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Physical evidence for past cold-climate events at Wombeyan Caves, NSW: Broken speleothems and other relict features within Fig Tree Cave and Victoria Arch

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Unless otherwise stated, all photographs and graphics are by the author.

Abstract

A preliminary study of broken speleothems and speleogens in Fig Tree Cave, Wombeyan Caves, NSW, suggests that a combination of cave geometry, chimney effect and past climatic conditions caused ice build-up in the cave during past ice ages. As temperatures fluctuated around freeze and thaw, stresses from ice expansion broke large speleothems and fractured bedrock in flakes. This empirical approach is supported by physical calculations of stress on a measured stalactite and extrapolated estimates of cave temperatures during the last glacial maximum. Additional support for the argument is based on the appearance of possible cold-temperature speleothems and bedrock grooves.

Introduction to the concept of permanent ice in karst caves

Limestone caves in Australia do not currently contain permanent ice, although seasonal ice may be present temporarily near entrances of caves in areas subject to snowfall. Some Australian caves, however, exhibit features such as naturally broken speleothems and bedrock, similar to those which occur in European caves containing permanent ice. The purpose of this preliminary study is to present observations and evaluate physical evidence supporting the idea that in the past, perennial bodies of ice existed within some Australian caves. The work also looks at unusual speleothem shapes, cave geometry and considers the effect of the past climate.

Kempe (2004) examined several famous large broken speleothems in the Postojna caves of Slovenia, and concluded that they had been broken by ice. He suggested that the ice came from more extensive regional glaciation during the Pleistocene than is generally accepted. A model was shown for one speleothem's breakage based on calculated ice expansion and contraction, and suggested a block-slide of ice was responsible for some other breakages, although the forces were not calculated.

Permanent ice is a feature of some of the world's limestone caves due to their cooler average annual temperature. This is caused by their geometry, higher latitude and in some cases higher altitude. Cave geometry is an important factor, allowing the pooling of cold, dense air in winter and preventing cool air from draining out of the cave in summer. This chimney effect creates cold traps containing ice in some caves (Gabrovšek 2023). Prevailing winds can also alter air movement in caves (Kukuljan and others 2021). In Europe, for example, dolines can fill with snow in winter and thaw in spring. Rainwater then percolates through cracks in the limestone. When groundwater encounters a much colder cave environment such as a cold trap, it can freeze to form icicles and other ice deposits such as flowstone and columns (for example, Figure 1) and can slowly move downwards in channels, enlarging holes and plucking loose stones which can act as an abrasive. By late summer, when warmer air has penetrated part of the cave, some of these deposits thaw, flow further into the cave and can re-freeze (see Hill and Forti 1997, pp. 123-124, 127-130).

Figure 1. Ice in Demänovská Ice Cave, a limestone showcave in Slovakia, July 2013. (Photographed during the 16th ICS post-conference trip.)

Ice showcaves of Slovakia have been instrumented and, for example, in Dobšinská Cave, solid ice flows slowly downwards like a small glacier at 2-4 cm per year (Zelinka 2008, p. 91).

Cryogenic Cave Carbonates (CCC) are common in limestone caves containing ice, with CCC precipitating as a grit on the surface of freezing limy cave water from the outgassing of CO2. The CCC is comprised of two different calcites, formed under different conditions. The main differences between the two are in morphology (fine versus coarse grain sizes) and stable isotope ratios, with the fine ones precipitating when a thin film of water freezes on existing ice in a cave, and the coarser ones precipitating as cave dripwater from thawing permafrost above the cave (Munroe and others 2021). The presence of these deposits is considered to be an important proxy for past cold temperatures in caves (Munroe and others 2021).

The force exerted by water expanding as it freezes to ice at atmospheric pressure is well known in physical chemistry. In limestone caves containing ice, broken stalagmites are sometimes found and it used to be thought that the breakage was from the flow of ice, or possibly earthquakes, but when stalagmites of various sizes and ice geometries were numerically modelled for ice deformation under gravity, a simple ice flow down a slope and past a stalagmite can only generate 0.05 MPa shear stress, which is considerably less than the 2 to 7 MPa shear stress needed to break stalagmites of the diameter seen in the field, and earthquake breakage leaves characteristic tectonic features in caves, not seen in the study site (Spötl and others 2023).

The same team noted that since the study site also had cryogenic cave carbonates, thermal expansion and contraction of ice was thought to cause the stalagmite breakages, so a different numeric model was run taking thermal expansion into account, using a stalagmite with a breaking strength of 4.3 MPa, various physical geometries and thermal ranges. This showed that the net force on a stalagmite embedded in ice undergoing thermal expansion near its freezing point is primarily upward; that is, a stalagmite embedded in expanding ice is subject to considerable stress from the differential thermal expansion characteristics of calcite and ice, sufficient to lift the stalagmite off its base with a very small displacement (Spötl and others 2023).

