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STROMATOLITIC CRAYFISH-LIKE STALAGMITES

by

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ABSTRACT

Stalagmites with a crayfish-like profile are found in two natural tunnels in New South Wales in windy, moderately-lit sites; some of them were noted tourist attractions 100 years ago. The morphology and orientation of these stalagmites has been examined in relation to the light intensity falling on them. The internal structure, mineralogy and microbiology of one stalagmite and a related flowstone have been studied, resulting in a hypothesis for the mode of formation of the crayfish-like stalagmites. The stalagmites are compared with other speleothems and similar surface concretions. It is concluded that these stalagmites can be classified as stromatolites.

INRODUCTION: HISTORY AND OCCURRENCE

Two large natural tunnels in New South Wales contain speleothems which have been given popular names likening them to lobsters or crayfish because of their elongated, hump-backed shape and 'segmented' profile. These have been known to tourists for many years, and are often large and distinctive structures (FIGS. 1 to 3, PLATES 1 and 2), but they have received scientific notice only in the last decade (James *et al.*, 1982; Cox, 1984b). They first attracted the attention of the authors because they have an external appearance which resembles cryptalgal laminate stromatolites (Aitken, 1967).

The first published descriptions of crayfish-like stalagmites are of those in the Nettle Cave, Jenolan, NSW. Nettle Cave is a high-level entrance into the Devils Coach House, a natural tunnel 80 m tall and up to 40 m wide. The crayfish-like stalagmites occur principally in the upper part of Nettle Cave which receives light from the Nettle Cave entrance in the south, a roof-hole and the northern portal of the Devils Coach House in the north east, and the Arch Cave in the south west (FIG. 6).

The earliest description is that of Cook (1889), who refers to 'One prominent stalagmite . . . like the back of a newly-shorn sheep, with shear-marks in the wool'. A much more detailed description of the area was given by Argus (1898). In his words: 'Other stalagmites take the form of immense lobsters. So close is the resemblance that an artist might envy their extreme "Naturalism".' This description is not unduly exaggerated—certainly the resemblance is much clearer than most zoomorphic ascriptions given to speleothems.

The name 'Lobsters' has persisted to the present day, and Argus seems to have been its source. It may of course have been in use by the cave guides of that period, but if so the term must have come into use in the nine years since Cook's account; it is so apt that Cook could not have failed to mention it in his lengthy and verbose account had it been in use at that time.

The smaller stalagmites on the western wall of the chamber (where the flight of steps seen in FIG. 1 once led up to Arch Cave) were also mentioned by Argus. 'On a rocky projection there is a beautiful figure of a child asleep. Further on one notes a man reposing under an eider-down quilt, with his hands on his head. Close by is a man suspended by the feet over a precipice. Miracles of rare device!' These all seem to refer to essentially the same sort of stalagmite, and most can be identified today. The 'man suspended by the feet over a precipice' is quite clear, though no 'artist' would envy its 'extreme naturalism'!

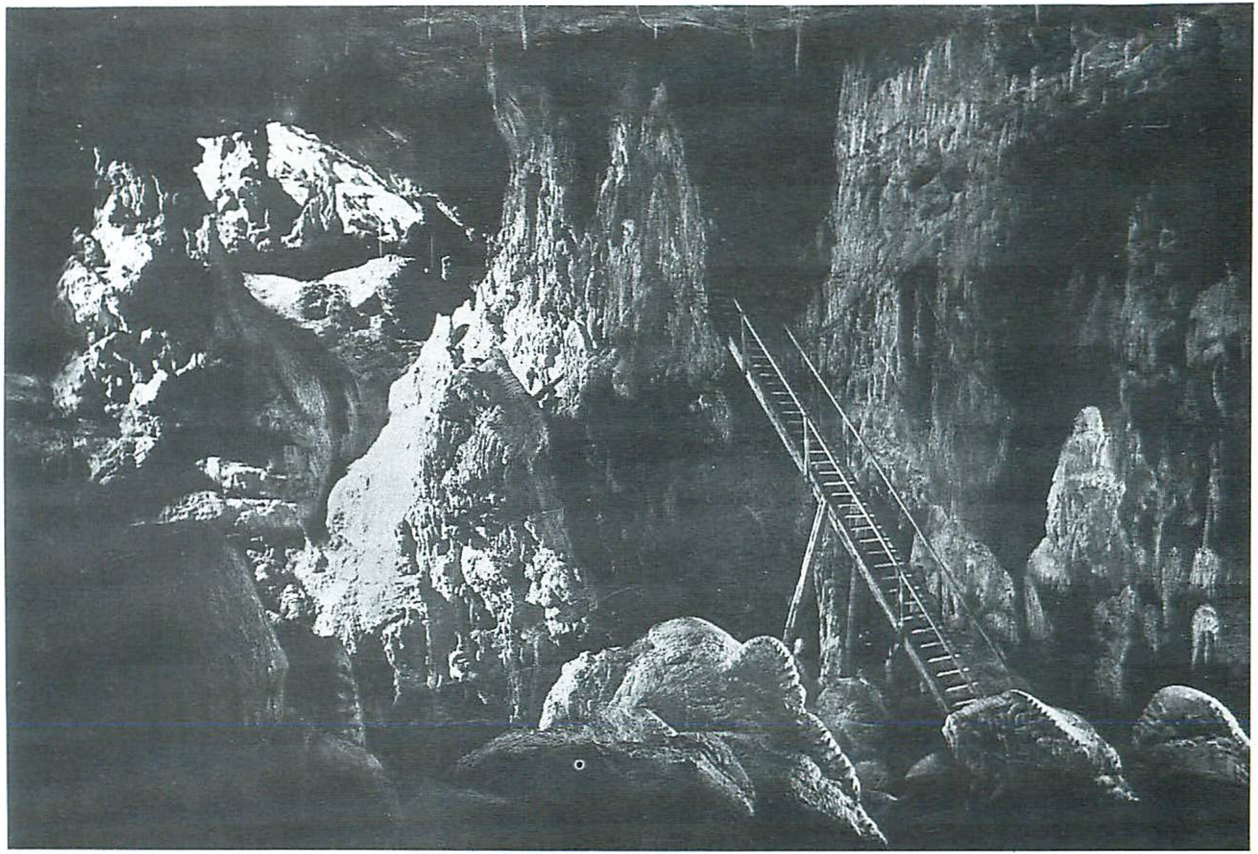

FIG. 1—PHOTOGRAPH OF THE NETTLE CAVE BY CANEY & CO., 1883 OR 1884, SHOWING THE LOBSTERS. IN THE CENTRE OF THE PICTURE, JUST IN FRONT OF THE SUPPORT FOR THE STAIRCASE, IS THE LOBSTER SHOWN IN FIGS. 3 & 13 AND PLATE 1

