Conveying the importance of stromatolites to self-guided tourists in Nettle Cave, Jenolan, NSW.

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Abstract

Stromatolites span all of geological time; they are the oldest evidence of life on Earth and are important in understanding how life began and first started to diversify. They also played a critical role in shaping the atmosphere as we know it today, causing an irreversible increase in atmospheric oxygen at ~2.4 Ga. Significantly, stromatolitic speleothems in Nettle Cave, Jenolan, resemble these truly ancient forms. Cyanobacteria growing on the surface of these stromatolites use hydrogen carbonate from roof seepage drip-waters as a source of carbon, and light from four entrances allows for photosynthesis and liberation of oxygen. Calcium from the limestone drip-water is deposited as calcium carbonate. The overall shape of these stromatolite structures is most influenced by wind, which causes drip-water to fall at an oblique angle, forming the asymmetric, segmented shapes. Wind also blows-in insects and sediment which become trapped on the surface of the stromatolites by biofilm produced by the microbes. One sample analysed previously shows growth over a period of 20,000 years, capturing an excellent source of information about recent past climates and could reveal environmental fluctuations over this time span.

In order to ensure their continued protection, it is important to promote an understanding of the scientific value of the stromatolitic speleothems in Nettle Cave to both visitors and guides at Jenolan. Linking these speleothems with information about the earliest life on Earth and the persistence of stromatolites through time plays a key part in engaging and educating the public about these interesting structures. Currently, tourists can take a self-guided tour of Nettle Cave using the Jenolan mobile application; however, there is minimal information available on the scientific value of stromatolites to our understanding of past climate and the early Earth. The proposed new visitor information project would involve: updating the stromatolite section of the current mobile application; placing a concise and attractive display board in front of the most prominent stromatolites; creating a pamphlet with more explanation, including pictures and diagrams, available from the guides office; and, updating the Jenolan Caves website to give further detail, including examples of other key stromatolites through time and links to scientific literature, for those wanting up-to-date and more in-depth information.

Keywords: *Stromatolites, Nettle Cave, Early life, Science Communication, Cave Management.*

1. Introduction

Nettle Cave, part of the greater Jenolan Caves system, has been open on and off as a show cave for the best part of 200 years, since 1838 (Cox 1984). It contains large, blue-green stromatolitic speleothems, which are able to grow and flourish in this particular cave due to the balance of microbial activity with sunlight, wind and the rate of cave drip-waters. These relatively rare speleothems were first described, although not directly by name, by Cook (1889): "One prominent stalagmite is like the back of a newly-shorn sheep, with shear-marks in the wool." However, it was not until a century later that these structures, more commonly known as 'lobsters' or 'craybacks' due to their asymmetric mound-shape and overall segmented appearance (Fig. 1A, B), were studied in more detail (Cox et al. 1989a). Cox et al. (1989a) looked at the morphology and mode of formation of the blue-green speleothems and concluded that they fit the definition of cryptalgal stromatolites after Aitken (1967): "(those structures which) originate through the sediment-binding and/or carbonate-precipitating activities of nonskeletal algae."

2. Formation and Morphology of Stromatolites

Stromatolites are most commonly found submerged in shallow-water environments, including; marine (e.g. the hypersaline lagoon of Shark Bay, Western Australia), fresh-water (e.g. Lake Pavilion, Canada), and hot spring environments (e.g. Rotorua, New Zealand). Stromatolites also occasionally occur in subaerial evaporitic settings, such as those from Nettle Cave, and also Wombeyan Caves (James et al. 1982). However, there are relatively few examples of stromatolites of this type worldwide. Cox et al. (1989a) proposed a model of formation of the stromatolitic speleothems in Nettle Cave, which involved a complex interplay between the photosynthetic cyanobacteria, rate of drip-waters, wind speed and direction, humidity and level of evaporation (Fig. 1C). These stromatolites primarily grow from "biologically driven inorganic calcite precipitation" (Cox et al. 1989b), enhanced by evaporation, on the surfaces where water falls from above. Depending on which stage a stromatolite is at in this cycle, its colour can change dramatically from deep blue-green (Fig. 2A), to dusty blue (Fig. 2B), to cream, as new calcite precipitates covering the cyanobacteria (Fig. 1A).