A speleothem type, called “cryogenic ridges”, is formed by calcite stalactites undergoing cold conditions in which dripwater freezes, forming pronounced ridges on their surfaces, with a fine channel along the ridge (Onac and others 2023), and isotopic analysis indicated the calcite near the ridges formed at much lower temperatures compared with the calcite forming the bulk of the speleothem.

In a detailed study of Kents Cavern, Devon, United Kingdom, Lundberg and McFarlane (2012) showed that calcite flowstone had been broken by episodes of frost heaving during Pleistocene glacial periods, even though the sites were periglacial and not subject to actual glaciation. Calculations showed that the breakage was caused by cold conditions over periods of time, enhanced by passage geometry, air movement and multiple entrances on different levels causing parts of the cave to exhibit extensive cooling. Wet sediment under flowstone heaved as it froze, causing the overlying flowstone to crack.

Geological and geomorphological setting of Wombeyan Caves

Wombeyan Caves is located in the southern highlands of New South Wales at an altitude of about 600-650 m asl. The area (see map, Figure 2) is drained by Mares Forest Creek and Wombeyan Creek which are part of the Hawkesbury/Nepean catchment. The caves are developed in Silurian limestone which has been significantly marmorised (metamorphosed) to a creamy saccharoidal marble by Devonian granite intrusions and volcaniclastics (Thomas & Pogson 2012). Marble used to be quarried from the area. Showcaves are located in the eastern part of the marble, around the steephead of Wombeyan Creek as it passes through Victoria Arch. Other caves are found throughout the area. The underground drainage is complex. Wombeyan Creek occasionally floods, re-arranging alluvium in flats upstream of Victoria Arch, resembling a small polje. Downstream of the Arch, Wombeyan Creek is often dry and runs in a small gorge south to Mares Forest Creek.

Wombeyan climate today

The temperature regime for Wombeyan Caves is similar to that of Taralga. Wombeyan is a little lower in altitude, but lies in a frost hollow. Taralga Post Office, station 70080 (Bureau of Meteorology) lies at 845 m AMSL and the mean maximum and minimum temperatures are 26.2 and