Trevor Shaw collection copied by C. J. Howes

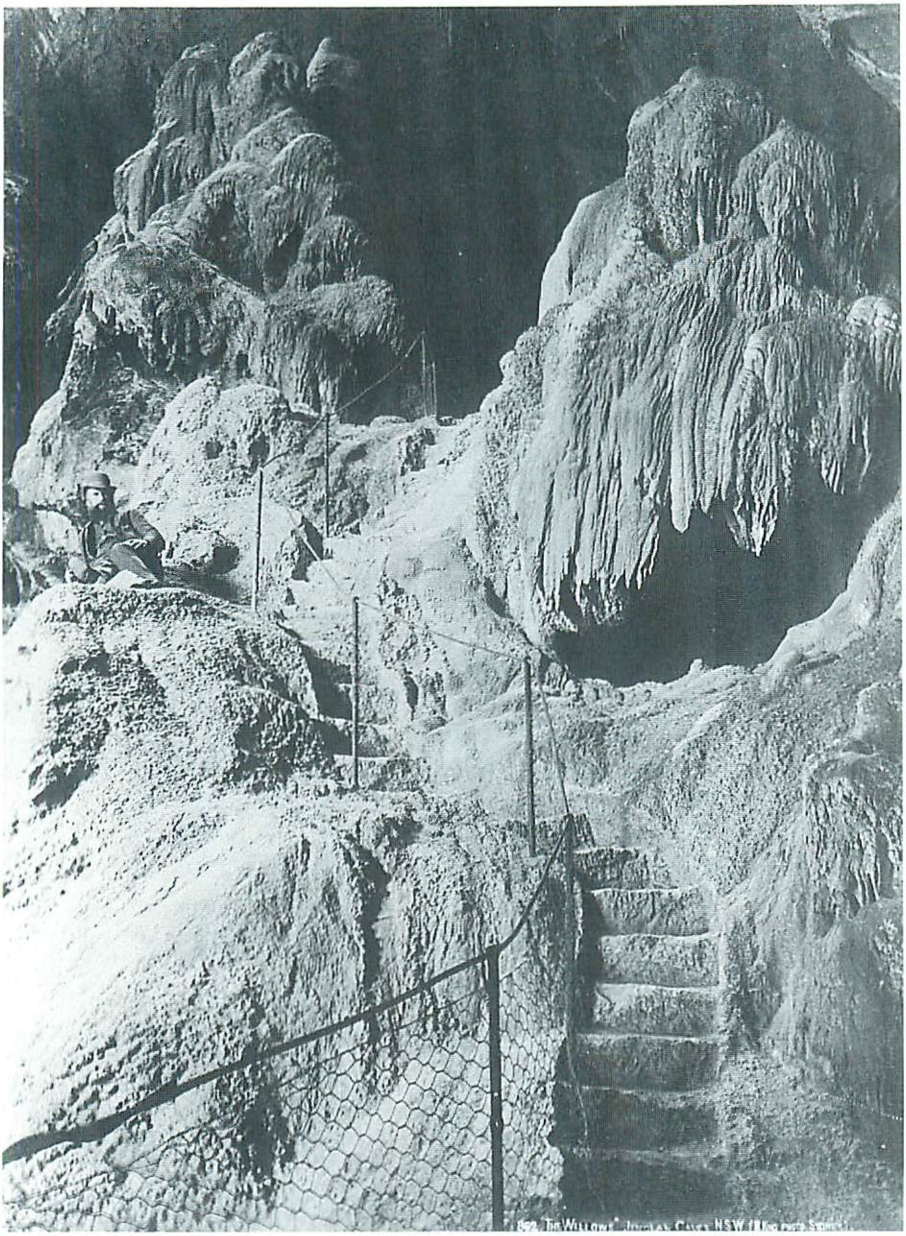

FIG. 2—PHOTOGRAPH OF NETTLE CAVE BY HENRY KING, C. 1888, SHOWING MANY OF THE LOBSTERS (BACKGROUND, UPPER LEFT)

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FIG. 3—A LOBSTER IN NETTLE CAVE AT JENOLAN CAVES. THE DARK COLORATION IS A DEEP BLUISH GREEN IN THE ORIGINAL COLOUR PHOTOGRAPH. THE HEIGHT OF THIS SPECIMEN IS ABOUT 1.5 M (SEE FIG. 13, AND ALSO PLATE 1 IN COLOUR)

At the time of writing Nettle Cave has not been open to the public for over 60 years, although plans to reopen it as a commercially 'self-guided' show cave are being proposed. These speleothems have therefore received little notice in popular or speleological literature in recent years, although they are the best examples known to us. Their rediscovery dates from an environmental study of the caves commissioned by the NSW Department of Sport, Recreation and Tourism in 1984 (Cox, 1984 a & b). The speleothems were a feature of the early tourist inspections of this cave, and they are to be displayed again as a prominent attraction of the cave inspection when the cave is reopened for the public.

The 'Craybacks' in Victoria Arch at Wombeyan Caves, NSW, are the other classic example of these speleothems. Although these are larger than those at Jenolan, they are not mentioned in any early account of the caves. Trickett's (1906) book does not refer to them, although one is visible in his photograph of Victoria Arch (p. 13). These large specimens are pointed out to tourists by the guides.

The Wombeyan Craybacks were first recorded in the book *Wombeyan Caves* (Dyson *et al.*, 1982). The article by Sefton and Sefton (1982) mentions them as one of the sights of the show cave, while James *et al.* (1982) goes into some detail about their likely mode of formation. As well as the monochrome illustration of an individual Crayback in James *et al.* (1982), they are visible in the colour plate of Victoria Arch on p. 107 of the book. This is the only previously published colour illustration of these crayfish-like speleothems, and gives a good idea of their colour in damp conditions.

There are many related speleothems both within these caves and in other cave entrances, for example the Abercrombie Arch, Abercrombie Caves, NSW, and in the Glory Hole at Yarrangobilly Caves, NSW, but they lack the close resemblance to crayfish. E. Hamilton-Smith (pers. comm.) has sent us details and photographs of what may be similar stalagmites from a large natural arch at Waitomo (North Island, New Zealand) and from Carlsbad Caverns (New Mexico, USA). A close examination of other arch caves and natural tunnels throughout the world may reveal other such stalagmites.

The present paper reports the results of our initial investigations of these unusual speleothems, based on field investigations and the examination of sectioned specimens. Our aims were to try to understand the contributions of biological and non-biological processes to the formation of these stalagmites, and to investigate the factors causing their distinctive morphology.