There are a number of differences between the Nettle Cave stromatolitic speleothems and other forms of stromatolites (Table 1). The evaporitic cave stromatolites are unique in that they are subaerial, gaining moisture and a source of carbon from the cave drip-waters (Cox et al. 1989b), whereas typical stromatolites are submerged in water and are only periodically, if ever, exposed. The morphology of stromatolites, whether exposed in air or submerged in water, is controlled by both the microbes and the prevailing environmental conditions. In the case of the Nettle Cave stromatolites, the cave environment is the primary control of overall morphology. The asymmetric, elongated shape of the stromatolitic speleothems is caused by the wind, which blows between the

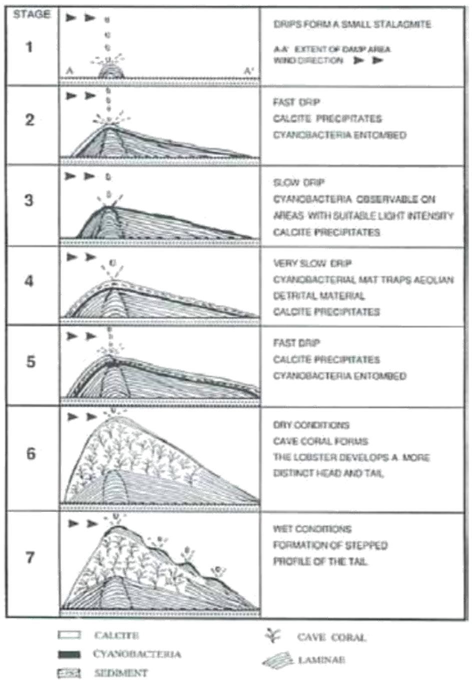


Figure 1. (A), (B) Sub-aerial stromatolitic speleothems in Nettle Cave were known as 'lobsters' or 'craybacks' due to their asymmetric and segmented appearance. (B) Shows blue-green cyanobacteria visible on opposite side of same stromatolite as in (A). (C) Mode of stromatolitic speleothem formation in Nettle Cave, from Cox et al. (1989a).

southern entrance to Nettle Cave and the large void opening into the Devils Coach House to the north (Fig. 3). In cross section, the tallest point (i.e. left-hand side of Fig. 1C) is where the drips fall straight down, whilst the tapering 'tail' is caused by the wind blowing the drips sideways to varying degrees. This effect is nicely displayed on the concrete walkway of the Devils Coach House (Fig. 4A). A similar phenomenon is observed with the modern stromatolites in Hamelin Pool (Shark Bay, Western Australia), where the stromatolites are elongated in the direction of the tides (Fig. 4B). However, unlike the submerged stromatolites in Shark Bay which are subject to erosion and sediment deposition from rough waves and storms, the stromatolitic speleothems are comparatively protected from the outside environment. This results in a relatively uninterrupted record of the environmental and climatic conditions being preserved in these cave examples.