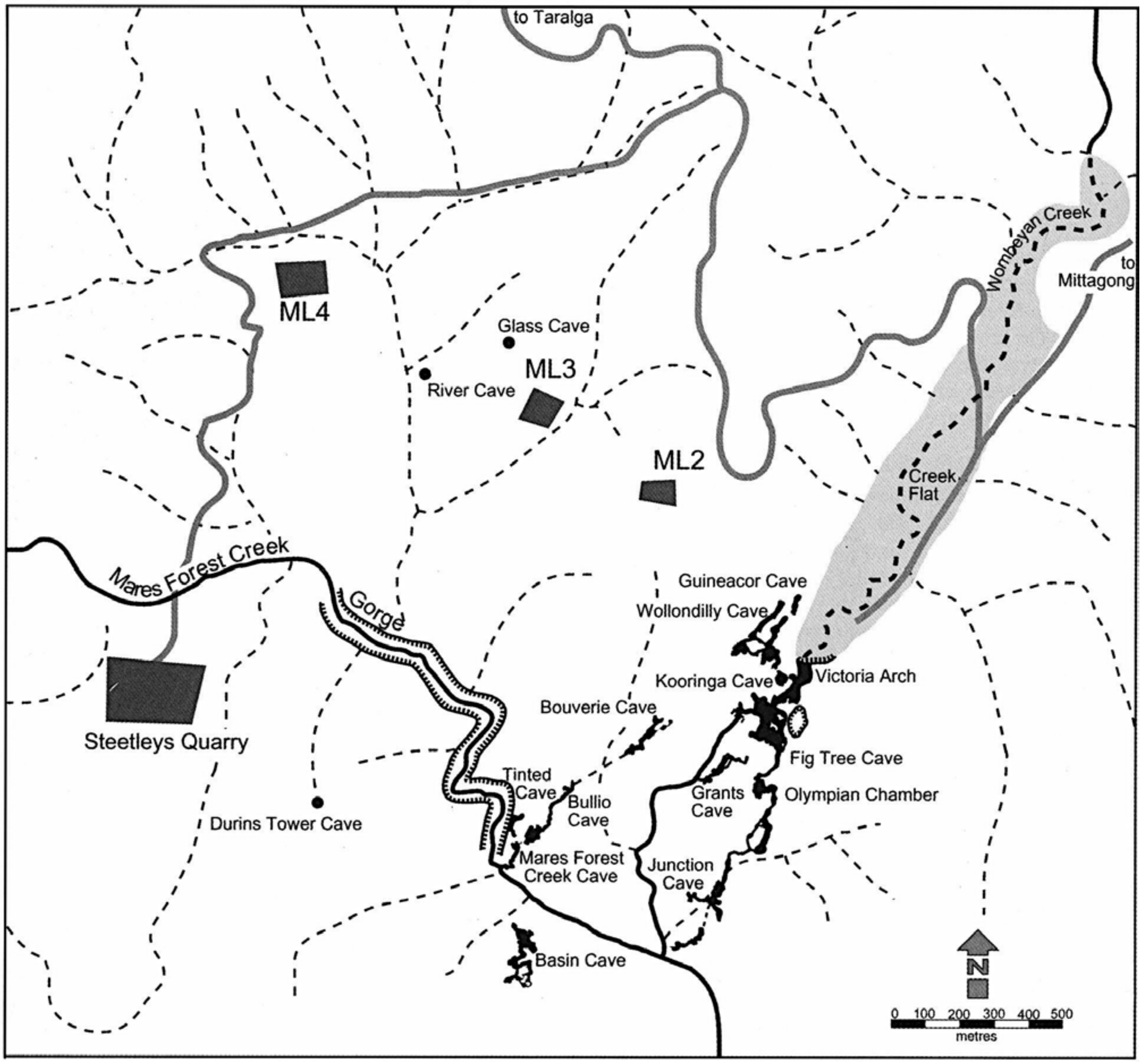

Figure 2. General map of the Wombeyan Caves area, reproduced from James and others (2004), p. 36.

0.7°C respectively, with July the coldest month. The lowest recorded is -3°C in 1982. Wombeyan Caves camping ground lies at 600 m AMSL, roughly the same for the lower part of Victoria Arch and Wombeyan Creek flowing through it. Anecdotally, cavers have reported temperatures as low as -7°C outside the caves office. Although the cave temperatures are typically the average annual temperature, the temperature ranges within some caves can vary, as there are multi-entranced caves, heat domes and cold traps. The caves at Wombeyan respond to changes in the weather, based on their geometry, and some caves have airflow reversals which alter the humidity in the caves (Halbert & Michie 1982). Experiments at Bullio Cave, for example, showed a variation of around 5 degrees Celsius in temperatures across parts of the cave in winter, and slightly less variation in summer. There has not been much work done recording the temperature variability in Fig Tree Cave, although the thermal variations are well known by both cave guides and cave surveyors.

Previous work at Wombeyan Caves

Platey exfoliation of the marble occurs in a phreatic tube near the exit gate of the Fig Tree Cave, and a similar large flake in Creek Cave (James and others 2004, pp. 135-136) which is part of the Fig Tree system. The exfoliation is similar to that caused by water getting into cracks and freezing, but it was not thought that the cave could get cold enough, based on current average annual temperatures. Several ideas were put forward to explain the exfoliation but dismissed, e.g. salt wedging, gypsum crystals, tectonics, plants. It was noted that on the Nullarbor, salt wedging tends to obliterate the soft bedrock rather than causing platey exfoliation. Wombeyan marble is more competent, but no salt has been observed at Wombeyan. Further work on the topic was recommended (James and others 1982).

Hockey Gully at Wombeyan Caves contains periglacial deposits comprising angular rock fragments from fine gravel to cobble size in roughly downslope beds of various sizes and with various amounts of fine grained material between the fragments. This was dated to 19 ka using radiocarbon dating of wood (Jennings and others 1982, pp. 62-63).

Toppled and then re-grown speleothems were noted in Fig Tree, Wollondilly and Kooringa Caves, and it has been suggested that straw stalactites growing from the stub of the large fallen stalactite near the platform at the northern end of the Colonnades could be a few hundred years old, based on their length, but the cause of the original break was unknown (Sefton & Sefton 1982; James and others 2004). Condensation corrosion occurs at Wombeyan Caves when a thin film of water condenses onto a calcite surface due to moist air encountering a cooler surface, and CO_2 from the air dissolved in the water makes the water aggressive to calcite (James and others 2004, p. 42).

Gillieson and others (1985) examined a solifluction deposit in Basin Cave at Wombeyan Caves. The material, found in the cave's lower entrance, comprised angular gravel of elongated platey to blocky clasts of Wombeyan marble with charcoal layers. This was carbon-dated to 27.8 ka. They concluded that since the processes which caused this and other solifluction deposits in the area were no longer occurring, that more extreme winter climates occurred at Wombeyan during the last glacial.

McDonald & Drysdale (2004) measured temperatures and groundwater drips in Wollondilly and Kooringa caves at Wombeyan. Two naturally-broken stalagmites from the Mulwaree Extension were analysed using U/Th techniques, suggesting that one of the stalagmites grew from 133 ka to 83 ka, and the other began growing at 79 ka, although the Wombeyan speleothems are particularly poor in uranium.