MATERIALS AND METHODS

Field Studies

The caves in which these speleothems are found are operated as commercial show caves by the NSW government. All detailed studies have been carried out in Nettle and Arch caves at Jenolan, since these caves are not at present shown to the public. The Devils Coach House (of which Nettle and Arch Caves are high-level branches) was also examined.

The positions of the major Lobsters in Nettle Cave were mapped on the existing survey of the cave (FIG. 6). The directions of 'head' and 'tail' (if present) were marked. The light intensity at each end of most of the major examples was measured with a Gossen Profisix exposure meter, which is calibrated in lux, at approximately midday in summer (12.15–12.45 on 2nd November 1985). This could, however, be expected to change considerably during the day and from season to season.

Laboratory Studies

Scrapings of the algae and cyanobacteria on the surface of the speleothems were collected for culture and further study. Cultures were raised in BG11 medium. Specimens of fresh and cultured material were studied in the light microscope and processed following the schedule of Cox, Benson and Dwarte (1981) for the transmission electron microscope (TEM). TEM sections were examined in a Philips EM 400 electron microscope.

The size and limited occurrence of these structures, and their status as tourist attractions, means that we have only been able to obtain two substantial specimens, from Nettle Cave, for laboratory study. Both of these had displaced from their original position, probably during the construction of paths in the late 19th century. One was a small Lobster, while the other lacked the characteristic shape but appeared otherwise similar. Both were sectioned longitudinally (one half of the Lobster was then polished and is now on display at Jenolan Caves; the other half was retained for laboratory work).

Samples were examined in a Philips SEM 505 scanning electron microscope, equipped with EDAX x-ray microanalysis attachment, after sputter coating with gold. X-ray diffraction analysis was carried out on a Philips X-ray powder diffractometer.

Organic residues in the speleothems were characterized using a variety of techniques.

RESULTS

Morphology of the Stalagmites

All of the stalagmites are elongate, having their long axis greater than their height. The most characteristic specimens (FIG. 3) have a smooth upper surface with large regular transverse corrugations. The majority have a distinct 'head' and 'tail' as illustrated in FIG. 3; symmetrical specimens (FIGS. 4 and 5) are rarer. The Jenolan specimens (FIGS. 3 and 5) tend to be slim and tall. They have a superficial coating of cyanobacteria which gives them the blue-green colour of an uncooked crayfish in wet conditions; when dry they have a grey-black appearance. The area of deepest colour may move around the light-facing stalagmite ends with season (E. Holland, pers. comm.). FIG. 4 shows a fat squat specimen of a Crayback at Wombeyan; it is a deep green when wet and a powdery paler green when dry. These appear to be subaerial speleothems with deposition still in progress; there is no evidence that they were deposited under water. The squatter proportions of the Wombeyan specimens are probably a function of the higher roof. In general, the diameter of a stalagmite is a function of the distance between the stalagmite and the dripping point; the further the drop falls the more it splashes and the broader will be the resultant stalagmite (Gams, 1981).

FIG. 4—A CRAYBACK IN THE VICTORIA ARCH, WOMBEYAN CAVES (FROM DYSON ET AL., 1982)

PLATE 1—THE LOBSTER SEEN IN FIGS. 3 AND 13. THIS PHOTOGRAPH WAS TAKEN SIX MONTHS AFTER FIG. 13, AND SHOWS CYANOBACTERIAL COVER RE-ESTABLISHED ON THE SURFACE
Photograph: Alan Warild & Julia James

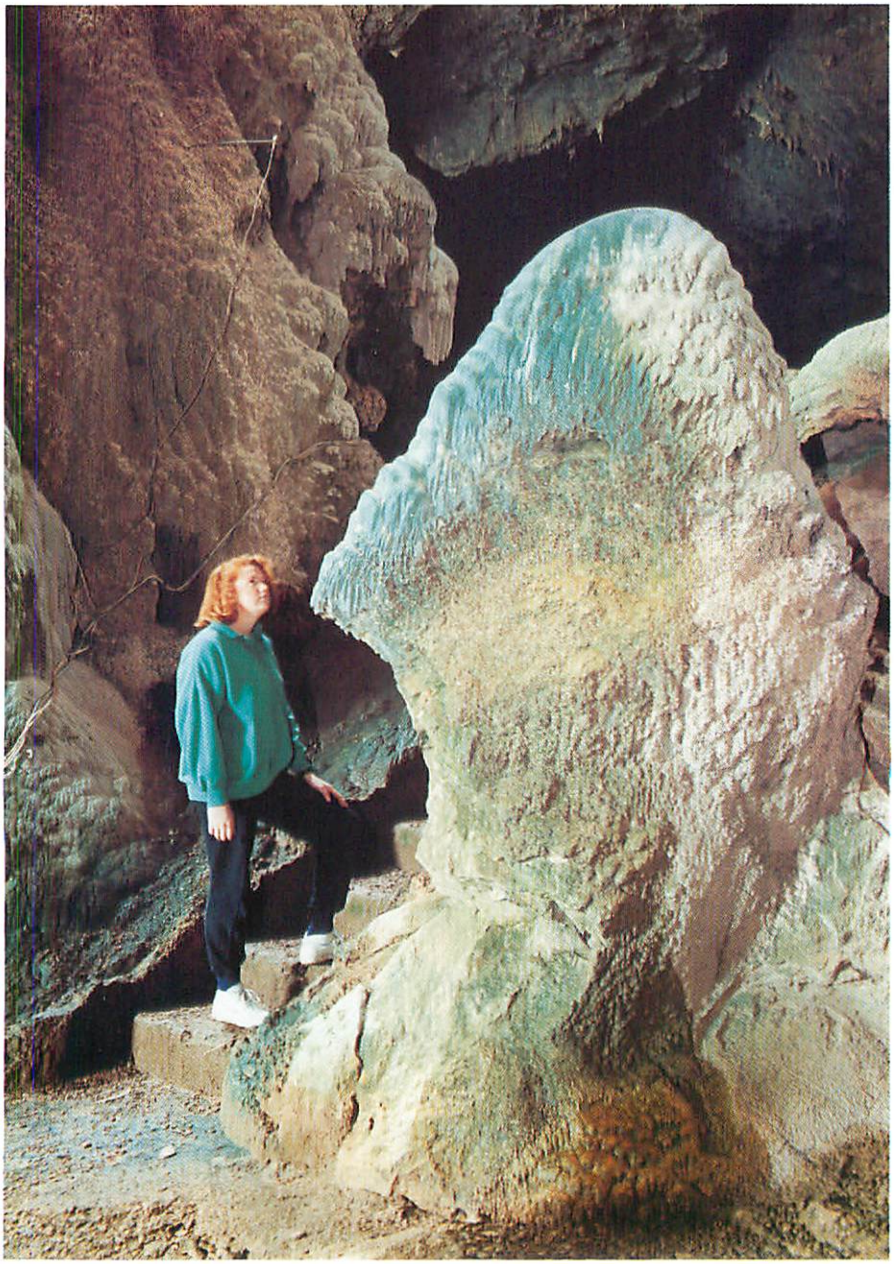

Plate 2—Another Lobster in Nettle Cave, alongside and somewhat undermined by the upper part of the path shown in Fig. 2

