Lake speleothems of the Nullarbor

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Abstract

Subaqueous speleothems occur in several cave lakes on the Nullarbor Plain, Western Australia. Samples from two cave diving expeditions in 2001 and 2005 were examined. The subaqueous speleothems include structures resembling helictites, shields and pool crystal. The unusual speleothem structures include highly porous helictites, and some speleothems may be precipitated around organic structures. Small flakes on the surface of the speleothems resemble microbial veils. The material was sourced from Tommy Grahams Cave and Mullamullang Cave (Grotto Lake, White Lake, Lake Sh'bula and Gurgle Lake). Analysis indicates calcite, magnesian calcite, aragonite, hydromagnesite, gypsum and other minerals. According to the divers, these deposits occur in the cave lakes at depths of less than 6 m, typically between 1 to 2 m and may be associated with haloclines. The variety of deposits, including aragonite helictites, suggests a seepage source within the highly porous Nullarbor Limestone bedrock containing ions of magnesium and sulphate.

Introduction

After separate expeditions to Mullamullang Cave and Tommy Grahams Cave on the Nullarbor Plain (Western Australia) in 2001 and 2005, cave divers Paul Hosie, Ken Smith and Stuart McGregor photographed and reported several types of subaqueous speleothem in the caves' lakes and sent me some samples for analysis. The 2001 material was analysed during 2001 and 2002, and presented at the ASF's "Under WAy" conference in Bunbury, WA in January 2003 (Rowling 2004*b*). This article summarises those results and describes new material from the divers' 2005 expedition. Although the latter requires more XRD analysis for positive mineral identification, several chemical and physical tests were used to estimate that their mineral components were similar to those of the 2001 expedition.

Apart from pool crystal, subaqueous speleothems are not often reported in the world's caves. Subaqueous helictites have been reported from Lechuguilla Cave, USA and other places (Hill & Forti 1997). The Nullarbor divers' samples include shapes resembling porous helictites, small cave shields and dense pool crystal. It is intriguing as to how these speleothems came to be deposited underwater, in cave lakes, deep in the dark zone. Some samples are fine-grained, suggesting a relatively rapid rate of deposition. Other material is quite coarse grained and may be of considerable age.

Materials and Methods

All samples were supplied by the cave divers. Specimens 6N37poolF and 6N37shbula were prepared by Jill at the University of Sydney, Electron Microscope Unit and photographed and examined at the Geosciences Department. The XRD work on specimens 6N37poolF and 6N37shbula was done by Jill at the Electron Microscope Unit at the University of Sydney using a 3kW Siemens Kristalloflex 710D X-Ray generator coupled with a Siemens D5000 Diffractometer and a small computer. The generator was operated at 40kV, 40mA, with a copper target. Slits used, in order: 1 mm at source, 1 mm, 0.2 mm, 0.6 mm (at receiver). The monochromator was a graphite crystal ($2d = 0.2708\,\mathrm{nm}$) for Cu $K\alpha$ radiation. $K\beta$ filters were nickel, $12\ \mu m$ thickness. Scans were made from 2 to 70 2θ in 28 minutes (2.4° per minute).

Chemical tests of the samples used a drop of 32% HCl on about 250mg of crushed sample to indicate whether carbonate was present. Reddish precipitates were most likely clays and oxides, and white crystalline precipitates most likely non-carbonate components such as gypsum. Slowly-dissolving grains may be dolomite (summary, Table 2). Crystal shape was observed under the microscope. Physical tests include observation of crystal cleavage, and observation of the response to the specimen with long wavelength ultraviolet light. The cleavage of calcite and aragonite is distinct, calcite having the typical rhombohedral cleavage and aragonite tending to cleave straight across the needles. Under UV light, cave calcite often glows green due to organic molecules in the crystal structure, whereas cave aragonite often has a poor UV response as organics are usually excluded from the crystal structure.

Samples sent to the Australian Museum were examined by Ross Pogson, curator of minerals, using XRD on new equipment. David Colchester had kindly prepared the samples for X-ray (Ross Pogson, pers. comm).

Results

Ross Pogson commented that major minerals noted in XRD were calcite and aragonite (and gypsum, in one sample).

The tests using optical, HCl and physical mineral properties had indicated calcite, aragonite, possibly huntite or hydromagnesite, possibly magnesian calcite and a non-carbonate component such as gypsum.

A summary of the samples and their mineral constituents is given in Appendix, Tables 1 and 3.

Observations: speleothem forms, based on samples

The divers report that these samples were found underwater in relatively still lakes, and it is assumed these are the conditions under which they were deposited. Seepage and direct precipitation of carbonate are significant. Gravity-influenced deposits include large raft cones, formed from the sinking of cave rafts under a drip point, reported from Tommy Grahams Cave (Stu McGregor, pers. comm.).

Subaqueous helictites, heligmites and pseudo-helictites

Introduction

Helictites are seepage speleothems, usually with one or more central canals and a tendency to develop worm-like structures. Heligmites are simply helictites which develop upwards from a flat or sloping surface. Pseudo-helictites are speleothems resembling helictites, but which may have another origin such as a carbonate coating over a fungal thread. Subaqueous helictites are not often reported. The Nullarbor subaqueous helictites are relatively large and porous, and take several forms: worm-like, shrub-like and conical. Instead of a seepage into an air-filled chamber, these speleothems are most likely formed by a seepage of mineralised water from within the porous limestone to a pool, with a higher concentration of minerals in the seep compared to that in the pool.

