 1990; Provencio and Polyak, 2001). They are named for their similarity to iron rusticles, features forming on deep water wrecks such as the R.M.S. Titanic (Wells and Mann,, 1997; Provencio and Polyak, 2001). Internal layers of carbonate and goethite contain abundant fossil filaments (Davis et al., 1990; our observations) interpreted as acidophilic bacteria (Provencio and Polyak, 2001). Although rusticles have a central canal, they are restricted to the region below the paleo-waterline and are apparently inter-layered with cave rafts (Davis et al., 1990); therefore they were tentatively considered subaqueous (Davis et al., 1990) and our observations confirm this. Provencio and Polyak (2001) hypothesized a highly acidic origin, similar to acid mine drainage. The pendant nature of the rusticles was explained by the rusticles tracking a falling pool level (Provencio and Polyak, 2001). However, the rusticles of the Titanic also hang down and grow at 3800 m water depth, supporting a completely subaqueous origin for the cave rusticles; this also implies more neutral conditions as the cave pool is buffered by the carbonate walls.

Guadalupe Localities: Lechuguilla Cave.

U-loops

U-loops are downward draping mineralized threads connecting pool fingers or other subaqueous features (Figures 1 and 4; Davis et al., 1990; our studies). The individual U-loops are usually a few millimeters in diameter and 1-2 cm long but some examples are over a centimeter in diameter and 5-10 cm long (Davis et al., 1990). They are composed of either micrite (with fossil microbial filaments, unpublished data) or clear spar. U-loops are commonly associated with webulites (see below), but may occur in isolation. Although they look like mineralized snottites (Hose et al., 2000), u-loops only occur in pool settings, unlike the subaerial snottites.

Guadalupe Localities: Carlsbad Cavern, Cottonwood Cave, Endless Cave, Hidden Cave, Lechuguilla Cave, Pink Dragon Cave, Pink Dam Cave, Madonna Cave, Omega Cave, Sand Cave, Three Fingers Cave.

Webulites

Webulites are mineralized sheets draping between fingers or other protrusions, commonly perforated, suggesting spider webs (Davis et al., 1990). As with u-loops, webulites can be either clear spar (Figure 1) or micrite (Figure 4); we have found abundant fossil microbes in the micritic examples (Figure 4; Melim, unpublished data). The draping appearance strongly suggests webulites are fossilized microbial slime. They can occur with u-loops, drips, and pool meringue (conical crust; Figure 1).

Guadalupe Localities: Carlsbad Cavern, Cottonwood Cave, Dam Cave, Dragon Cave, Endless Cave, Lechuguilla Cave.

Type II

Blades and Chenille Spar

Blades and chenille spar are both elongate sheets of calcite with a thickened axial zone and lateral or downward flaring (Figure 5). Blades often show tapering barbs. Chenille spar is more elongate and may grade into pool fingers (which are round). Blades occur in clusters beneath ceiling overhangs in once-flooded passages while chenille spar is more commonly found hanging from shelfstone just below the water line. Blades and chenille spar are sometimes associated with u-loops and webulites, suggesting they are