Photograph: Alan Warild & Julia James

FIG. 5—A LOBSTER FROM NETTLE CAVE THAT IS SYMMETRICAL, WITH TWO TAILS (HEIGHT OF PICTURE ABOUT 1 M)

TABLE I shows the orientation of the 'heads' and 'tails' of the Lobsters in the Nettle Cave (FIG. 6) and relates it to the direction of illumination. Within a group, the axes of the Lobsters are close to parallel (FIG. 2). The table shows that there is no relationship between the orientation of the stalagmites and the midday light intensity at their surface. The head (presumably the region of maximum calcite deposition) is often not the best illuminated section of the speleothem.

The Depositional Environment

All of the sites are areas of arch or tunnel caves where illumination is from both entrances; in many cases illumination is mainly from one direction, but sometimes both directions are more nearly equal. The caves exhibit a wide range of humidity, from very damp with streams flowing across the floor of the cave (Victoria Arch, Wombeyan) to dry conditions with dust in the atmosphere (Nettle and Arch Caves, Jenolan). The annual temperature range is from below freezing to above 30°C. All of the crayfish-like stalagmites are found in areas of high air movement. The wind direction at the various sites changes with surface meteorological conditions; however there is a prevailing direction at most sites.

The two sites are in fluvio-karst areas and the tunnel caves are at the bottom of deeply incised blind valleys. In similar surrounding valleys the bottoms are filled with pockets of temperate rain forest. Thus the humidity may remain higher for longer than if the arch were in a more exposed position.

All of the stalagmites are forming below drips, which have variable drip rates. Their flow rate varies from a steady stream of seepage waters to totally dry. Erratic flow from drips is to be expected in a mature karst at shallow depth. The stalagmite may or may not have a corresponding stalactite above

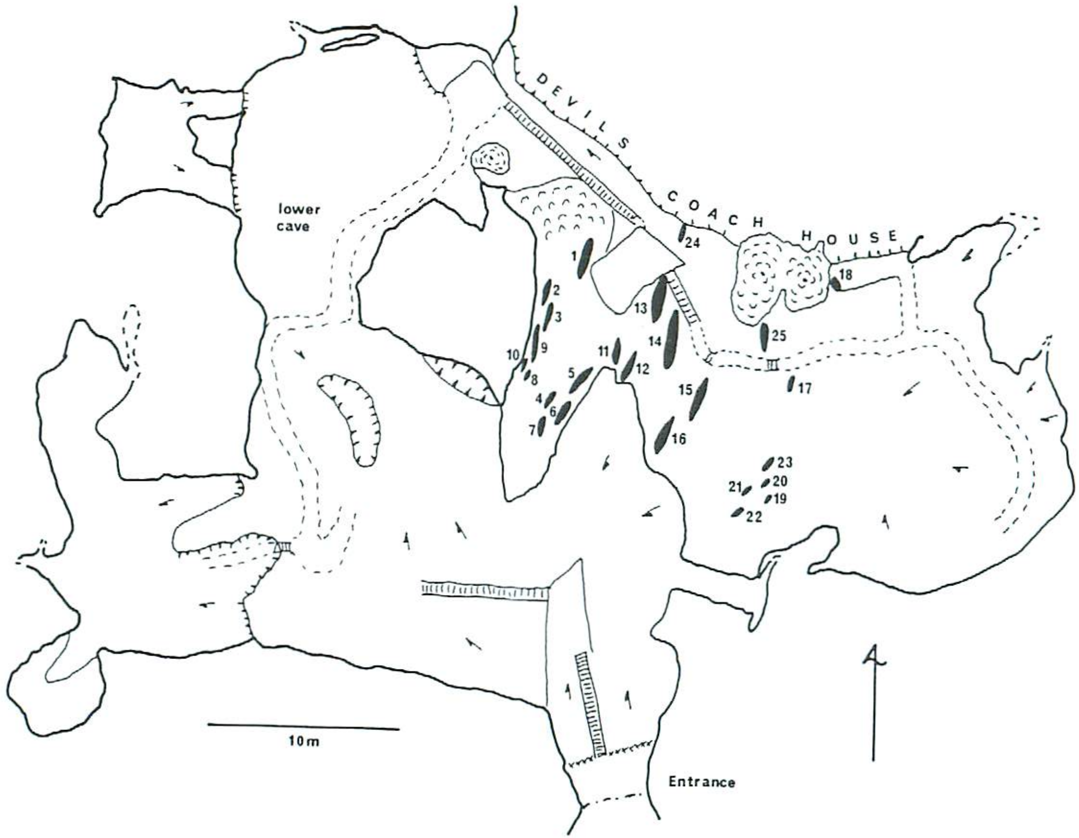

FIG. 6—PLAN OF NETTLE CAVE, SHOWING LOCATION OF MOST OF THE LOBSTERS IN TABLE I

it. Where there are stalactites above, they are normal structures hanging vertically with no tendency to grow towards the light. In some cases the stalactites are covered with mosses and cyanobacteria.

Embryo crayfish-like stalagmites are forming on the paths in the Devils Coach House and on the earth floor of Nettle Cave in areas where they are likely to have existed previously but would have been removed to clear paths for tourists.