Mullamullang Cave, Pool Fingers, sample 6N37PoolF

Pool Fingers were named by Paul Hosie and described as a type of subaqueous helictite with cylindrical symmetry Rowling (2004*b*). They are mostly composed of calcite, with some aragonite, hydromagnesite and magnesian calcite, minor gypsum, halite and celestite (XRD). A fibrous crystalline core is surrounded by hydromagnesite powder, ray-fan aragonite crystals and isolated gypsum crystals. An outer yellowish coating with 3-sided crystals terminations (magnesian calcite) includes some biological component such as microbial veils. The helictite’s tip appears to be its growth point, developing by fracturing along the sides near the tip, similar to the model presented by silica gardens.

Lake Sh’bula “Shbulatites”, sample 6N37shbula

“Shbulatites” were named by Paul Hosie and described as a subaqueous helictite from Mullamullang Cave with triangular symmetry (Rowling 2004*b*). They are composed of aragonite, calcite, crystobalite, magnesian calcite, gypsum and hydromagnesite, with huntite and trace halite (XRD). The interior of the specimen is similar to “Pool Fingers”, but the exterior has a curious triangular symmetry with square lobes.

The material is very similar to “6N37PoolF” in structure, with a tendency to form flat plates instead of cylinders. The central core appears to be aragonite. Outer yellow and white coating is most likely high magnesian calcite (yellow) and calcite. Chalky material is probably gypsum, hydromagnesite and huntite. Dark specks on outer surface may be bat guano. The sample is from hypersaline water, hence some halite. Crystobalite peak is large in XRD and may explain why the specimen was hard to cut.

Grotto Lake helictites, sample 6N37PHGL1

This yellowish lump vaguely resembles a large helictite, 100 mm long x 50 mm diameter, tapering to a point with a crumbly prickly coating and irregular lumpy branches (Figures 1 & 2). Paul Hosie commented this occurred as a “horizontal layer growing upwards on the edge of the rocks.” Like other samples, the outer yellow coating has shrunk and cracked since collection, indicating that it originally had a high water content. This outer coating is very fine grained and is most likely gypsum and magnesian calcite. The structure is very porous, with numerous holes in the outer surface. Dried organic material (possibly microbial veils) is present around pores in the structure, suggesting that water coming through the pores may contain some nutrient (possibly may be sulfur-cycle bacteria as per Contos (2000)).

The prickly surface resembles partially etched and recrystallised aragonite, with needle crystal aggregates forming spheroidal clusters. Fine hairlike crystals similar to “lublinite” (needle-fibre calcite) or gypsum are also present in the structure.

In the porous base of the helictites is a white powder resembling huntite or hydromagnesite, and radiating needle crystal masses with isolated areas of more solid crystal resembling calcite. More dense regions are possibly dolomite (clear rhombs seen).

The tip resembles that of a “normal” helictite. Pores near tip are crystal-lined rounded cavities containing remnant clusters of “microbial veils” and “lublinite” hairs, as a thatch. Dried flakes, assumed to be microbial veils are delicate, translucent grey with a metallic lustre under polarised light.

Figure 1: Side view, cut helictite 6N37PHGL1, about 80 mm long.

Figure 2: Base view, 6N37PHGL1, about 60 mm wide.

Figure 3: Helictite 6N37PHGL2, base, about 23 mm wide.

Figure 4: Helictite 6N37ken2, base, about 25 mm wide.

Figure 5: Grotto Lake fibrous aggregate, about 20 mm wide.

Figure 6: Grotto Lake coralloid, about 17 mm wide.

Grotto Lake flattened helictites, sample 6N37PHGL2

These are white to pinkish, oriented nodules typically 70 mm x 30 mm x 20 mm and superficially resembling helictites with a branching form, including some flattened shapes (Figure 3). Paul Hosie reported that these "blobs had developed on a crystal substrate".

Under the microscope, one sees a multi-layered structure. The outer yellow layer is cracked (dehydrated?) and pores can be seen. Some of the outer surface vaguely resembles scales (like proto-dolomite or hydromagnesite). Other surface crystals resemble clear dolomite. Fine dark threads seen on the surface may be organic or fungal.

The flattened parts are composed of two halves with a gap inside; the cylindrical parts have a low density centre and multiple canals appear in broken section. A multi-branched specimen indicates that branches can re-join. This structure is composed of very fine crystals compared to the Lake Sh'bula or 6N37KEN3 samples.

Discussion: They may be pseudo-helictites, formed around organic sheets or microbial veils. Alternatively they may be conventional helictites, but the open structure and high porosity allows the branches to re-join. The flattened structures may have developed along a crack, like a cave shield. Interestingly, the Lake Sh'bula specimen 6N37shbula also features flattened areas. The finer crystal size suggests the helictite developed faster than the other samples.

Lake Sh'bula helictites, sample 6N37ken2

The samples comprise a few lumps of soft material, pale brown to yellow to white, about 50 mm x 90 mm x 60 mm, forming a somewhat crenulated, irregular folded shape with a white crystalline inner section (Figure 4). Diver Ken Smith mentioned the substrate was a "large rock covered in white crust", and the "speleothems occur in lines at 1.7m depth associated with a yellow band on surrounding rock. Yellow band is extensive in this part of the cave, is 0.2m high, horizontal, possibly a specific chemical layer in the water."