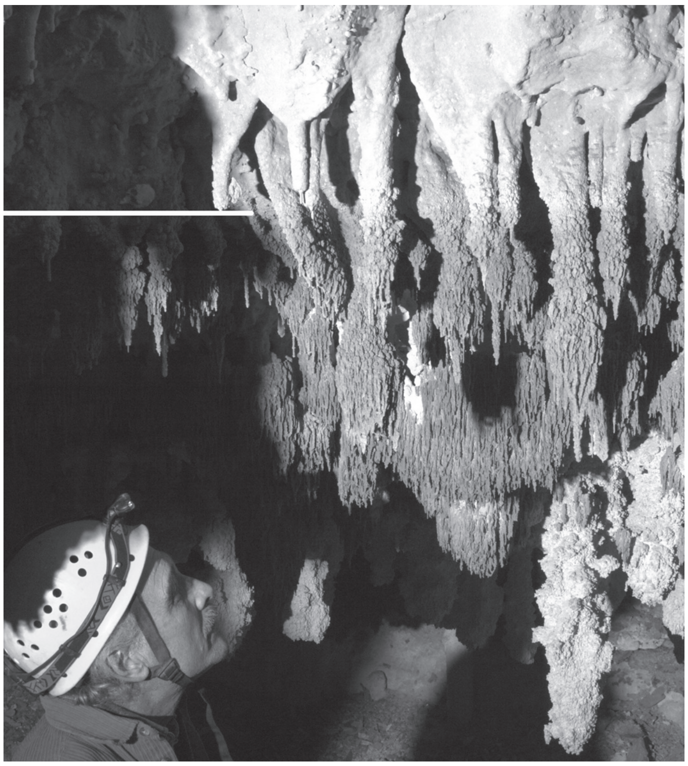

FIGURE 4. U-loops, drips, and thin pool fingers coating and extending down from older stalactites, Cottonwood Cave. Note the obvious paleo-waterline (indicated by the white line). J. Michael Queen for scale. Photograph by K. Ingham.

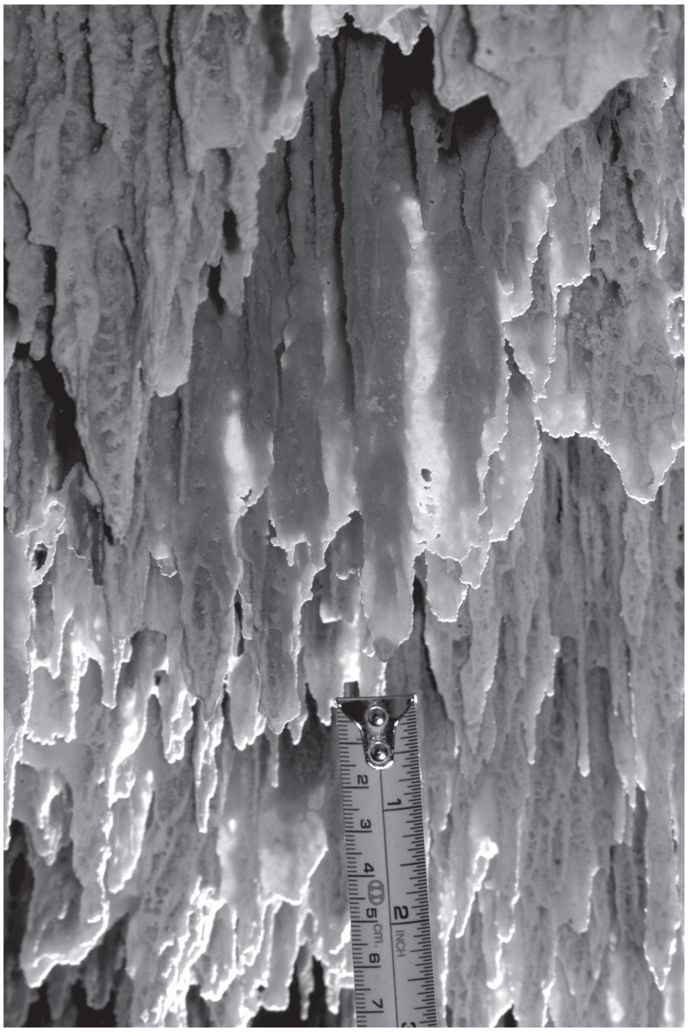

FIGURE 5. Chenille spar and blades extending down from a submerged cave ceiling in Endless Cave (water line visible elsewhere in the cave). Metric tape for scale. Photograph by K. Ingham.

calcified slime. However, they are usually clear spar rather than micrite; none have been examined in SEM for fossil microbes.

Guadalupe Localities: Carlsbad Cavern, Cottonwood Cave, Endless Cave, Lechuguilla Cave, Sand Cave, Virgin Cave.

Drips

Overhanging surfaces, especially those associated with bryolites, u-loops and webulites, may display downwardly pendant precipitates up to a few millimeters in diameter and 1-2 cm long (smaller than typical soda straws). In some pools, the drips extend from the lower edge of overhanging pool spar (Figure 6). These are interpreted as mineralized drips of slime and/or filaments. Subsequent mineral precipitation along the sides of these drips may lead to pool fingers. If a pool wall has common sites of mineralized drips, subsequent precipitation may form bryolites.