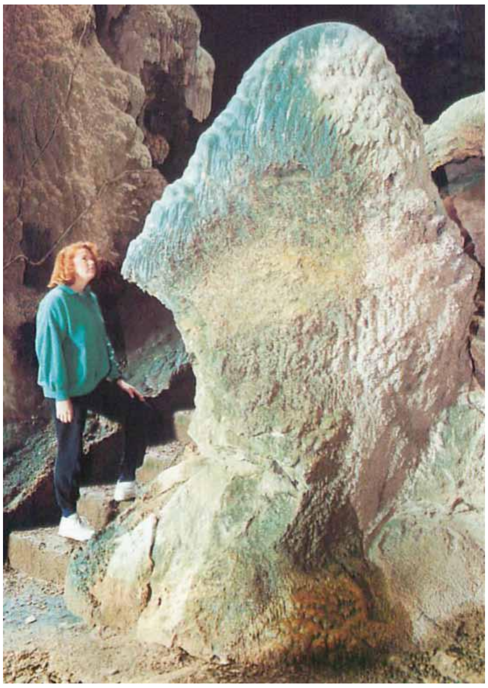
3. Value of Stromatolites

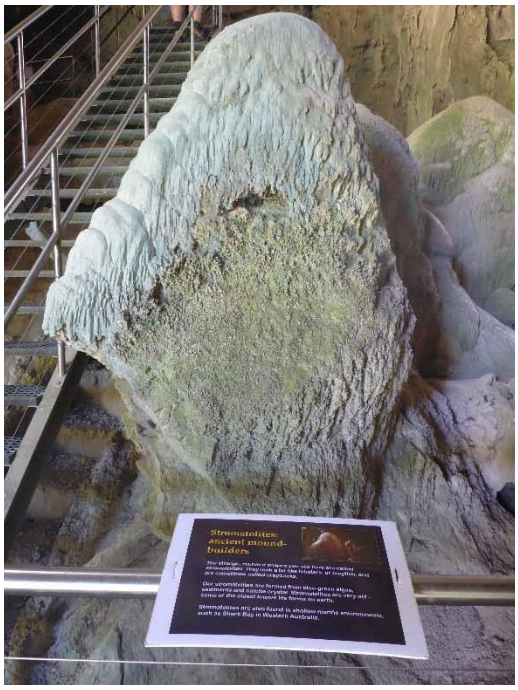
Fossilised stromatolites are important clues in understanding how life began and first started evolving on Earth. They are the oldest evidence of life, with good examples preserved from the c. 3.5 Ga Dresser Formation in Western Australia (Walter et al. 1980), and new, controversial stromatolites reported from c. 3.7 Ga in Isua, Greenland (Nutman et al. 2016). Stromatolites are known from throughout the global geological record, persisting through to the present day. Interestingly, it is not until c. 1.8 Ga that individual fossilised microorganisms are large enough to be visible with the naked eye (Grypania, see: Walcott 1899; Han 1992; Sharma & Shukla 2009, among others); microbial life apparently persevered alone for over 1.7 billion years.

Microbes also played a huge role in shaping the Earth as we know it today. The Archean atmosphere was very oxygen poor, with <10-5 of the present atmospheric level (PAL) (Pavlov & Kasting 2002). It was not until the Great Oxidation

Table 1. Comparison between shallow-water stromatolites and stromatolitic speleothems:

Shallow-water stromatolites	**Stromatolitic speleothems**
Fully or partially submerged in water	Completely subaerial
Source of carbon from surrounding sea/fresh water	Source of carbon from cave drip waters (freshwater)
Water-borne sediment is trapped by microbial biofilm	Wind-blown sediment, along with dust and small insects are trapped by microbial biofilm
Primary influence on shape is sunlight, and tide strength and direction	Primary influence on shape is wind (Cox *et al.* 1989a) and sunlight from cave entrances
Range of morphologies present with increasing water depth	One broad morphology present, just different sizes
Growth of stromatolite primarily controlled by sediment input, as well as carbonate precipitation by microbes	Growth of stromatolite primarily controlled by inorganic calcite precipitation driven by microbes, as well as evaporation
Affected by erosion from wind and wave action, as well as potential to be partly or wholly smothered by sediment, and damaged by storms	Primarily affected by erosion from rate of drip water, but very protected from storms, wind erosion and potential to be completely smothered by sediment
Most common form of stromatolite at present day and throughout geological record	No known fossilised examples from geological record, and only rare examples exist today


(A)



(B)

Figure 2. Then and now:
(A) Stromatolitic speleothem from Cox et al. (1989a), wet with drip waters, highlighting vibrant blue-green colour of cyanobacteria.
(B) Same stromatolite in 2017 with cyanobacteria still present, but much less colour due to cessation of drips. In foreground is current, temporary A3-sized poster board on display to public.