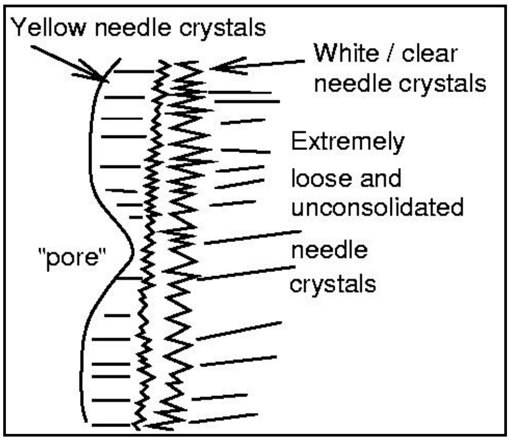

Figure 7: Sketch of pore cross section, sample 6N37ken2

Under the microscope, the outside of the speleothem has a soft crumbly yellow crystalline coating, about 2 mm thick, which has shrunk and cracked since collection. The tips of crenulations have multiple pores (canals). Directly below the yellow coating is a white crystalline region (at the base of the pores, Figure 7). Within this white region are aragonite needle crystals, based on cleavage; some look partially recrystallised. The white crystals radiate from a denser central region which may include calcite and has hollow channels in it. This is a very open structure. Loose hard cores in the structure are surrounded by aragonite needles. The overall shape is formed by many spherulites.

Another piece from this sample comprises parallel plates of the same material, with an inner low density part filled with fairly loose aragonite needles (Figure 8).

Discussion: The divers' notes say that these occur in lines, "at depth of 1.7m" and are "associated with a yellow band on surrounding rock" and that the band is "0.2 m high". This may infer a halocline of stratified mineralised water. The yellow band could be dolomitic, organic, or gypsum – it has very little reaction with HCl. The parallel plate example suggests that this structure develops along the top edges of subaqueous cave shields.

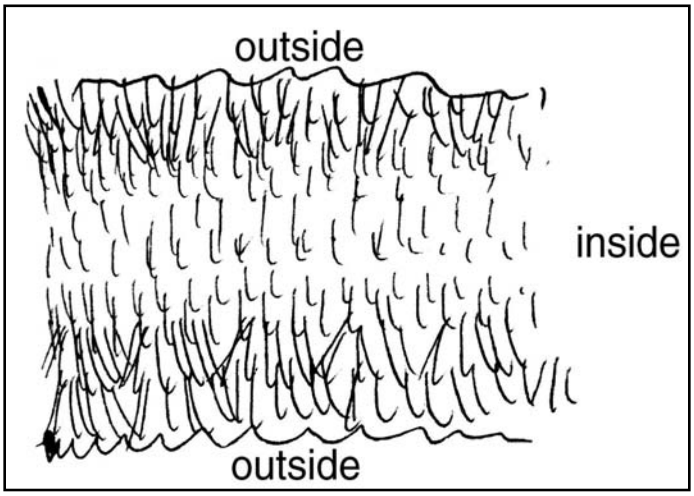

Figure 8: Sketch of structure, sample 6N37ken2

Subaqueous cave coral and related forms

Grotto Lake subaqueous popcorn and coralloids, sample 6N37PHGL3

The samples comprise two types of lumps and crumbly bits, mostly white (Figures 5 & 6).

Fibrous aggregates:

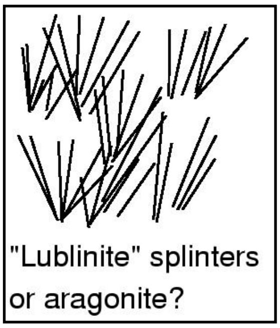

Figure 9: Sketch of growth habit, fibrous aggregate 6N37PHGL3

These are porous aggregates with a radial fibrous to oriented fibrous appearance (Figure 9), typically 40 mm x 40 mm x 30 mm, and are a mixture of calcite and aragonite, based on cleavage. The surface is somewhat flattened e.g. by corrosion, and recrystallised to calcite, with numerous surface pores. Individual crystals are coated with finer crystals and possibly microbial veils. Material appears to be "lublinite" calcite and aragonite based on cleavage.

Coralloids: These form crystalline hemispheres with a yellowish coating, typically 20 mm x 20 mm x 10 mm. Four pieces were examined. The general structure comprises a central core of linear yellow aragonite surrounded by clear radiating aragonite. Some samples have an inner layer of yellow material. The radiating area may contain clear crystalline balls of possibly calcite or dolomite. The outer coating is a very fine yellow or yellow-brown crystalline material with pores, aragonite aggregates and possibly microbial veils. The inner and outer yellow material has shrunk and cracked since collection.

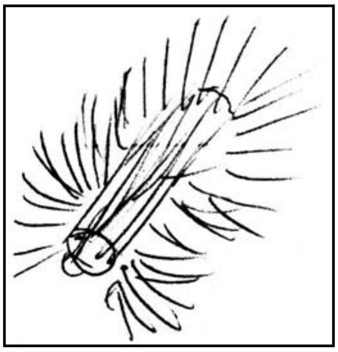

Figure 10: Sketch, coralloid growth habit, sample 6N37PHGL3.

Below the yellow coating is a soft white layer of radiating aragonite crystals and possibly "lublinite". (Figures 10 and 11).