Guadalupe Localities: Carlsbad Cavern, Cottonwood Cave, Dam Cave, Dragon Cave, Endless Cave, Lechuguilla Cave, Madonna Cave, Sand Cave.

Hemispheres

In Sand Cave, the lower surface of some shelfstone displays small hemispheres of carbonate precipitate located along select growth-rays perpendicular to the growth-rings. Hemispheres show an outward decrease in diameter, from a maximum of 2-3 cm near the wall to 0.5 cm near the edge of the shelfstone. Individual chains of hemispherical lumps commonly show an outward branching habit. These relationships suggest that hemisphere growth begins contemporaneously with shelfstone growth and they become thicker and wider as the shelfstone grows wider. Hemispheres appear to result from locally higher precipitation rates, something unlikely to be present in the well-mixed waters of a pool without biologic influence.

Guadalupe Localities: Sand Cave.

Pinnacles and Conical Mounds

Pinnacles and conical mounds are both upwardly growing features that form in cave pools. Conical mounds are best developed on the walls of pools while pinnacles form in a variety of pool locations. Pinnacles are more elongate than mounds, but intermediate forms are possible. Individual pinnacles are <10 cm but they can coalesce into larger composite forms or divide upward into smaller peaks. Conical mounds may be 20 or more cm high. Both

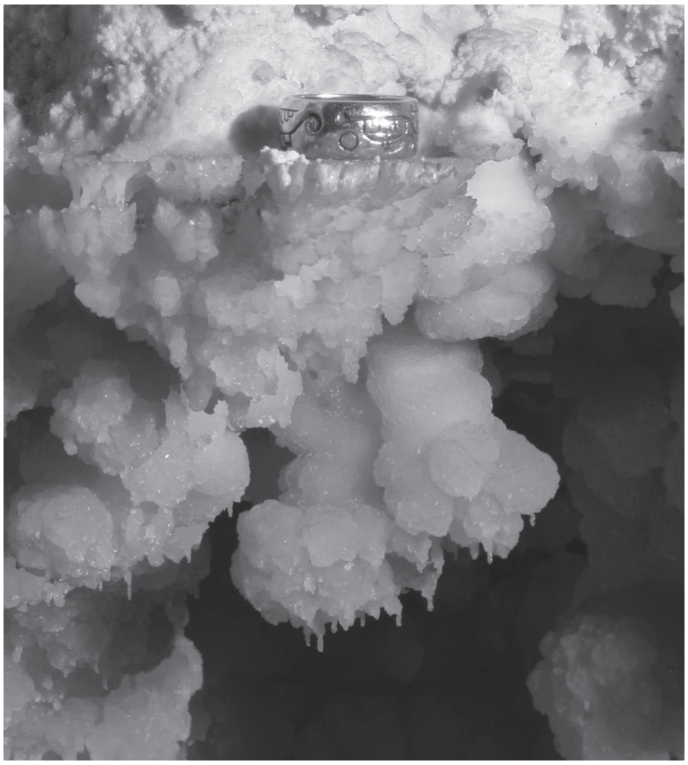

FIGURE 6. Fine drips extending from the lower tips of pool spar, Lower Cave, Carlsbad Caverns. Ring (center, 1.5 cm) is sitting on thin shelfstone layer that marks the paleo-waterline. Photograph by K. Ingham.