Wombeyan marble is well-known from an architectural perspective (e.g. its use in the floor of the Mitchell Library, Sydney) for both its creamy colour and unusually large calcite grain size. Various workers have modelled and analysed the strength of Wombeyan marble in a laboratory and found its strength varied depending on how it was confined and any imperfections in the piece. In low confinement, marble samples failed at 3.5 MPa, compared with 100 MPa in high confinement (Bahrani and others 2011). Other workers found unconfined samples failing below 35 MPa by spalling or shearing, with low-end failures at 0.1, 3.5, 10 and 14 MPa, but in high confinement, 70 and 100 MPa, it has ductile behaviour and microfractures can be associated with acoustic emission long before peak stress is reached (Hueckel 2016, pp. 11-12).

Low-altitude periglacial scree slopes occur in several sites around NSW, including the volcaniclastics at Hockey Gully, Wombeyan Caves at 650 m (Barrows and others 2021). During the mid-Pleistocene, winter temperatures could be on average some 8 degrees Celsius colder than at present and there was a lack of trees during this time, which increased erosion; rivers were larger, with high sediment loads. Techniques used with the Wombeyan site included radiocarbon (24 ka) and stratigraphic logs (Barrows and others 2021). In a study of relict periglacial block deposits of the New England area, it was suggested that mean annual temperatures during the last glacial cycle were on average more than 8 degrees Celsius colder than today (Slee and others 2023).

Members of Sydney University Speleological Society (SUSS) have surveyed and mapped Fig Tree Cave and Victoria Arch. The map (see Figure 3) has been drawn up by the author using "Therion" software, and a model prepared and viewed using "loch" software (see Figure 4). This paper arose during the author's project to describe the cave, as some speleological problems emerged regarding the past climate.

Study sites and methods

The study sites for this project are Fig Tree Cave and Victoria Arch. These sites were chosen as they are relatively easy to access for repeat visits, they are large showcaves and contain features which are difficult to derive using conventional karst solution and deposition.

As this project is at a preliminary stage, the methods involved physical measurements using a Leica Disto A4, a steel tape and a Suunto Twin