Event (GOE) at c. 2.4 Ga that there was a significant rise in levels of atmospheric oxygen (Farquhar 2000; Holland 2002; Bekker et al. 2004). This irreversible rise is regularly attributed to oxygenic photosynthesis by stromatolites (Schopf 2014). Thus, through research into – and comparison with – modern analogues, fossilised stromatolites provide key information in understanding and reconstructing the original environment of deposition (Table 2). For example, Barlow et al. (2016) determined the relative water depth of different fossilised stromatolites from 2.4 Ga and was able to reconstruct the position of these different morphologies within the carbon-ate reef system, which allowed analysis of transgression and regression cycles. In a similar way, stromatolitic speleothems preserve a neat record of the paleoclimatic conditions during formation. Cox et al. (1989b) dated a piece of cyanobacteri-ally-covered flowstone from Nettle Cave at over 20,000 years old, and estimated some of the larger structures to be at least 100,000 years old. Studying layer thickness and variability, as well as carbon and oxygen isotope data of stromatolitic speleothems such as these can reveal terrestrial paleoclimate information such as temperature, pH, rainfall and changes in overlying vegetation (Blyth et al. 2016; Wong & Breecker 2015).

4. Promoting Education

Since first use of the term stromatolite more than a century ago (Kalkowsky 1908), much research has gone into the dif-ferent environments stromatolites inhibit and the array of microbes associated with each, resulting in an understand-ing of their importance in being able to unravel information about the past. In order to manage and protect the stromatolites at Nettle Cave, this needs to be communicated effectively to both the guides and visitors to the cave. The aim is to com-municate scientific knowledge in an engaging way through a mutli-layered approach, using different media. This would include:

Table 2. Environmental and depositional information available from studying stromatolites:

Type of environment (lagoon, carbonate reef, lake, etc.)
Tide direction and subsequent shoreline
Approximate water depth
Location within the carbonate platform system (intertidal, subtidal, etc.)
Compositional information of water
Relative stability of environment (thickness of units)
Other environmental influences on stromatolite shape: relative tide/current strength, presence of storms, changes in amount of sediment input, changes in water depth.
By compiling information about stromatolites, inferences can be made about the changing and potentially increasing diversity over time, both in the form of morphology and microbial make-up.

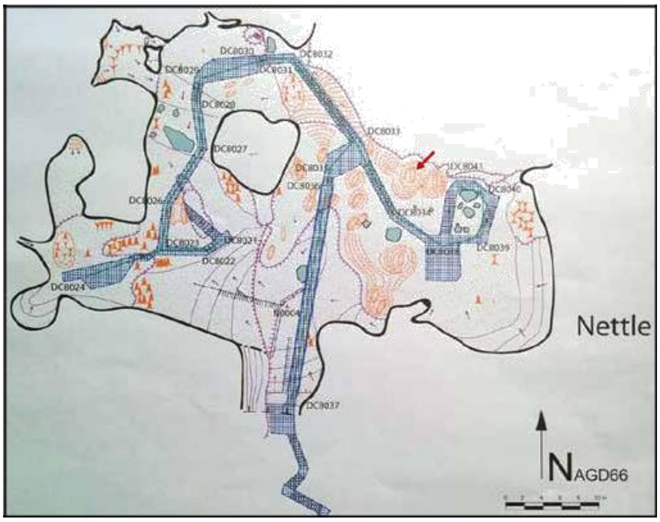


Figure 3. Nettle Cave map (© Jenolan Survey project, 2014), with stromatolitic speleothems shown by the elongated, segmented ovals in the central right-hand side of the cave (e.g. arrow).

1. Updating some of the content of the mobile application, linking stromatolites with evidence of early life in the Archean, whilst keeping it easy to understand.
2. A poster board displayed in front of the most prominent stromatolite, where the current temporary sign is now (Fig. 2B), with more detailed information than is currently there. Proposed size would be A2 and it would cover: how stromatolites grow; that these particular stromatolites are at least 20,000 years old and by studying the layers, scientists can get information on past climates; stromatolites more commonly grow in shallow marine environments (e.g. Shark Bay, WA), which is why these cave examples are so special; the oldest evidence of life on Earth are fossilised stromatolites (from at least 3.5 Ga). The board would refer visitors who want more information to a pamphlet avail-able at the Guides' Office.
3. A pamphlet, with further details on the above information including more diagrams and pictures, would be made available at the Guides' Office. This could be in the form of a folded, double-sided A4 sheet of paper, for ease of reproducibility. The pamphlet would direct those seeking even more information to the Jenolan Caves website.
4. Updating the stromatolitic speleothem page on the Jenolan Caves website, with extra information made available through links to articles and journal papers on stromatolites, both modern and fossilised. Using this method means it would be easy to update and add to the page as new research is reported, keeping the information current.