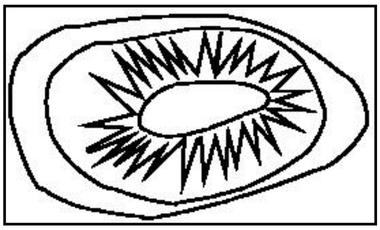

Figure 11: Sketch, coralloid growth habit.

Gurgle Lake coralloids, sample 6N37PHGL7

These creamy yellow nodules are about 40 mm x 30 mm x 20 mm with concentric layers. A soft core is surrounded by harder layers and a powdery and crumbly surface (Figure 12).

Figure 12: Gurgle Lake coralloid, about 17 mm wide.

The outermost layer is yellowish, fairly thin, and shiny in areas. It has cracked (shrunk since collection) to expose a white powdery layer just below it. Occasional whisker-like crystals may be "lublinite".

Below the yellow layer is a porous white layer of radiating needle crystals (aragonite, based on cleavage) forming a layered structure, with some layers harder than others.

The innermost area is crumbly, powdery and soft, possibly recrystallised, with isolated needle crystals and resembles the interior of a subaerial "cave turnip". The needle crystals are coated. Small remnant dark shiny microbial veils are visible. A soft white powdery region apparently contains hydromagnesite with aragonite needles.

Pool crystal, crusts and rafts

Grotto Lake over-coated cave rafts or crusts, sample 6N37PHGL4

These samples are soft and crumbly, coloured white, cream, yellow and brown, and are mostly a flat shape. Typical sizes are 10 mm x 20 mm and are possibly over-coated calcite or aragonite rafts or crusts (Figure 13).

Under the microscope, randomly-oriented fine needle crystals have cemented together to form a soft crust. One side, possibly the up-side, is porous and its yellow and brown surface appears cracked or shrunk. Other parts of the sample resemble pool crystal (i.e. an overgrowth) with small hemispheroidal aggregates which may be aragonite.

It is not clear whether these are sunken rafts or crusts; the flatter samples resemble rafts and the curved ones resemble crusts. Both appear to be over-coated with aragonite, so possibly they originated from the water's surface and have since sunk to the bottom of the lake.

Figure 13: Fragment of Grotto Lake cave raft, about 16 mm wide.

Grotto Lake pool crystal, sample 6N37PHGL5

This bowl-shaped lump of pool crystal is rounded and crystalline, with a layered clay and carbonate substrate. Its approximate dimensions are 110 mm x 130 mm x 50 mm (Figure 14).

The laminated clay substrate is composed of both crystalline carbonate sediment, clays and other materials (possibly bat guano, quartz, hydromagnesite). Crystalline carbonate septa or veins separate areas of sediment and cut through the layers.

Figure 14: Grotto Lake pool crystal with sediment substrate, cut, about 100 mm long.

The area between the clay and the pool crystal has a gradual transition from loose brown sediment, then brown carbonate-cemented clays, white laminated carbonate, and hemispheroidal carbonate aggregates (aragonite cement).

The outer crystal coating is a white and yellow mixture of fibrous, needle-shaped radiating aggregates (possibly aragonite) and massive material (possibly calcite).

Discussion: This appears to be a conventional pool crystal deposit on sediment. The aragonite isomorph may be influenced by calcite crystal poisoners in the substrate (e.g. Mg in hydromagnesite) and ions in the water (e.g. SO_4^{2-}). Carbonate septa in the substrate suggest that the lake and the clay may have dried out at some period, cracked, and was later cemented forming a type of boxwork.

Lake Sh'bula crust, sample 6N37ken1

A white crystalline coating on a brown clayey substrate has formed a shard with a smooth clay substrate, darker cemented layer and a white prickly crystalline surface. The sampled piece is 80 mm x 50 mm x 10 mm (Figure 15). Diver Ken Smith noted that this deposit occurred at a depth about 1 m as a white crust flaking from the tops of large submerged rocks about 1 m diameter. They are common in shallow water and a similar white crust is common on rocks above water.

Under the microscope, the soft porous brown laminated crystalline substrate has small interlocking grains and contains some aragonite crystals. The substrate becomes less porous closer to the white crystal area. The white area is porous and is composed of needle to columnar crystals, terminated across the flats of the needles. It appears to be a mixture of calcite, aragonite and lublinite variety of calcite. The aragonite needles terminate as "church steeples", etched and partially redissolved with some (calcite) cement.

Discussion: It is unclear whether this is a subaqueous or subaerial deposit as it is reported from both above and below water around the lake. As it is apparently flaking from the tops of submerged rocks, this suggests the deposit is related to the surface of the lake, rather like cave rafts. If it can deposit as aragonite at times, there is something present in the water preventing calcite from depositing. Possibilities include SO_4 concentration, Mg, or both.

Figure 15: Lake Sh'bula crust with porous substrate, about 10 mm thick.

Tommy Grahams Cave: Massive pool crystal, sample 6N56SMTG1

This rock was found loose in the sediment of the lake in Tommy Grahams Cave by diver Stu McGregor, and measures about 300 mm x 100 mm x 100 mm (Figures 18, 19). One side is limestone, the other side is a subaqueous speleothem, partially eroded. The eroded area contains lots of needle crystals, originally greenish and full of water, and since sunken in. The divers report that the walls of the lake are covered with a similar pool crystal.