TABLE I—*Light intensity and shape measurements of lobsters in Nettle Cave 12.15–12.45pm 2 Nov. 1985*

Site	*Axis* degrees	*Height* m	*Intensity* *N* lux	*S*	*Drips* min^{-1}	*Tail*	*Description*
1	190	1.15	200	100	Dry	none	Cave coral covered, dusty, green algae
2	190	0.34	80	60	Dry	N	Smooth, off-white, with grey algae
3	185	0.44	44	55	Dry	N	Much cave coral, good tail black-grey from algae + dust
4	190	0.1	18	44	Dry	N	Smooth, no head or tail no evidence of algae
5	190	0.90	50	44	Dry	N	Cave coral; cyanobacteria on tail
6	190	1.25	88	50	17	N	1798 engraved one end. Holes in laminated shell
7	195	0.49	20	44	15	S	Blue-green algae; head coral, tail smooth
8	190	0.25	11	44	3	tiny	2 small grey-green stalagmites—algae, cave coral
9	190	1.15	33	66	Dry	none	Grey-green smooth surface evidence of laminae
10	200	0.95	15	60	Dry	none	Double humped stalagmite inactive. Grey-green
11	200	0.35	100	175	26	N	Small dry dusty stalagmite largely cave coral
12	205	0.15	100		Dry	N & S	Large cavity at top, smooth tail, shows laminae
13	210	3.0	350	120	2	N & S	Stepped profile, cyanobacteria
14	200	2.2	300	120	Dry	N & S	Hollow—can see laminae inside shell
15	190	0.85	150	90	9	N	Inactive, green, dry, dusty
16	195	2.5	150	150	Dry	N	Coral on dry side, cyanobacteria on wet areas
17	190	0.15	22	22	5	S	Grey, smooth, slight evidence of algae
18	190	0.25	15	13	Dry	S	Good development believed to be *in situ*, grey green
19	135	0.94	13	5.5	Dry	S E	Cave coral, no algae
20	180	0.35	22	15	Dry	N	Cave coral knob
21	180	0.6	15	17	Dry	S?	Stalagmite, inactive
22	190	0.82	17	15	Dry	N & S	Stalagmite, coral, inactive
23	200	1.42	44	22	Dry	S	Stalagmite, blue-green stepped profile on top
24	190	0.4	700	500	9	S	Very active—blue-green long tail
25	215/190	0.53			Dry	S	Double tailed
26	240	0.15			Dry	S	Baby-blue-green. Coral tail
27	245	1.0			Dry	S	Cave coral no cyanobacteria
28	220	0.11			Dry	S	Stalagmite, no algae

N : north
S : south

Surface Microbiology

Scrapings from the surface of the stalagmites reveal predominantly coccoid cyanobacteria, with abundant sheaths. In cultures from the same material apparently identical cyanobacteria grew readily; they can be assigned to the genus *Gloeocapsa*. Further details are being published elsewhere (Cox *et al.*, 1989). Cyanobacteria (popularly called blue-green algae) are not true algae but prokaryotes (allies of the bacteria). They do, however, carry out photosynthesis in exactly the same way as true (eukaryotic) algae.

Internal Structure of the Stalagmites

The Nettle Cave Lobster which was sectioned (Figs. 7 and 8) is a small specimen approximately 300 mm long by 200 mm tall. Parts of its surface are covered by cave coral while other areas are smooth. The flowstone specimen (Fig. 9) has a smooth external surface, parts of which were coated in dry cyanobacteria. It has an internal structure like the Lobster and has clearly been formed by similar processes. All destructive laboratory tests have so far been carried out on the flowstone to avoid destroying any of the irreplaceable Lobster sample.

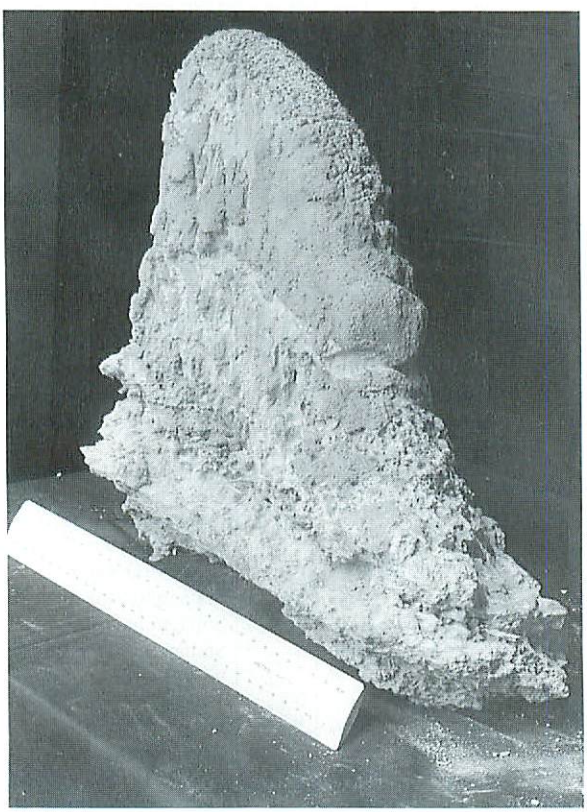

Fig. 7—The Lobster which was removed from Nettle Cave, before sectioning

FIG. 8 shows that the internal structure of the Lobster is complex. The lower levels are laminated with layers of massive calcite interdispersed with layers of aeolian sediment and other detrital materials. Within the lowest laminated levels there is a small stalagmite (FIG. 10). The higher levels are

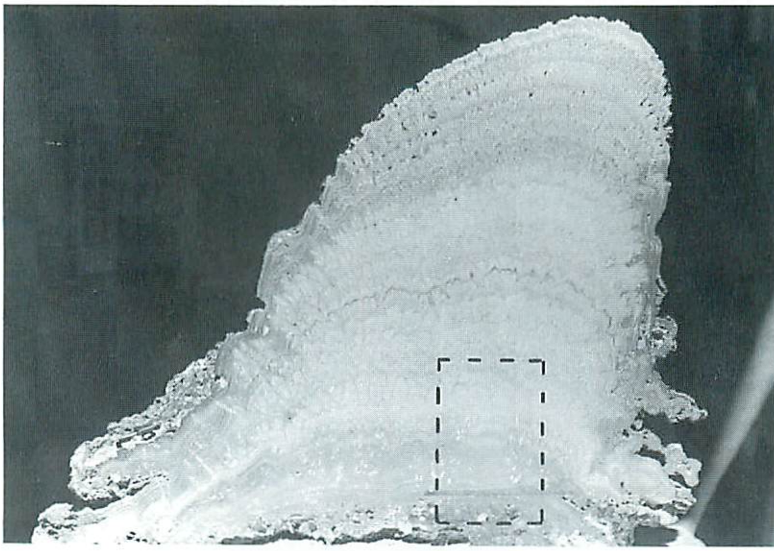

FIG. 8—SECTIONED LOBSTER; THE BOXED AREA IS ENLARGED IN FIG. 10

FIG. 9—THE SECTIONED ALGAL FLOWSTONE SAMPLE, SHOWING CORALLOID AND LAMINAR REGIONS

coralloid calcite structures surrounded with sediments. The head is largely coralloid and the tail laminated. There are areas of lamination interdispersed with and covering the coralloid sections. Some layers of the structure contain a higher percentage of dark aeolian sediment and stand out as dark bands. Within some laminated sections and throughout the coralloid areas are many small cavities (FIG. 10).

