Helictite, (2011) **40**(2): 51-54

Sand structures cemented by focussed flow in dune limestone, Western Australia

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Abstract

Pendants, pillars and concretions of cemented sand are exposed in a dune limestone cave in southwest Western Australia. These are the result of focussed flow of carbonate-saturated water through the sand in a very early stage of eogenetic diagenesis. Vertical vadose fingered flow has cemented the pillars and pendants, and horizontal phreatic flow has produced a layer of elongated concretions along a bedding plane. Later cave development has exposed the cemented sand bodies.

Keywords: syngenetic karst, eogenetic diagenesis, concretions, speleogens, sand speleothems, fingered flow, dune calcarenite, Australia.

Introduction

This short note draws attention to cemented sand features in a calcarenite cave, which have significance in the broader study of focussed flow through sandy sediments.

Witchcliffe Cave (6MR-1), in the Margaret River area of southwest Western Australia, occurs at the inland edge of a belt of coastal dune calcarenite, close to the steep-dipping contact with the underlying impermeable granite (Hall & Marnham, 2002). Dunes in a similar setting 40 km to the south are at least 600 ka old, based on speleothem dating in caves (Eberhard, 2004).

This is an area of syngenetic karst, where the karst and cave formation has occurred simultaneously with the calcareous dune sands being cemented into limestone (Bastian, 1964; Grimes, 2006; Webb & Grimes, 2009).

Boodjidup Brook cuts a narrow, 80 m deep, valley through the dunefield to the sea. The cave entrance is in a vertical cliff in the side of the valley and about 25 m above the valley floor, which suggests that it predates the present valley. The cave is a single broad chamber with a gently undulating ceiling 1-2 m high above a flat sandy floor (Figure 1 and see detailed map in Webb & Grimes, 2009). A large stalagmitic mound outside the cave indicates that there has been some cliff retreat since the cave formed. A spring emerges from rubble at the cliff base, about 5 metres beneath the cave floor. This might be at the contact with the underlying granitic basement, but there is no outcrop to confirm that.

The cliff exposure shows that the ceiling of the cave is at a stratigraphic break between an upper unit of flat, thin-bedded and moderately-hard calcarenite and an underlying unit of softer, more cavernous and less well-bedded calcarenite. This boundary possibly represents

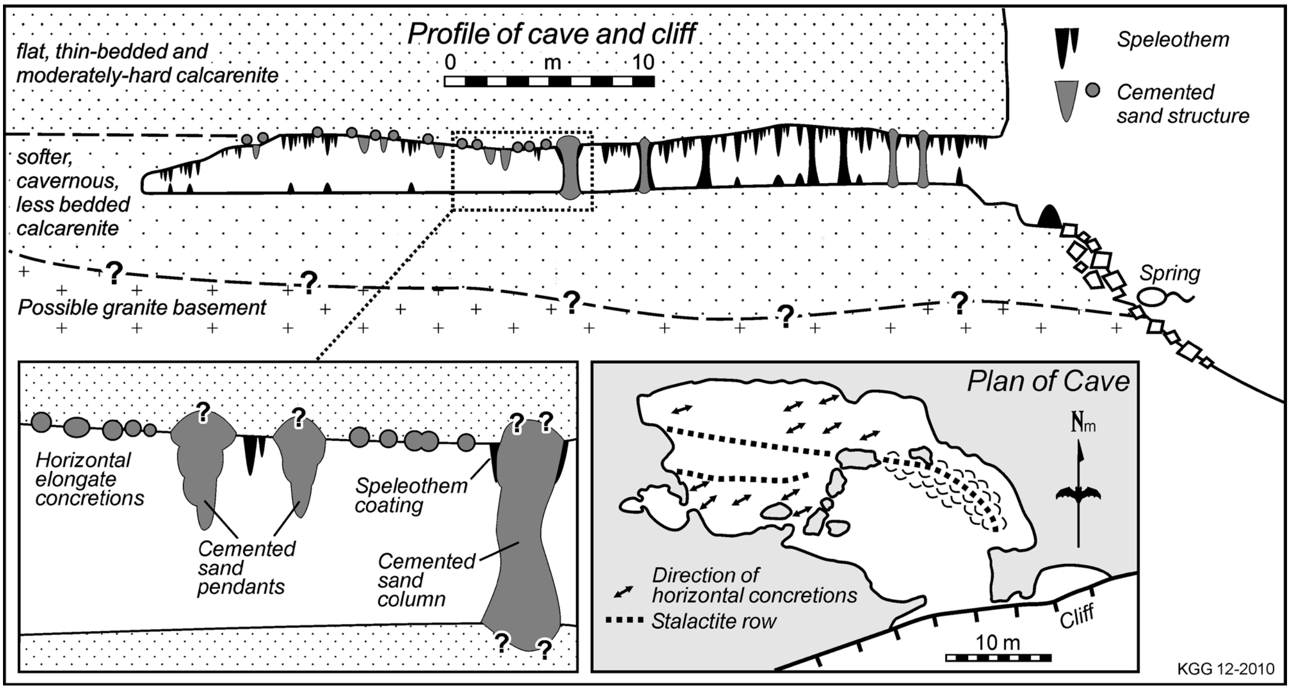

Figure 1: Diagrammatic cross-section of the cave and content. Based on a map by B. Loveday, 1986