Under the microscope, highly porous pale orange Nullarbor Limestone contains sand-sized grains, including brown and sparkly "dolomite" shells (bioclasts). One area of porous bedrock has little micrite, with only the larger bioclasts remaining. The limestone is coated with a dense white cement layer, 5 mm thick, and very fine-grained. The white layer merges with a pale olive aragonite layer, 10 mm thick, featuring typical aragonite ray-fan needles, developed from clusters on the white cement layer. The pale olive layer is surmounted by clusters of hard, dense aragonite 40 mm thick. This is a massive deposit featuring larger and longer aragonite crystal blades compared to the pale olive layer. Crystal aggregates form bundles (columns) of about 10 to 20 mm diameter. The base of these aggregates contains a white powder similar to hydromagnesite. A white powder terminates this layer (also possibly hydromagnesite). This layer has split horizontally (across the needles), possibly by specimen shrinkage. Part of this layer was exposed to the lake water where it had developed a solution notch, indicating that at times the water is aggressive to aragonite.

Outer layers: The outer layers are complex, with several different types of coatings and textures. The porous outer surface appears to be recrystallised with indistinct crystals, skeletal needle crystals, sugary coatings and small hemispheres. A surface brownish patch has little round holes in it: it may have once housed microorganisms. Some aragonite crystals are skeletal, others are complete.

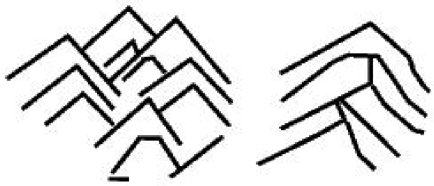

Figure 16: Sketches, cube corners and en-echelon crystals.

En-echelon cube-corner crystals resemble dolomite (Figure 16) and are opalescent usually the result of multiple fine layers.

In the corrosion notch, small white and black grains are lodged between long loose needle crystals, thought to be hydromagnesite and bat guano respectively. Surface irregularities like blunt spikes appear to be coatings over filaments or over original bedrock bioclasts. In this case, a soft porous core is coated with harder external layers and could be described as pseudo-helictites (Figure 17).

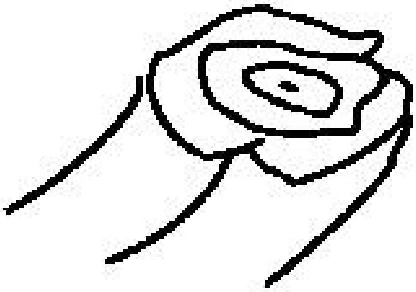

Figure 17: Sketch, pseudo-helictite.

Discussion: This material appears to have been deposited underwater as aragonite, possibly at a particular depth where mineralised groundwater in the limestone meets the lake water in Tommy Grahams Cave. The general form could be described as aragonite pool crystal. The outer surface of the material may have housed microbial veils, and the chemistry appears to have at times favoured the deposition of a variety of minerals on the surface such as calcite, dolomite and gypsum. Judging by the massive aragonite of the main structure, this deposit may be very old, and has broken off the main deposit due to structural failure of the soft porous underlying bedrock.

Figure 18: Pool crystal, Tommy Grahams Cave, photo by Stuart McGregor.

Figure 19: Pool crystal, Tommy Grahams Cave. Cut surface, about 125 mm wide.

Figure 20: Subaqueous cave shield, about 40 mm wide, after brushing.

Figure 21: Cave shield interior, about 40 mm wide.

Cave shields and related forms

Grotto Lake cave shield, sample 6N37PHGL6

This small hollow crystalline "shell" is a small cave shield measuring about 40 mm x 20 mm x a few mm and is a brown/tan colour. The specimen was cleaned with a dry brush to remove a clay coating as it had been packed with sample 6N37PHGL5 (Figures 20, 21).

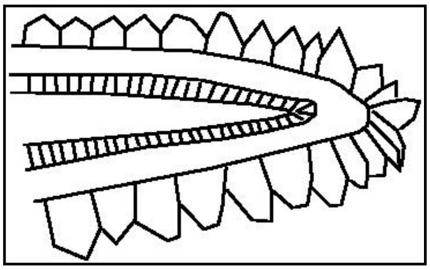

Figure 22: Symmetrical ridge development.

Under the microscope, the "shell" outer surface has a rough surface caused by neat pyramids (crystal terminations). A sparkly appearance when rotating the specimen is caused by the alignment of numerous 3-sided crystal terminations, possibly en-echelon calcite similar to "Bizarre forms" (Folk, Chafetz & Tiezzi 1985). Crystal terminations are aligned in approx. 10 mm-wide arrays of the specimen faces, resulting in reflective lines (rows) at some angles. This material covers the outer surface of the speleothem, especially around the edge of the plates. At a broken edge, the pale coloured corner has spiky crystals on the inside, forming part of the shell. The C-axis is 90° outwards from the "shell" (Figure 22). The two halves of the shell are cemented by a seam with an interesting edge (Figure 23) and a small hole. Symmetrical ridge development either side of the edge for a few mm of length infers they are developed together. A dimple in the base of the structure leads to a tepee shape (Figure 24).

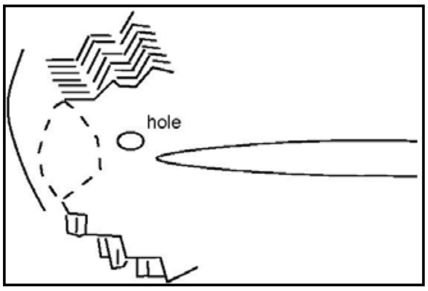

Figure 23: Sketch: area close to edge.