The flowstone shows a similar sequence of development—laminated, coralloid and then laminated again. The flowstone does not have a head and tail structure but it does have a region of predominantly laminated texture.

FIG. 10—PART OF THE LOBSTER, SHOWING THE STALAGMITE STRUCTURE WITHIN THE LOWEST LAMINATED LAYERS

Mineralogical Studies

The major structural material of the speleothem has been shown by X-ray powder diffraction to be calcium carbonate in the crystal form of calcite. The detrital material is a variety of allochthonous materials which have either been blown into or around the cave sand, soil and limestone dust, or have entered through the seepage waters (e.g. colloidal clays). The laminated layers of the flowstone can be prised apart and the detrital material between these layers was examined by optical and electron microscopy. Both fragments of insects and sand grains were found as inclusions (Cox *et al.*, 1989).

Organic Geochemical Studies

These chemical studies were designed to obtain evidence that cyanobacteria had been involved in the early growth stages of the stalagmite. Cyanobacteria produce decay products that contain low molecular weight nitrogen-containing lipids and alkanes (Brooks *et al.*, 1976). These organic materials were identified as being present in the stalagmite. Other organic materials that were identified were humic and fulvic acids whose source would be the seepage waters. In the samples studied the organic material was predominantly found in the laminar sections.

DISCUSSION

Formation of Crayfish-like Stalagmites

The only published explanation of the formation of these stalagmites (James *et al.*, 1982) was based on external examination of the limited number of specimens in Victoria Arch, Wombeyan Caves. In every case their long axis was close to a line joining the entrances, leading to the conclusion that they were growing towards the light (James *et al.*, 1982). The identification of cyanobacteria on the surface of the stalagmites suggested that the stalagmite morphology resulted from photosynthetic removal of carbon dioxide from the seepage waters, precipitating calcium carbonate. The detailed field study of Nettle Cave specimens (TABLE 1) showed that while the orientation was again always close to a line joining the entrances, the heads were not uniformly orientated towards the light. This suggested that light may not be the major determinant of their form.

Calcium carbonate precipitation occurs when the the equilibrium shown in equation (1) is displaced towards the right, either by removal of water by evaporation or by the loss of carbon dioxide.

$$Ca^{2+}(aq) + 2HCO_3^-(aq) \rightleftarrows CaCO_3(s) + CO_2(g) + H_2O \qquad (1)$$

Seepage waters feeding speleothems normally have a higher partial pressure of carbon dioxide than the cave atmosphere and thus carbon dioxide is continuously lost by diffusion, usually precipitating calcium carbonate. A rise in temperature of the saturated carbonate solution will reduce the solubility of CO_2 and so have the same effect.

Deep inside most caves where the relative humidity is close to 100% and temperature is almost constant, loss of carbon dioxide by diffusion from saturated solutions is the major cause of calcium carbonate precipitation. The diffusion of carbon dioxide is slow and the crystals that form are massive macrocrystalline calcite; on occasions whole speleothems can be formed as just one macro-crystal.

In cave entrances, carbon dioxide is still lost by diffusion but another driving force for precipitation (except during periods of high humidity) is water loss by evaporation. Thus when temperatures are high and humidity low, evaporation and temperature rise become dominant processes causing precipitation. In these circumstances microcrystalline calcite is deposited forming quite different speleothems. These have a characteristic trabecular or rugose morphology giving rise to their name cave coral (Hill and Forti, 1986). In the sites in which the crayfish-like speleothems are growing cave coral would be expected to be prolific.

Where cyanobacteria (or true algae) are present there is, however, another mechanism at work removing CO_2 from solution and thus driving equation (1) to the right. This is photosynthesis—the conversion through the action of light of carbon dioxide and water to carbohydrate, with the liberation of oxygen. During daylight there will be a large excess of photosynthesis over respiration, with a consequent substantial removal of CO_2. At night CO_2 will be liberated by respiration, but over 24 hours the net effect will still be very much in the direction of CO_2 removal. The drips from the cave roof contain high partial pressures of carbon dioxide and are well provided with mineral nutrients so, provided that light and water are adequate, conditions are ideal for cyanobacterial photosynthesis. This is still inorganic deposition of calcium carbonate—the action of the micro-organisms is solely the removal of CO_2.

Certain cyanobacteria and true algae can also deposit calcium carbonate biologically, that is by enzyme action. This is known in marine, fresh-water and cave environments, and is chemically rather different in that it can take place from solutions which are not saturated. The cyanobacteria *Geitleria* and *Scytonema* are the best-known examples of such organisms in caves (Couté, 1985). We have not found these or any other calcite-depositing cyanobacterial species on the Lobsters, so biogenic calcium carbonate deposition is probably not a significant process in their formation.

The sectioned specimens all show extensive internal coralline structures, which probably represent calcium carbonate deposited through evaporation of water. They also show substantial laminar structures, in which precipitation driven by photosynthetic removal of CO_2 is likely to be a substantial contributor (Cox *et al.*, 1989). The suggestion that visible green patches can move around the speleothem with season implies that increased light intensity (probably morning or evening sunlight shining directly into the cave entrance) can promote increased cyanobacterial growth. This in turn suggests that availability of light may sometimes be the limiting factor for photosynthesis. The maximum amount of calcium carbonate deposited as a result of photosynthesis can, in principle, be assessed by oxygen budget studies—calculating from oxygen produced how much carbon dioxide has been taken up. It is planned to carry out such a study in the future.

It is clear from the presence of sand grains and insect fragments in the speleothems that the cyanobacterial mat is capable of trapping sediments, and that these will contribute a finite amount to the mass of the stalagmite (Cox *et al.*, 1989). Some proportion of this will be allochthonous carbonate, derived from wind-blown dust, but its overall contribution is likely to be small. Decay of the cyanobacteria and their voluminous sheath material when they are deeply buried by growth of the stalagmite probably plays a significant part in subsequent diagenetic changes.

Stages in the Development of a Crayfish-like Stalagmite

Based upon our field observations of the Lobsters and related forms, and the internal structure of our two sectioned specimens, we present here a putative scheme for their growth and development. The series of events shown in Fig. 11 is simplified; the areas of lamination and coralloid development in the sectioned specimen vary in a more complex manner than is illustrated. However, this scheme is consistent with our observations to date and provides a hypothesis on which to base future work.

Stage 1. Seepage drips fall onto the cave floor and a small stalagmite builds up directly below the water source. If the wind is blowing, then on one side of the stalagmite will be a long thin wet area. The drip falls on various parts of the wet area depending on the intensity of the wind. The cave floor becomes consolidated with calcite (Fig. 12).