Using this multi-layered approach, where each of these media would contain slightly more information than the last, means visitors to Nettle Cave can gain as much, or as little, information as they would like about the stromatolites, allowing them to easily investigate further if they wish. Furthermore, the pamphlet and website would be a good resource for the guides to use, and to direct people towards more information. Most importantly, the proposed approach will have minimal impact on Nettle Cave and the stromatolites.

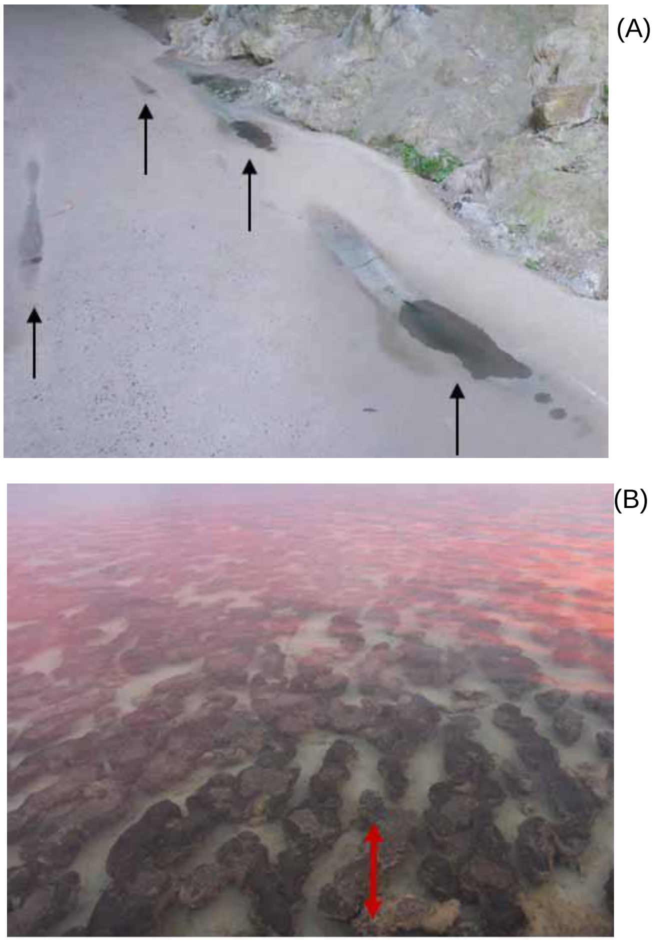


Figure 4. (A) New stromatolitic speleothems growing on the concrete walkway in Devils Coach House, Jenolan, highlighting the effect of wind on stromatolite form (arrows). (B) Submerged, shallow-water stromatolites in Shark Bay, Western Australia, showing elongation with tide direction (arrow).

5. Summary

It is extraordinary that the stromatolite form has persisted for at least the last 3,500 million years, across a range of different environments. To accurately encompass this range, and include both modern and fossilised stromatolite examples, an updated and more widely accepted definition is now used: "Stromatolites are... layered, early lithified, authigenic microbial structures… that develop at the sediment water interface in freshwater, marine and evaporitic environments" Riding (2011). The stromatolitic speleothems in Nettle Cave are an uncommon but important example, as they preserve a consistent paleoclimatic record from the last 20,000, and possibly up to 100,000 years (Cox et al. 1989b). The introduction of the self-guided tour and installation of floating walkways has allowed visitors to view the stromatolites and surrounding cave with minimal impact, whereas previously, they could walk right up to and around the speleothems. It is proposed the value and importance of stromatolites be further conveyed in a series of engaging and multi-layered media for the public, including a poster board, pamphlet and updated webpage, to go alongside the existing mobile application.

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