The outer material may be aragonite, based on surface crystal cleavage and low UV response, but could also be calcite or dolomite. The inner fill may be magnesian calcite as it seems to have a calcite cleavage. The inside is partly filled with crystal, including one long crystal oriented horizontally (parallel to plates) and may be dolomite or Mg-calcite.

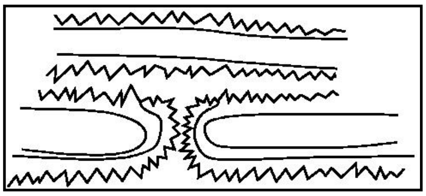

Figure 24: Sketch of dimple.

Discussion: Assuming this is a conventional cave shield, developed underwater, it appears to have developed a little like a helictite with a slot rather than a capillary tube. The edge seems to be the main region of growth. Imagine a small capillary tube around the edge, similar to that depicted in Figure 23, like the central canal of a conventional helictite only connected to the substrate at both ends.

Such a structure may originate from a small crack in the substrate. Like conventional helictites, this small tube can be slightly dissolved by the fluid in the substrate, however instead of breaking open at one end like conventional helictites, it breaks open along the outer edge of a short segment of the tube due to the alignment of crystallites and the thickness of the inner wall. Where the tube opens, carbonate precipitates. Additionally, calcite can glide / cleave without breaking. If the pressure of crystal growth inside the shield is sufficiently high, the material may glide apart while still precipitating carbonate. This would result in symmetrical crystal development at the edge and develop a cave shield.

A slight green afterglow with long-wave UV suggests that the main material is calcite with very little organic material (organics make the calcite afterglow a brighter green). If the en-echelon material is calcite, it may be like the sides of ribbon helictites (Rowling 1998).

Figure 25: End of flat speleothem 6N37ken3, about 54 mm wide.

Lake Sh'bula flat speleothem: cave shield or coating? Sample 6N37ken3

This flat, pale coloured speleothem is about 55 mm x 25 mm x 10 mm (Figure 25) with soft prickly outer coating and has formed in two halves like a cave shield. Diver Ken Smith noted that the "substrate was large rock. Area covers several metres. All rocks at this depth (2.8 m) appear to have this cover. This sample is part of a flake which is cemented to the base rock."

Under the microscope, the surface appears to be recrystallised aragonite. On some needle crystal tips is a loose, shiny coating (microbial veil?) which resembles a thin dry dark snail trail under crossed polars and is easily disturbed. The needles are a little coarser than 6N37ken2 and radiate as spherulites from the median plane of this "shield" (Figure 26). The spherulite nucleation points is a white and powdery substance resembling hydromagnesite and the whole structure is highly porous.

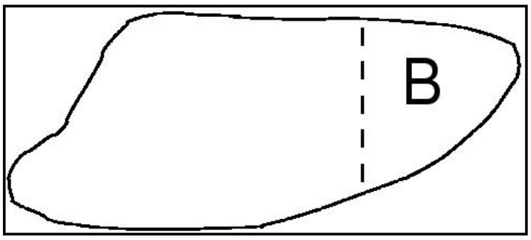

Figure 26: Sketch of pieces, flat speleothem 6N37ken3.

What is it? It may be part of a cave shield, developed around a crack on the base rock, out of which has come hydromagnesite around which aragonite has deposited. The porous structure may continue to develop as long as the underlying crack continues to seep. Alternatively, it may be an aragonite coating over a microbial veil containing hydromagnesite. The porous structure may eventually thicken and become engulfed by pool crystal.

Discussions

Helictites, heligmites and pseudo-helictites

Subaerial helictites have a large variety of shapes and sizes, as do the subaqueous Nullarbor lake helictites. The samples are mainly heligmites, that is, they developed upward from a substrate (typically from boulders or from pool crystal).

The finger-shaped forms typically have a central canal (or set of them), supprounded by radially-oriented carbonate crystals such as calcite or aragonite. Pores near the tip are connected to the central canals through less dense mats of needle crystals. The outer surface may be coated with magnesium calcite, dolomite or gypsum. Development is from the tip.

There is a branching form, where the branches may join up, forming a structure consisting of both cylindrical and flattened shapes. The cylindrical parts have cylindrical central canals, and the flattened parts have a slot-shaped central canal (similar to a cave shield). These structures are enigmatic; they may have both helictite and cave shield structures, or they may be developed around organic filaments and microbial veils. Microbial veils (also known as snot-tites) have been recorded from Nullarbor cave lakes (Contos 2000). Several samples have what appears to be remnant microbial veils attached to their surfaces.

Cave coral and related forms

Conventional cave coral is a subaerial speleothem, with a film of mineralised water on the surface. Growth is near the area of maximum air movement, where CO_2 exchange is highest.

Cross-sections of a coralloid show the growth layers. A particular sub-type is the cave popcorn and coralloid, usually made of aragonite, and developing along the lines of aragonite "shrubs", filling in the spaces, as it were.

In the case of the Nullarbor cave lake coral, the material appears to be alternating calcite and aragonite, with hydromagnesite supplying calcite-poisoning Mg. Development is like that of subaerial cave popcorn and coralloids, only larger and less dense. Some of the forms resemble helictites, but sectioning reveals them to be overcoated acicular spheroids (i.e. cave aragonite).