Stages 2–5. Build-up of laminated layers. (Calcite stalagmites are not usually laminated, unless they are in areas of the caves that flood. Flood sediments coat the stalagmite and when the flood recedes a fresh layer of calcite is deposited on top of the sediment.) The area where the crayfish-like stalagmites are growing at Jenolan is a relict passage and some 20 metres above current flood levels.

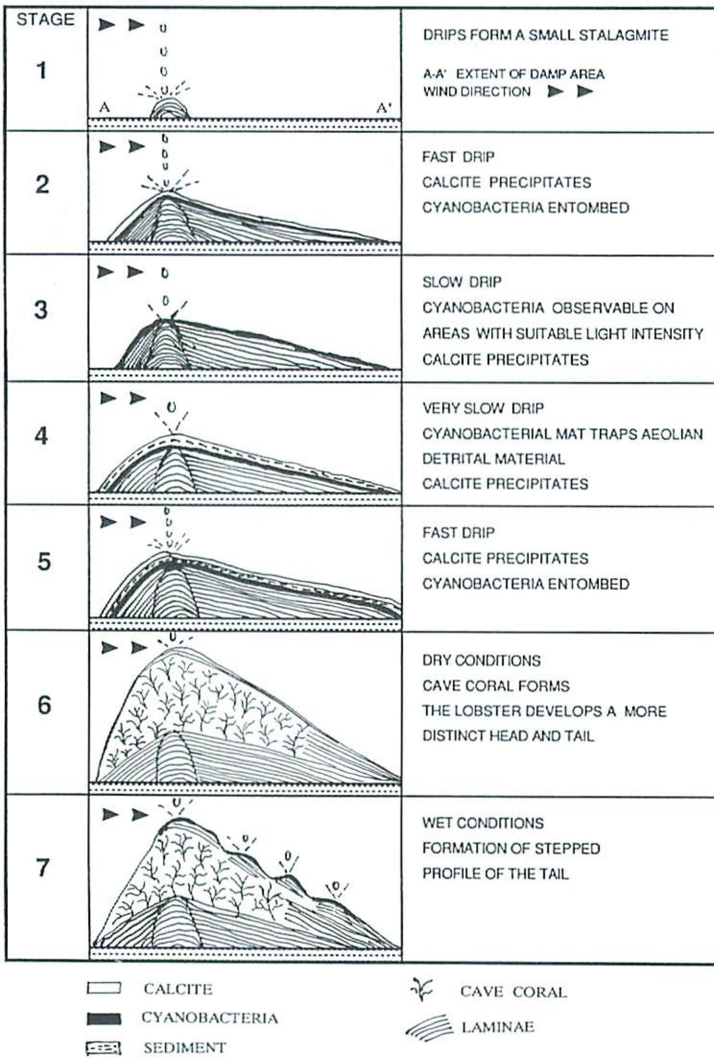

FIG. 11—PROPOSED MODEL FOR THE FORMATION OF A CRAYFISH-LIKE STALAGMITE

Stage 2. The drip rate is high and the surface is kept covered with water, allowing calcite to be deposited. Photosynthesis may well be a major driving force for deposition but calcite is deposited faster than the growth of cyanobacteria so that few are seen on the surface.

FIG. 12—LINE OF NEWLY-FORMED SMALL STALAGMITES (POLISHED BY VISITORS' FEET) ON THE PATH THROUGH THE DEVILS COACH HOUSE

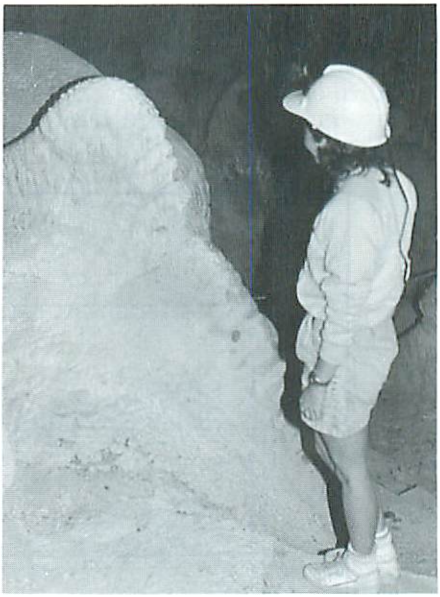

FIG. 13—THE STALAGMITE SHOWN IN FIG. 3 PHOTOGRAPHED ON 12 NOVEMBER 1988, AFTER A PROLONGED WET PERIOD; THE COLOUR IS NOW WHITE BUT A FAINT SHADOW INDICATES THE BURIED CYANOBACTERIAL LAYER. ONE MONTH LATER THE LOBSTER WAS A PALE ICY BLUE-GREEN COLOUR

Stage 3. The drip speed slows and cyanobacteria build up on slopes and sides with suitable light intensity. Most deposition takes place on the peak of the Lobster which therefore shows fewer visible cyanobacteria, as they are continually being covered.

Stage 4. When there is a long period with no rain the cave atmosphere becomes dusty; aeolian materials are trapped on the copious mucilaginous sheath of the cyanobacteria. Some calcite will continue to be precipitated by cyanobacterial photosynthesis, cementing together the organic and aeolian materials.

Stage 5. As the drip rate increases again Stage 2 is repeated. The cyanobacteria are actively growing and dividing in very favourable conditions, but are mostly covered by a calcite layer, and the organic-sediment layer is buried. FIG. 13 shows a shadow where the cyanobacterial colony seen in FIG. 3 has been covered by calcite. Those cyanobacteria which are buried too deeply for photosynthesis decay, and chemical modification of the sediments and calcium carbonate takes place.

After a wet spell the cyanobacteria grow through the newly deposited calcite layer. One month after FIG. 13 was taken the stalagmite was mostly pale blue-green in colour and PLATE 1 shows cyanobacterial cover thoroughly re-established on the surface after six months. The laminated areas of the stalagmite are those of low gradient and thence are likely to retain a film of water over their surface longer. It is also possible that the cyanobacterial sheaths assist in retaining a moisture film on the surface of the speleothem.

These stages (2–5) do not represent annual events; since the first detailed examination of the stalagmites three years ago in 1986, there has only been one period of rapid calcite deposition. It is likely that these structures require many thousands of years to form; to quantify this, we have submitted samples from the lowest laminated levels of the Lobsters for carbon dating.