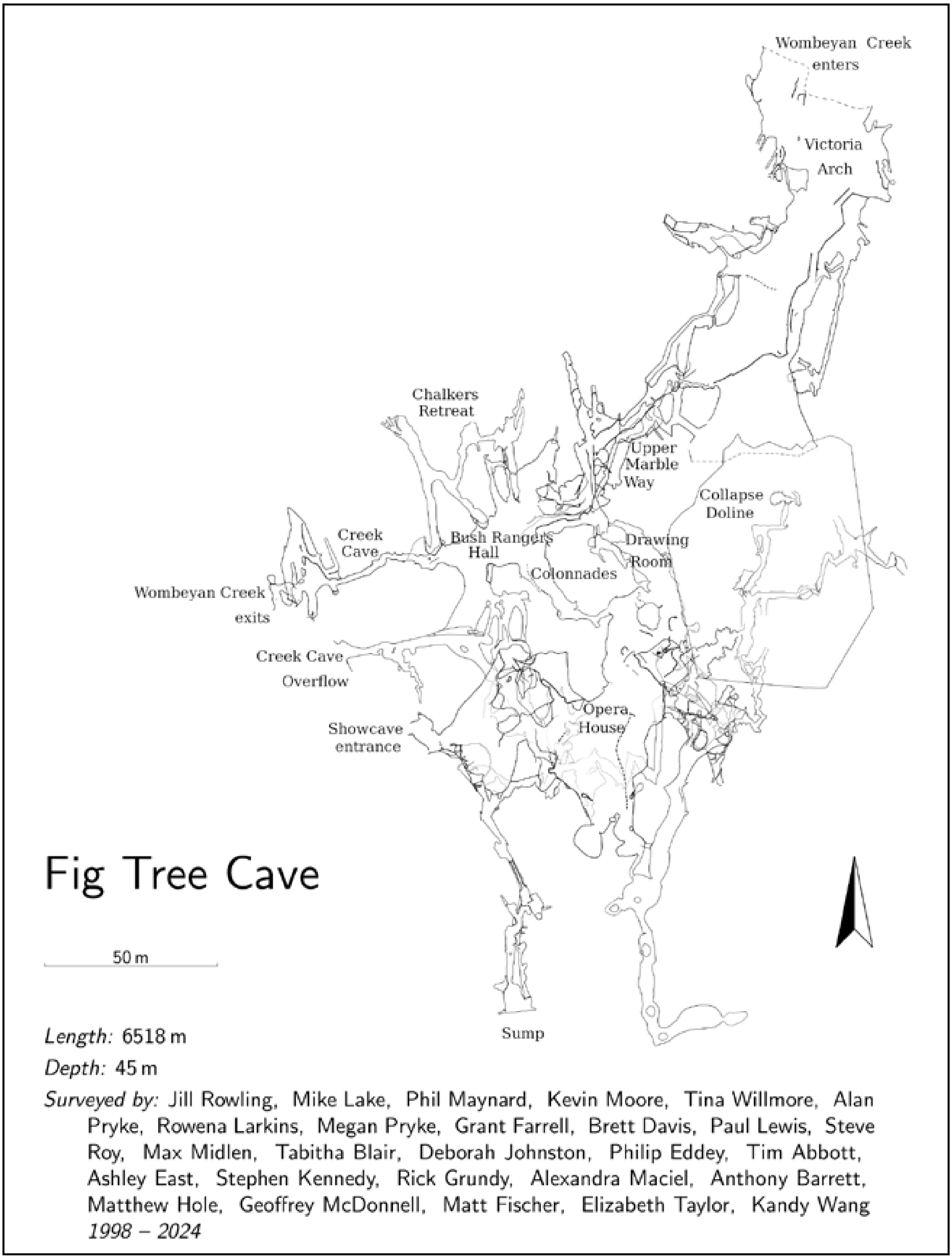

Figure 3. Plan of Fig Tree Cave (simplified). 50 m scalebar.

(for levels), and photographs using a Canon EOS digital camera with a hand-held LED lamp. No sampling was done for this stage of the project. The author took the photographs and physical measurements, often assisted by members of SUSS. Disto measurements were to 4 decimal places but when aimed at irregular shaped speleothems were downgraded to +/- 1 cm; tape measurements were +/- 5 mm but similarly downgraded to +/- 1 cm; inclinations are +/- 0.5 degrees from horizontal.

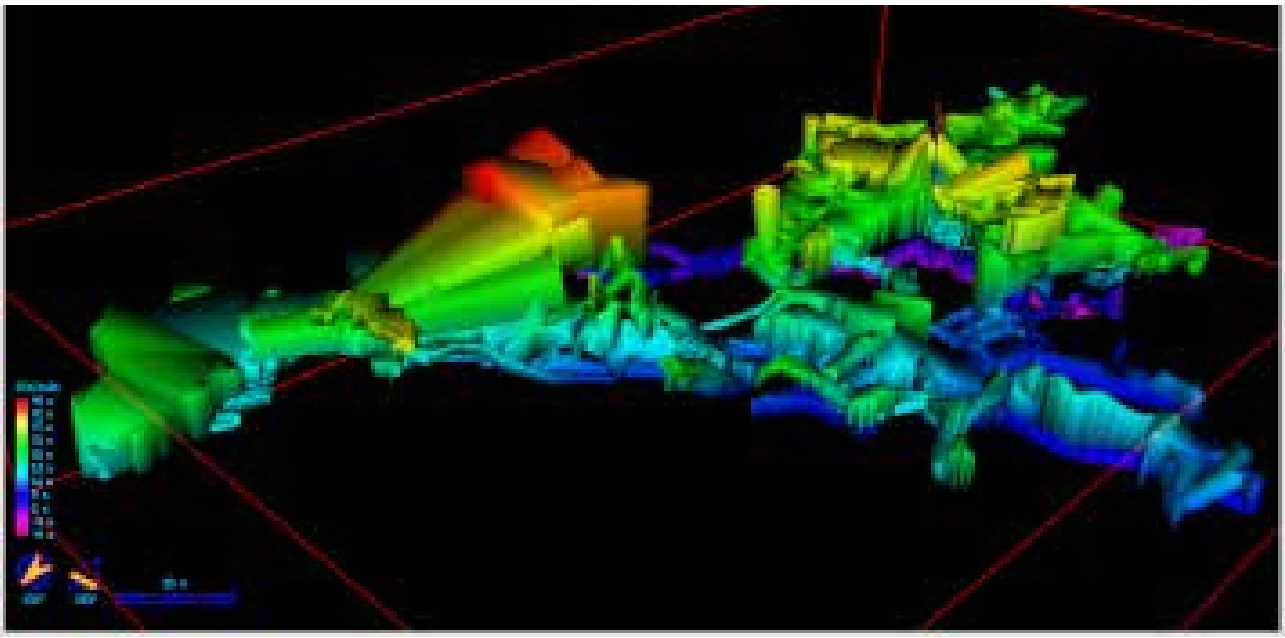

Figure 4. 3D model oblique view to the south-east of Fig Tree Cave and Victoria Arch. Scalebar is 25 m. Coloured by height. Speleothem breakages are mostly in the area shaded light blue-green, about 20 m above the level of the sumps (shaded purple).