A similar form has been recorded from a marine (coral reef) setting, where aragonite "mamelons" partially fill cavities in the reef (Ginsburg & James 1976).

Pool crystal, crusts and rafts

These are more conventional, and are often reported from caves. Pool crystal often lines the sides of standing pools of mineralised water. In the case of the Nullarbor pool crystal, it occurs at specific depths, possibly corresponding to particular layers in the rock or to a depth at which CO_2 exchange is optimal, or may simply follow the lake levels. Divers report haloclines in the lakes although there are no reports correlating pool crystal with haloclines. The usual polymorph deposited is calcite, whereas the Nullarbor cave samples appear to be aragonite (Tommy Grahams Cave) with hydromagnesite and gypsum, suggesting crystal poisoning by Mg and SO_4 leaching from the bedrock.

Cave rafts are relatively common, caused by the out gassing of CO_2 from the surface of the lake to an air filled chamber. This allows carbonates to precipitate. What is unusual in the raft samples is the crystal polymorph, which is normally calcite but in the samples they appear to be aragonite. One possibility is the rafts precipitated as calcite, but were later overgrown with aragonite after they sunk.

Crusts are also common in caves. The divers reported a crust (6n37ken1) which occurs both above and below water, flaking off the rocks. The sample is most likely formed at the water's surface, dependent on the lake level, and is a simple carbonate coating formed on the rocks by mineralised water. The flaking is most likely due to the clay in the substrate expanding and contracting with water level. They appear to be a mixture of carbonates, including calcite and aragonite.

Cave shields and related forms

There appear to be two types of cave shield-like speleothems. One type is a relatively conventional cave shield, comprising two halves like a bivalve, hollow inside, and with a fine linear capillary along the edge. Growth appears to be by pressure-gliding along cleavage planes, with the edge crystals oriented such that they form a mirror image of each other about the two halves. In many respects, cave shields resemble helictites with the direction of growth at 90 degrees to the central canal instead of at one end.

The other type of cave shield (if it is one) is a porous, loose structure forming a blade or plate, with a powdery core (possibly hydromagnesite) surrounded by acicular carbonate crystals such as aragonite. The divers reported that these developed on the surface of some of the pool crystal. One possibility is they have developed over particular cracks in the substrate, from which mineralised water seeps, allowing the development of a shield. Another possibility is they develop around microbial veils, as a simple coating, although in that case one would expect a more random structure.

Possibly the less dense structure develops where there is water to support the speleothem's weight, and the growth habit of aragonite promotes a less dense form than does calcite.

Conclusions

A variety of subaqueous speleothems occur in some cave lakes on the Nullarbor Plain. The following conditions may lead to the deposition of carbonate speleothems on rocks in a cave lake:

- The limestone and dolomite rocks in the lake should be porous.
- The concentration of HCO_3 in the rock pore water should be higher than that in the lake.
- The exchange of CO_2 between the rock water and the lake water allows CO_2 to escape from the rock water to the lake water (or dissolve in it).
- The rocks may be conducting highly mineralised groundwater to the lakes. As some of the speleothems were reported from isolated rocks, possibly the rocks are dissolving.
- The actual form (helictite, shield, pool crystal etc) depends on the physical conditions during deposition.

- The mineral species deposited depends on the chemistry during deposition. For example, aragonite may deposit instead of calcite if there are sufficient calcite crystal poisoners present (Mg, sulphate and Mn are the most common).
- Dedolomitisation of the bedrock may be the source of Mg present in the speleothems.

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Most samples from Mullamullang Cave were collected by Paul Hosie. Samples 6N37ken1...3 were collected by Ken Smith. Sample 6N56SMTG1 was collected by Stuart McGregor from the lake in Tommy Grahams Cave.

Bulk intact specimen 6N56SMTG1 was photographed by Stuart McGregor. All other specimens were prepared, photographed, scanned and examined by Jill at Thornleigh.

For specimens 6N37poolF and 6N37shbula, micro-photography, preparation, XRD work and spectral analysis was done by Jill using equipment at the Geosciences Department and the Electron Microscope Unit at the University of Sydney under the supervision of Drs A. Osborne and T. Hubble as part of a study on cave aragonite (Rowling 2004*a*).

References

Contos, A. (2000), ‘Microbial mantles on the Nullarbor’, *Bulletin of the Sydney University Speleological Society* **40**(2-3), 32–33.

Folk, R. L., Chafetz, H. S. & Tiezzi, P. A. (1985), ‘Bizarre forms of depositional and diagenetic calcite in hot-spring travertines, Central Italy’, *In: Carbonate Cements, special publication No. 36, The Society of Economic Paleontologists and Mineralogists, a division of the American Association of Petroleum Geologists*.

Ginsburg, R. N. & James, N. P. (1976), ‘Submarine botryoidal aragonite in Holocene reef limestones, Belize’, *Journal of Geology* pp. 431–436.

Hill, C. A. & Forti, P., eds (1997), *Cave Minerals of the World*, 2nd edn, National Speleological Society, Huntsville Alabama, USA.

Rowling, J. (1998), ‘Ribbon helictites: A new category’, *Helictite* **36**(1), 2–10.

Rowling, J. (2004*a*), Cave aragonites of N.S.W., Master of Science Thesis (unpubl.), The School of Geosciences, Division of Geology and Geophysics, The University of Sydney.