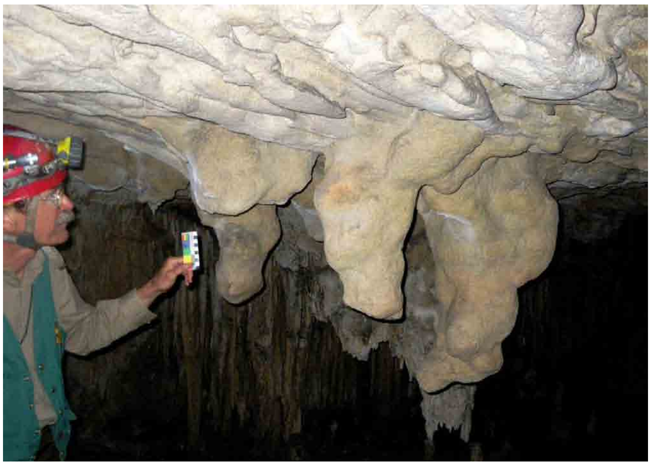

Figure 2: Elongated horizontal concretions in the ceiling and several small sand pendants. Photo by Jay Anderson.

a short time break between two dune units, but there is no obvious soil or calcrete hardpan formation that might indicate an extensive period of exposure before the upper unit buried the lower one.

The cemented structures

Two types of cemented-sand structures occur in the cave, but neither were seen in the cliff face outside, so we cannot tell how far they extend above or below the cave level. They are formed within the dune limestone and appear to be a result of focussed cementation that preceded cave development. Solution and erosion of the less-cemented dune sand to form the cave has left these harder structures protruding onto it.

Horizontally elongate sand concretions

Elongate concretions are exposed in a single sub-horizontal layer in the ceiling of the rear section of the cave. They are not seen in the entrance area, but the high density of speleothems there may be concealing them.

The concretions are hard, white to pale grey (lighter than the surrounding less cemented dune sand), horizontal elongated cylinders tapered at each end – from 5 to 30 cm wide and up to 2 metres long. The smaller ones are reminiscent of French loaves or bread-sticks, but with a greater variety of shapes, and some have coalesced into composite structures (Figure 2). The concretions are aligned parallel to each other with a direction that is consistent across the chamber with a magnetic bearing between 050° and 072° (average 063° from 11 measurements, Figure 1). This direction is roughly parallel to the cliff face and perpendicular to the edge of the dunefield. It differs from the direction of two prominent (joint-controlled) lines of stalactites that strike 095° and 102°. The broad flat ceiling of the cave may be a consequence of the presence of this layer of partly-cemented sand.

Ceiling pendants and vertical pillars of cemented sand

These are also of cemented dune sand, but differ from the concretions in being softer and the same colour as the surrounding pale brown dune sand. The original shallow dune bedding is visible in places within them, so they are not the cemented fill of a solution pipe. However, there are no broken examples, so one cannot see whether they have a central pipe. They are rather lumpy structures hanging from the ceiling, 15 to 60 cm in diameter and up to 2 m long with the longest ones reaching the floor to make pillars (Figures 1, 2 & 3). They are best developed in the rear section of the cave but a few also occur in the entrance area. Some pendants are partly coated with white speleothem material and it is possible that thick bulbous stalactites seen near the entrance might have a core of cemented sand hidden behind an outer layer of speleothem. Some pendants show a case-hardening effect – possibly from surface cementation associated with the later speleothem coatings.

Figure 3: Columns and pendants of cemented dune sand. Pale areas are a secondary speleothem coating.

At the ceiling the pendants and concretions co-exist, but it is not possible to judge which formed first.

Discussion

Williamson (1980) briefly described these features, but interpreted them as due to erosion by a strong phreatic stream flow. Both types are interpreted here as the result of localised cementation of the dune sand by carbonate-saturated waters, followed by exposure in the cave by the erosion of the surrounding, softer, less-cemented sand. Strictly speaking, they are neither "speleogens" nor "speleothems" but a hybrid of the two with localised precipitation followed by erosion.

The horizontal elongate bodies appear to be typical concretions such as occur in many sandstones, including calcarenites (e.g. McCullough, 2003). These grow by cementation within the pores between the sand grains. If elongated the orientation of a concretion may indicate a structural control (e.g. by a porous bed) or the direction of water flow. In the case of the concretions in Witchcliffe Cave both factors may be involved. They are found in a horizontal layer that may be a porous bed or a bedding plane, but are also elongated into rods with a consistent direction which might indicate a past, horizontal, flow of water, probably at or beneath the old watertable. The rods are symmetrical and oriented 063-243°, which is sub-parallel to the cliff and valley direction (Figure 1) so are probably not related to the modern drainage towards the valley, but rather to an earlier flow direction, westward towards an old coastline, that occurred before the present valley formed. An eastward flow is much less likely because of the ridge of impermeable granite in that direction. McCullough (2003) made a similar deduction for elongate concretions in dune limestones in Victoria. The gently-inclined "sand stalactites" described by Diller (1899) may be similar.