Broken speleothems were viewed and noted, whether they were considered old breakages (typically embedded in flowstone) or whether the breakage could have been anthropogenic. Wall notches of various sorts were viewed for scallops or other patterns such as striations. Sediments such as cobbles were checked for roundness. Also the general shape of a passage was considered for the type of erosion it had apparently experienced. In particular, cold-climate effects were considered in cases where a site had a combination of features in one area such as spoon-shaped wall hollows, broken speleothems or speleogens in a line, small ridges on speleothems with a fine line running along them, striations and grooves in the wall. Some speleothem settings, dimensions and geometry were measured, with particular attention given to the large broken stalactite at the platform near the junction of three passages: Upper Marble Way, Colonnades and Bush Rangers Hall. The methods of Spötl and others (2023) were considered as a general guide to modelling the likely forces produced by ice on a stalagmite. These concepts were extended to include other geometries and settings such as the theoretical forces required to break a large speleothem (canopy).

Brief description and nomenclature of Fig Tree Cave and Victoria Arch

Referring to the map (Figure 3) and 3D model (Figure 4), Fig Tree Cave is a large, self-guided showcave, and was opened as a guided cave a little after 1897. It has at least 5 entrances and connections to two other caves (Lots O Numbers Cave and Junction Cave). Victoria Arch is considered part of the cave and has been noted since at least 1828. It was likely well-known to the local Gundungurra Aboriginal people. Wombeyan Creek flows into the spacious northern entrance of Victoria Arch, down Marble Way and exits through Creek Cave at times of high flow. It also flows through a series of sumps, appearing in Junction Cave to the south. A large daylight hole in the south side of Victoria Arch, called the "collapse doline", has a steep scree slope comprising cave sediments and marble bedrock. This is in contrast to the volcaniclastic and granite cobbles in the bed of Wombeyan Creek below the scree slope. The Fig Tree showcave comprises several large well-decorated chambers and a high cantilever pathway above the canyon of Marble Way to Victoria Arch. The showcave entrance is on the western side of the cave, and opens out to a large chamber with pits in its southern and northern end which connect to the lower sumps and Creek Cave Overflow respectively. The Opera House is a large chamber in the middle of the cave with a relatively flat ceiling and large boulders on the floor. The Drawing Room is a steeply sloping chamber off the northeast of the Opera House, connecting to several other areas and lies below the western wall of the collapse doline. The Colonnades is a rift passage between the Opera House and Bush Rangers Hall, which is a large chamber in the northern part of the cave through which Wombeyan Creek flows. The northern end of the Colonnades has a platform overlooking Bush Rangers Hall and illuminating both halves of a calcite canopy called the “large broken stalactite”. Chalkers Retreat, in the northwest part of the cave, is an abandoned passage at the same level as the Colonnades but on the other side of Bush Rangers Hall. Creek Cave and Creek Cave Overflow are two streamway passages west of Bush Rangers Hall. Upper Marble Way is the north-east trending passage in the north part of cave and is a developed showcave track on a cantilever walkway above the underground part of Wombeyan Creek. Victoria Arch is the large daylit arch in the most north-eastern part of the cave.

Within Fig Tree Cave, sedimentary deposits range from conventional calcite speleothems to sediment fines with charcoal layers, bat guano deposits, red earth layers, rounded and angular gravels and other fluvial deposits including large cobbles similar to those seen outside in Wombeyan Creek. The cave has apparently experienced a range of climatic changes different from the present environment. Being a multi-entranced cave, it is common to find a range of temperatures across the cave, with the coolest parts usually being experienced around Marble Way, Creek Cave and Chalkers Retreat.

During the survey of Creek Cave, a near-vertical south-dipping fault was found by examining slickensides in the ceiling near the Creek Cave entrance. The general trend of Creek Cave follows the strike of this fault, roughly 80° from North, and it may correspond with the southern end of Victoria Arch, that is, the northern end of the collapse doline. Although bedding is mostly destroyed by marmorisation, apparent bedding in the cave dips about 45° to the north-west, striking roughly north-east as measured in Bush Rangers Hall, Drawing Room and Opera House.

Cave Observations

Observations are listed in order of a speleological visit to the cave, starting in the upper Fig Tree show-cave entrance, then the Opera House, the Drawing Room, Creek Cave, Chalkers Retreat, Upper Marble Way through to the exit in Victoria Arch. These observations concentrate on unusually broken speleothems and speleogens. Surface coatings are also noted such as apparent calcite “dribbles” (small sinuous forms resembling candle wax dribbles, discussed later) and possible cryogenic forms. Some of the cave has been modified as part of track development, so it is plausible that most of the toppling and breakage discussed here was from natural causes.

Near the top of the pit at the northern end of the Fig Tree Cave entrance chamber is a small stalagmite, apparently broken in half. In the middle of the Opera House, a long stalactite (possibly a cave shield) has broken off the ceiling and lies almost intact on the rockpile 15.5 m below, near the large stalagmites in the main part of the Opera House, yet not exactly under its apparent detachment point on the ceiling. The enormous boulders forming the central rockpile have not come from the ceiling, which is relatively smooth apart from a ceiling canyon. Instead, they may have either come from the walls or the collapse of an intermediate level early in the cave’s development. Toppled and broken speleothems and speleogens lie on a slope in the northern end of the Opera House below the Drawing Room.