Rowling, J. (2004*b*), Underwater helictites of the Nullarbor, *in* ‘Proceedings of Under WAy 2003: 24th Biennial Conference of the Australian Speleological Federation.’, Bunbury Cathedral Grammar School, Western Australia, pp. 86–93.

Appendices

Summary of Samples

Most samples are from Mullamullang Cave (on private property) and collected by Paul Hosie and Ken Smith. Stu McGregor collected the sample from Tommy Grahams Cave. Details are as indicated in Table 1. Sample numbers are based on the divers’ sample numbers (1, 2, 3, etc) but with additional information such as cave ID and collector. Sample depth was recorded by the divers’ depth gauges.

Sample No.	Cave	Lake	Description	Collector	Date	Depth
6N37poolF	Mullamullang	White	“Pool Fingers” helictites	Paul Hosie	Jan. 2001	
6N37shbula	Mullamullang	Sh’bula	Small “Sh’bulatite” helictite	Paul Hosie	Jan. 2001	
6N37PHGL1	Mullamullang	Grotto	Large lumpy helictite	Paul Hosie	13/01/2005	-1.7 m
6N37PHGL2	Mullamullang	Grotto	Branching flattened helictites.	Paul Hosie	13/01/2005	-3.5>-6 m
6N37PHGL3	Mullamullang	Grotto	Radial fibrous aggregates and crystal hemispheres	Paul Hosie	13/01/2005	-3.5>-6 m
6N37PHGL4	Mullamullang	Grotto	Coated calcite rafts.	Paul Hosie	13/01/2005	-3.5>-6 m
6N37PHGL5	Mullamullang	Grotto	Bowl-shaped radial fibrous precipitate, clay substrate.	Paul Hosie	13/01/2005	-3.5>-6 m
6N37PHGL6	Mullamullang	Grotto	Small cave shield.	Paul Hosie	13/01/2005	-3.5>-6 m
6N37PHGL7	Mullamullang	Gurgle	Pebble-sized layered nodule.	Paul Hosie	13/01/2005	
6N37ken1	Mullamullang	Sh’bula	Rough crystalline shard with clay substrate.	Ken Smith	13/01/2005	-1 m
6N37ken2	Mullamullang	Sh’bula	Soft, crystal-cored lumps.	Ken Smith	13/01/2005	-1.7 m
6N37ken3	Mullamullang	Sh’bula	Flat prickly piece.	Ken Smith	13/01/2005	-2.8 m
6N56SMTG1	Tommy Grahams	Lake	Thick fibrous sedimentary deposit.	Stuart McGregor	2004	

Table 1: Summary of samples

Tests using HCl

32% HCl was applied to a small sample of the material and the resulting reaction observed for effervescence indicating carbonate, any residue, and any coloured material. Table 2 shows the results.

Sample No.	Carbonate	Clear residue	Coloured residue	Comments
6N37poolF	High	Small	-	
6N37shbula	High	-	-	
6N37PHGL1	High	-	-	May be calcite
6N37PHGL2	High	-	-	Slowly dissolving grains may be dolomitic
6N37PHGL3	High	small	-	""""""
6N37PHGL4	High	-	Yellow grains	""""""
6N37PHGL5	High	-	Small brown grains	""""""
6N37PHGL6	High	-	Small brown grains	""""""
6N37PHGL7	High	-	Small yellow grains	""""""
6N37ken1 (substrate)	Medium	-	Brown	Clayey
6N37ken1 (crystal)	High	-	-	Slowly dissolving grains may be dolomitic
6N37ken2 white needles	High	-	-	""""""
6N37ken2 yellow coating	Low	-	Yellow grains	Possibly gypsum residue
6N37ken3	High	-	Yellow grains	""""
6N56SMTG1	High	-	-	Slowly dissolving grains may be dolomitic.

Table 2: Tests using HCl 32%

Sample mineral constituents

Most samples discussed in this paper have been estimated using physical properties only, and are compared with the few samples analysed with XRD.

Sample No.	Calcite	Aragonite	Magnesian calcite	Gypsum	Hydro-magnesite	Other
From XRD						
6N37poolF	major	minor	minor	minor	minor	minor celestite & halite
6N37shbula	major	major	major	major	major	major crystobalite, minor huntite, trace halite.
6N37PHGLx	major	major	-	-	-	
6N37PHGL2	major	major	-	major	-	
6N37kenx	major	major	-	-	-	
Estimated only						
6N37PHGL1	high	medium	-	-	medium	
6N37PHGL2	high	high	high	high	high	crystobalite, huntite
6N37PHGL3 (fibrous)	medium	high	low	low	low	
6N37PHGL3 (shells)	medium	high	medium	low	low	dolomitic
6N37PHGL4	high	high	medium	medium	low	
6N37PHGL5	high	high	medium	-	low	minor clays
6N37PHGL6	high	low	high	-	-	minor clays, dolomite
6N37PHGL7	medium	medium	medium	medium	high	
6N37ken1 (substrate)	low	medium	-	-	-	clays
6N37ken1 (crystal)	medium	high	medium	-	medium	dolomite
6N37ken2 white needles	medium	high	medium	-	-	
6N37ken2 yellow coating	low	low	medium	high	low	
6N37ken3	medium	medium	medium	medium	medium	
6N56SMTG1	low	high	medium	-	low	dolomite

Table 3: Mineral constituents.