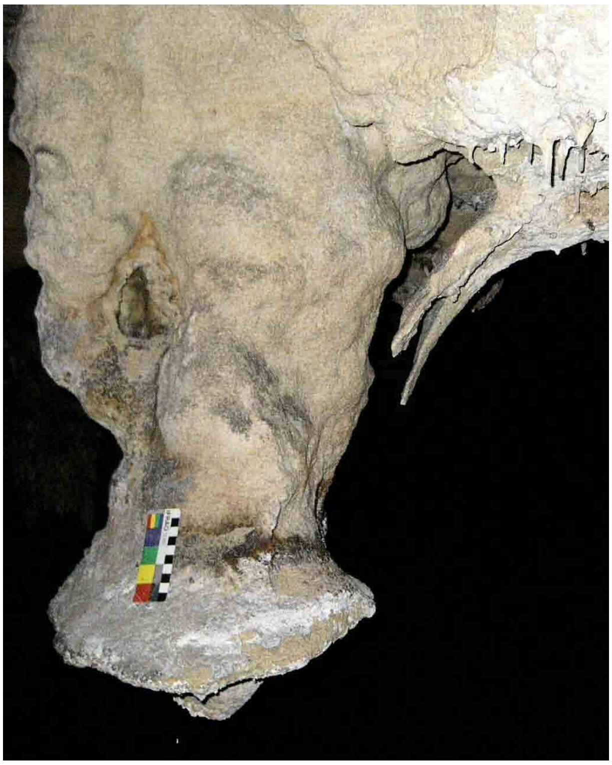

Figure 4: Sand pendant with speleothem coating on right, now partly separated by later weathering.

The vertical pendants and pillars are similar to concretions but bigger and suggest a focussed vertical, vadose, flow. There are strong analogies with the "sand speleothems" of Loch Ard Gorge in Victoria (Grimes, 1998), although those formed in a beach sand that had filled a pre-existing cave. One can also compare the pillars to the larger Nambung Pinnacles (McNamara, 1995; Lipar, 2009; Grimes, 2009), and there are analogies with the pendants, pillars and pinnacles seen in laterite and sandstone karsts (Grimes & Spate, 2008; Aubrecht, et al., 2008, plates 1 & 2).

There is an extensive literature on "fingered flow" in sandy soils (e.g. Dekker & Ritsema, 1994; de Rooij, 2000). After rain, downward vadose flow through dry porous sand tends to focus spontaneously into fingers of wet sand surrounded by dry sand. It is easier for water to flow through sand that is already wet, than to enter dry sand. The downward flow can also be focussed by other factors such as stem flow from overlying trees, down tap roots or by variations in the permeability of the caprock (Grimes, 2009).

Where the focussed vertical flow is saturated, localised cementation occurs, as here. Where it is under-saturated, solution pipes can form, as seen elsewhere in the region. Solution pipes are, in fact, the more common result (Grimes, 2009).

Timing of the events

The location of the cave 25 m up the side of the valley suggests that it predates at least the final stage of valley incision. The horizontal concretions would have been cemented before the present valley was cut, as their orientation does not suggest a water flow towards that. Both of the processes of localised cementation (horizontal and vertical) would have occurred before the cave formed. However, the relative timing of the two types of cemented feature is difficult to deduce. Although the two forms co-exist it is not possible to decide whether the concretions were later forms penetrating the pendants or whether the pendents were a later cementation that surrounded the concretions. However, it has been deduced above that the horizontal concretions formed in phreatic conditions, and that the pendants and pillars were cemented by vertical vadose flow.

It is possible that as the dunes stacked up against the granite slope the local water table may have risen in accord with the surface, so that within each individual dune unit there would have been an initial vadose stage, followed by a phreatic stage as more dunes were stacked above it, and then, considerably later, a return to vadose conditions as the valley was cut and the local watertable dropped. Changes in sea level would have had little influence as the granitic basement would have provided a local base-level. The cave would have formed near the top of the watertable, possibly as the watertable was dropping; so, given that both types of cemented structure predate cave formation, it seems likely that the cementation of the pillars and pendants by vertical vadose flow of saturated water came first and at a very early stage in diagenesis and syngenetic karst development.

We know that caprocks and solution pipes occur quite early in syngenetic karst (Bastian, 1964; Grimes, 2006), it seems that vertically focussed cementation can also occur then.

Acknowledgements

Thanks to Matej Lipar and Susan White for discussions of fingered flow and comments on the draft. Anne Wood, of the Department of Environment and Conservation, arranged access to the cave.

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