The Drawing Room contains a small forest of columns and many broken stalagmites (e.g. Figure 5), with many of the broken bits lying nearby or cemented into the flowstone. The substrate is a rockpile, well-cemented by flowstone in its northern end. As the lower part had been used in the early days as a basic showcave, we ignored all the loose broken speleothem tips which had apparently been “tidied” into lower areas west of the mini-track. Apparently bent columns (for example, Figure 6) with multiple areas of regrowth resemble calcified tree roots, although no organic material was seen. Bent speleothems and tree roots are discussed later. Fine lines on a flowstone shelf and nearby speleothems also resemble plant roots but again no organic matter was seen.

Figure 5. Columns, broken and flat-topped stalagmites, Drawing Room.

Apparently bent stalactites and stalagmites occur in the area. Surfaces of speleothems here commonly feature “dribbles”. Regrowth has occurred on some broken stalagmites and on numerous columns. Typical breakage varies, but seems to have mainly

Figure 6. Apparently bent column, Drawing Room.

affected the smaller speleothems, although some larger ones have cracks. Cave welts are speleothems similar to cave shields, but have formed along a horizontal crack in a column, as per Hill and Forti (1997, p. 99). Nearly every column has a welt, which was thought to be due to movement (Figure 7), discussed later. The columns have a variable diameter, assumed to correspond with varying drip rates, with the length ratio of stalactite: stalagmite typically 3:1. Regrowth of some broken stalactites and stalagmites was around 8 cm, indicating considerable age. On the ceiling in the middle part of the chamber, fairly high on the east side, we noted one broken cave shield and on the other, lower (west side), cave shields were intact. A glittering cave shield has a fringe of stalactites and columns below it. On the fringe, the small columns are perfect but stalactite tips have been broken suggesting the force that broke them was insufficient to break the small columns and could have been rotational. Some of these are cemented to the flowstone substrate below the shield, not far from where they originated. It was unclear as to how they were broken.

The northern end of the chamber features a scalloped ceiling channel with apparent flow from the east (high side). Scallops are more intense in the ceiling, whereas lower down they are much broader (around 1 m across). Just below the ceiling scallops are faint shallow horizontal grooves, 20 – 30 cm long x 10 cm high, which appear to have worn smooth earlier scallops.

A thinner part of a pendulous marble speleogen at the upper north-eastern corner of a side passage is broken off, suggestive of some force having been applied to the corner. The broken-off piece can be seen embedded in flowstone on the passage floor and has not moved far horizontally (Figures 8, 9). Below the flowstone lies a deposit of sub-rounded gravel and cobbles, indicating that at an earlier time,

Figure 7. Column with welt and regrowth in the Drawing Room.

Figure 8. Part of broken speleogen embedded in flowstone, Drawing Room.

Figure 9. Area from where speleogen apparently fell, and scalloping, Drawing Room

a stream flowed through this part of the cave. Oddly, the side passage has little scalloping, yet it connects to an area of the scalloped passage right through the scallops. Opposite this passage is a similarly broken section of bedrock (Figure 10).

Figure 10. Wedged bedrock, Drawing Room.

The northern part of the Drawing Room is adjacent to, and slightly above the Stalactite Cluster of Upper Marble Way, described later. A short drop connects these two parts of the cave. Air flows freely between these chambers, and sometimes during a weather change, a fog will develop where cold air flows from Creek Cave / Marble Way through the Drawing Room and down to where it meets the warmer, more humid air of the Opera House.

When walking from the Opera House to the Colonnades through the narrow connecting passage, the most obvious difference is a change in atmospheric temperature. The Opera House is relatively warm and humid, whereas the Colonnades is often cold and draughty. Broken stalactites in the Colonnades could be from human activity although some are quite high up and could be due to other causes. Thickness of regrowth on some of the broken pieces suggests the breakage pre-dates showcave development. A group of three stalagmites near the north-eastern wall have “dribbles”; one has an apparent lean. Closer to the track are several stalagmites with flat tops which appear to have all broken at the same level (Figure 11).

Figure 11. Stalagmites broken at similar level, Colonnades.

The floor of Bush Rangers Hall is covered with cobbles and gravel deposited by Wombeyan Creek, but there are also some water-worn broken speleothems. Some of these have clearly toppled by undermining of the gravel on which they developed, but others appear to have fallen from the ceiling. On the western wall (the left-hand side of the viewing platform) is a relatively horizontal angular cut in the bedrock, which lines up with a crack in a column (Figure 12).

Figure 12. Crack in speleothem group, Colonnades; lines up with notch in wall of Bush Rangers Hall.