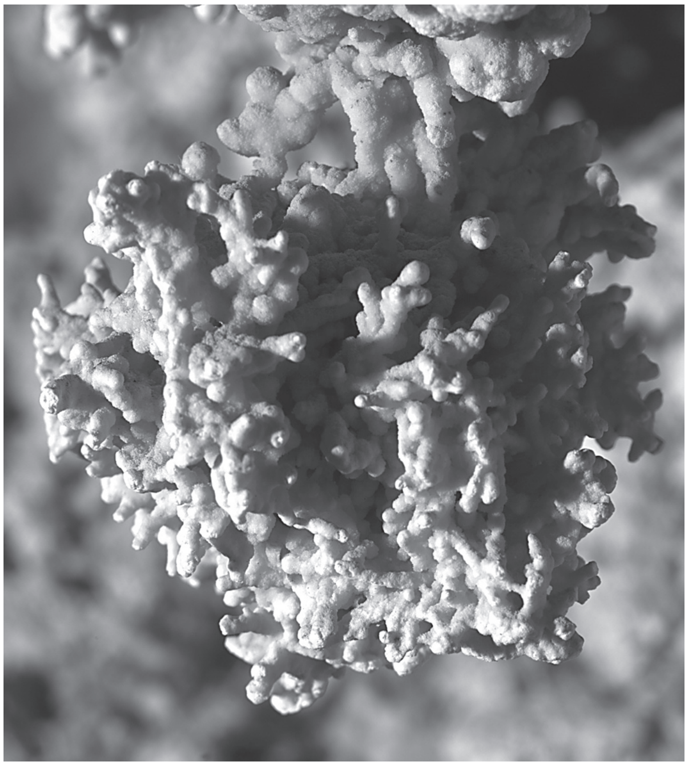

FIGURE 7. Ramose ball in small paleo-pool in Hidden Cave. Ball is about 4 cm across. Photograph by K. Ingham.

features are composed of smaller lumps of dense micritic calcite. The imbricate features on the sides of mounds are similar to **scales** (see below), and more regular than the seemingly random lumps of pinnacles. Both pinnacles and mounds are closely associated with u-loops and webulites suggesting a similar origin.

Guadalupe Localities: Cottonwood Cave, Dam Cave, Dragon Cave, Endless Cave, Hidden Cave, Sand Cave, Slaughter Canyon Cave.

Radiating Flowers

Radiating flowers are composed of radiating clumps of tapering, petal-like carbonate attached to the ceiling of the Paleo-Lake Room, Sand Cave. Individual protrusions may be up to 7 cm long and 1-2 cm wide, tapering to a fine point. They often occur in flower-like sprays up to 20 cm across radiating out from the growth surface. Although these are rare features, they are amongst the most spectacular and dramatic of Guadalupian biothems. Radiating flowers are associated with webulites and u-loops, and may coat pool fingers.

Guadalupe Localities: Sand Cave.

Scales

Vertical and slightly overhung surfaces beneath the pool surface may be the site of scale development. Scales exhibit an undulating, upward facing upper surface, which slopes slightly outward. Scales can be up to 2 cm deep, 7 cm wide and 10 cm high, although they are typically much smaller. This upper surface rolls over outwards into a longer outer side parallel to the rock substrate. Scales tend to occur in imbricate groups, which in some cases show larger scales on the bottom.

Guadalupe Localities: Cottonwood Cave, Dragon Cave, Endless Cave.

Tangential chips

Tangential chips are thin chips of rafts or cave-ice that hang from shelfstone, in one location in Sand Cave. These thin chips hang vertically beneath the shelfstone with the middle of the chip tangential to the growth bands of the shelfstone. Unlike typical cave rafts, these features were somehow attached to and now hang from the shelfstone. This pool also contains conical lumps, drips, u-loops and irregular pool fingers so we suggest that the attachment was biofilm.

Guadalupe Localities: Sand Cave.

Tufted cushions

Tufted cushions are only found in several adjacent pools in the Left Hand Tunnel, Carlsbad Cavern, where they form scattered clumps on the walls and ceiling of the deep pools just below the water line. The basic structure resembles a squat cushion of small calcite spar crystals on a narrower pedestal. The cushions are 1.5-2.5 cm long, equant-to-slightly elongate, with more-or-less vertically oriented axes of elongation. Cushions are composed of interlaminated calcite spar and micrite although, no preserved cellular remains have been recognized to date.

Guadalupe Localities: Carlsbad Cavern.

CONCLUSIONS

Since microbes are present on most moist cave surfaces (Northup et al., 1997; Northup and Lavoie, 2001), they should affect speleothem formation. Proving biogenicity, however, is very difficult as the products of microbial precipitation often mimic those formed during inorganic processes (Jones, 2001). The morphology of speleothems is one clue often overlooked in this determination, but we think the morphology can help guide more detailed studies by identifying suspect features.