Stage 6. Coralloid development. As previously noted, cave coral is formed where evaporation is the major controlling factor. This occurs in the driest times when cyanobacterial colonies become less viable as the surfaces of the speleothem dry out. The stalagmite growth is now dominated by cave coral formation. Cave coral grows on tops, steep slopes and sides of the speleothem in the areas where evaporation is likely to be greatest.

The coralloid structures may play an important role in determining the shape of the stalagmite. They are better developed on the side facing into the prevailing wind and thereby form the stalagmite head. Cave coral is commonly better developed into the prevailing wind; Hill (1978) explained this phenomenon by citing higher evaporation rates on this side which faces the drier air flowing into the cave.

Stage 7. The stepped profile of the tail. The older specimens of Lobsters have well developed stepped profiles to their tails.

Steps can form in conventional stalagmites in dark caves. These usually start with a projection such as a coralloid on the stalagmite surface. The water film over the projection is curved, so that CO_2 diffusion (or evaporation) takes place more rapidly; thus calcite is preferentially deposited in the higher place, and while it is supplied with carbonate solution the step will continue to grow. As illustrated in FIG. 14, a succession of steps can form with the one below being fed by the overflow from the one above.

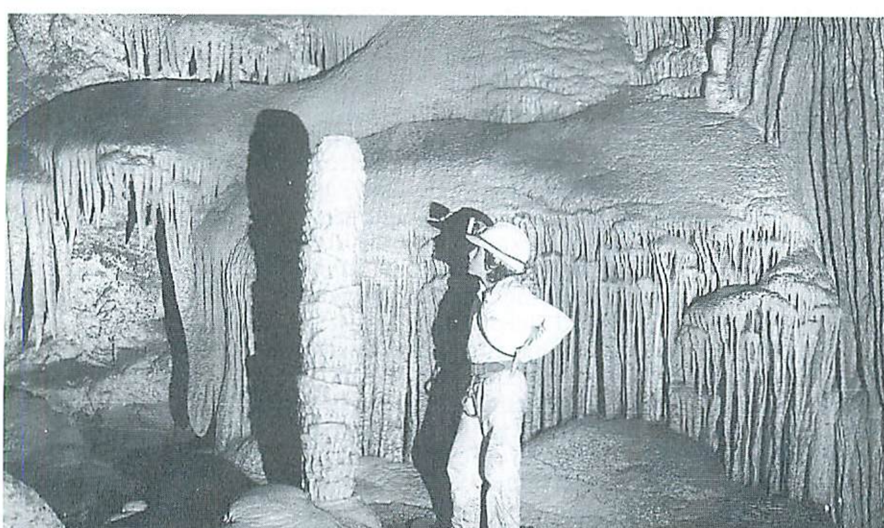

FIG. 14—A STALAGMITE FROM TATTERED SHAWL CAVE, WOMBEYAN, SHOWING STEP FORMATION

On a crayfish-like stalagmite, cyanobacterial photosynthesis and sediment trapping will accentuate this process. Any small irregularity along the ridge will cast a shadow, so that photosynthesis will be faster above it than below, and increased deposition will form a step. The process will be self-limiting since reduction in gradient will eventually limit the flow of water over the step, restricting both cyanobacterial growth and the supply of calcium carbonate. Sediment trapping will reinforce the process; the reduction in gradient as a step forms will slow the flow of water, leading to sediment deposition and accentuating the step.

On the sloping tail, once a sizable step develops it channels the water down the sides of the speleothem so that the carbonate solution is not available for development of the next step on the tail ridge. However, wind movement of the drips feeding the stalagmite will scatter drips along the ridge, so that multiple steps form simultaneously.

This model is tentative and to some extent speculative, but it is consistent with our observations to date. The implication is that while light is essential for the growth of the crayfish-like stalagmites, wind effects play an equal or greater part in determining their form. Further research is planned to test the model.

Comparison with Other Structures

The Lobsters and Craybacks are stalagmites which are deposited, in part, by the action of cyanobacteria. It is therefore of interest to consider them in the context of both speleothems and stromatolites.

Stromatolites are structures in which sedimentary material is accumulated by trapping or agglutination of particles from suspension on an organic film or by direct or indirect precipitation resulting from the life processes of the microbiota (Aitken, 1967). Fossil stromatolites in Precambrian rocks provide the first evidence for life on earth; they are a major component of the early fossil record but are now extremely rare, found only in a few rather specialized environments. The Lobsters and Craybacks are clearly stromatolites by Aitken's definition.

In their internal and external morphology, the crayfish-like stalagmites resemble some forms of both ancient and modern marine and lacustrine stromatolites. However, they are forming in a quite different, and unusual environment since they are growing both completely subaerially and with a roof above them. The closest comparable environment hitherto reported as a site of stromatolite deposition is a freshwater karst sinkhole in South Africa (Gomes, 1985; Smith, 1986), but the stromatolites there are subaqueous and unable to withstand prolonged exposure to the atmosphere.

The Lobsters and Craybacks differ from other speleothems in that they are confined to very specific tunnel and arch cave sites. Stalagmites of similar morphology are never found deep inside caves, although many dark caves have comparable draughts. This further confirms that both light and wind are required for the crayfish shape to be formed.

Phototropic speleothems sometimes develop in cave entrances with stalagmites, stalactites and flowstones growing towards the entrance. Most speleothems formed purely by algal or cyanobacterial deposition are relatively small and insignificant (Cubbon, 1976; Braithwaite and Whitton, 1987). However, some phototrophic speleothems in cave entrances are probably formed by photosynthetically-driven calcium carbonate precipitation (de Saussure, 1961) and these can sometimes reach substantial sizes. We believe that on closer examination many of the entrance speleothems in temperate and tropical karst areas will contain photosynthetically-deposited calcium carbonate, and many will probably have internal structures similar to the crayfish-like stalagmites.

CONCLUSIONS

The crayfish-like stalagmites found at Wombeyan and Jenolan, NSW (and possibly elsewhere) can be classed as stromatolites and thus can be added to the select group of freshwater stromatolites. They are the only known stromatolites which have formed without even periodic submersion. They are unusual speleothems which require an arch location, wind action, variations in humidity and the presence of cyanobacteria to explain their shape.

If our proposed model for the formation of these stromatolitic speleothems is correct, they could be a source of valuable information about past climates. Organic compounds can be extracted from various sections of the speleothem and dated by carbon-14 accelerator mass spectrometry enabling comparisons to be made with conventional carbon-14 dating of carbonates in order to establish whether there is equilibrium deposition of the speleothem. If the speleothem is deposited under equilibrium conditions then stable isotope studies will enable a record of palaeo-temperatures to be established. Examination of the internal structure of a dated stalagmite will reveal the frequency of wet and dry periods.

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