Features that suggest biologic involvement include patchy distribution, projecting form, downwardly pendant forms, active slime, mineralized slime, internal micritic or pelmicritic fabric and fossil filaments and/or biofilm. We distinguish between Type 1 biothems, those containing direct evidence of microbial involvement, and Type 2 biothems, those suspected of biologic involvement but currently lacking direct evidence. Type 1 biothems include bryolites, conical crusts, moonmilk (some varieties), pool fingers, ramose balls, rusticles, u-loops and webulites. Type 2 biothems include blades/chenille spar, drips, hemispheres, pinnacles/conical mounds, radiating flowers, scales, tangential chips and tufted cushions. Some material, such as moonmilk, may fall within a different category in different caves.

To facilitate ongoing research on biothems, we will develop a web site of photos of biothems linked from Melim's homepage (www.wiu.edu/users/mflam). We actively seek additional examples and photos of interesting features. We see this web site as a meeting ground for interested researchers and cavers.

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Jordan
Stop 3
Day 1
2005

PLATE 12: CAVE FEATURES

PLATE 12A. Green Lake room in Endless Cave. Penny Boston and Diana Northup are collecting samples of pool microorganisms. Photograph by Kenneth Ingram.

PLATE 12B. Lion's Tail in Carlsbad Cavern is an example of speleothem overpriinting. A conventional stalactite first forms aerially by the usual dripwater mechanism. Subsequently, the stalactite may be resubmerged by a rising water level forming a pool. Additionally, precipitation of crystals then grow on top of the stalactite producing the characteristic bushy appearance. Image courtesy of Dr. J. Michael Queen.

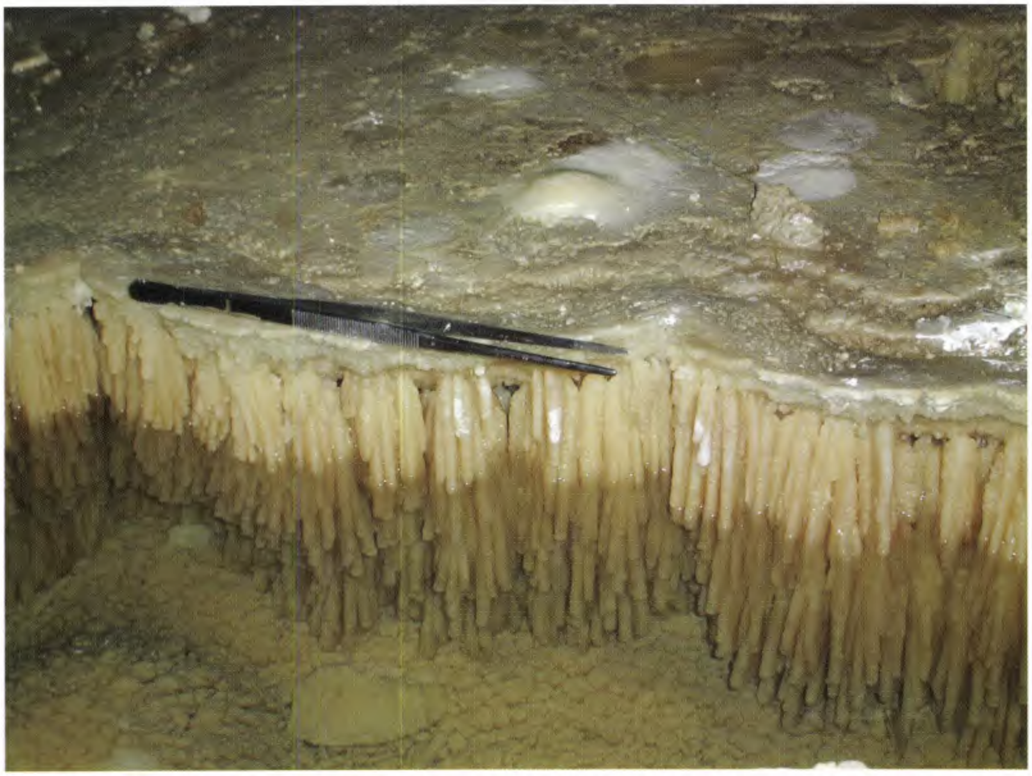

PLATE 13A. Carlsbad pool fingers. These sstructures may be created partly by cave pool microorganisms. Photograph by Kenneth Ingram.

PLATE 13B. "Picasso Rock." Multicolored ferromanganese on a boulder in Lechuguilla Cave. Photograph by Val Hildreth-Werker.