Very high up in the ceiling are broken canopies (Figure 13). One of these was measured as having broken about 5.9 metres below the ceiling, about 10.5 m above the platform. The lower part of the “large broken stalactite” is lit, showing its complex folds (Figures 14, 15). The dimensions of this speleothem are described below. The stub end of the remaining upper part has small active straws, 100 – 200 mm long (Figure 16). The actively depositing part of the canopy is its outer edge, and

Figure 13. Broken canopies, Colonnades, Bush Rangers Hall.

Figure 14. "Large Broken Stalactite", upper area, upstream side from Upper Marble Way.

Figure 15. "Large Broken Stalactite", lower area, upstream side from Upper Marble Way.

the straws are not very active. 4.1 m below the sheared end is a stalagmite boss in which a variety of broken speleothems are embedded – mainly shawl and stalactite tips. These broken pieces are assumed to originate from nearby broken-tipped speleothems, and a straw tip which is presumably from the sheared area above (Figure 17). The rest of the lower canopy near the wall appears quite firmly cemented, forming pillars, and only a couple of additional broken-tipped stalactites can be seen on the upstream side. Also upstream is a blade of bedrock with a damaged upper part.

Figure 16. Straw stalactites have regrown under the "Large Broken Stalactite", Bush Rangers Hall.

Figure 17. Broken speleothem tips embedded in stalagmite boss below the "Large Broken Stalactite", Bush Rangers Hall.

Detailed measurements of the large broken stalactite

The bottom points have broken from the large detached part of the “broken stalactite”. Its remaining tips face upstream and a collection of broken stalactite tips lie close to it in sediment near the drop to the creek, but it is unclear whether these were moved during showcave development or are in their natural position (Figure 18). They would add another 30 cm or so to the length which is 0.95 to 1.4 m long, depending on which broken tip is measured. Adding in the tips would mean the length of the detached part could be up to about 1.7 m - see Hb in Figure 19.

By surveying the “broken stalactite” from a nearby post, relative vertical positions were calculated for the top of the canopy and the base of the canopy using measured distance x sine (inclination). Thus the length of the upper remaining canopy, Ht, was calculated as 2.2 m. Adding in the length of the broken pieces, Hb, it is possible to estimate the original canopy height H: 2.2 + 1.7 = 3.9 m. So it has broken a little less than half-way along.

Figure 18. Detail, broken lower part of "Large Broken Stalactite", Bush Rangers Hall.

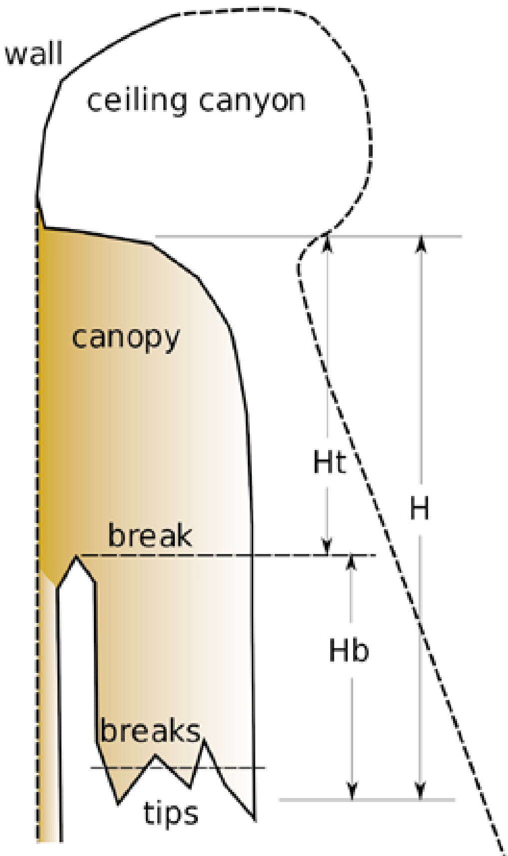

Figure 19. Sketch of the "Large Broken Stalactite" virtually reconstructed canopy near platform at Bush Rangers Hall with dimensions discussed; based on Figures 14 and 15.

The illuminated end of the detached part is roughly oval shaped (Figure 20) with oval diameters 1.8 x 1.1 m, and faces downstream. Ribbing is pronounced on one side. A photograph of the broken surface of the stalactite was used to estimate the percentage of calcite compared with gaps, by counting pixels in Gimp software and the face was estimated to be roughly 80 to 86% calcite by volume. Its calcite cross-sectional area, A, could be estimated as A = 0.8 x π x d1 x d2, about 5 m2. These values will be used later (see Discussion).

Figure 20. Oval shaped break, "Large Broken Stalactite", Bush Rangers Hall.

Continuing with the cave observations, the embankment on which the platform is developed contains the remains of other broken and toppled speleothems, some of which appear corroded by bat guano, but are no longer in position (Figure 21). Bats no longer roost in this area in significant numbers.

Figure 21. Tilted stalagmites, Bush Rangers Hall.

At the junction of Creek Cave and Creek Cave Overflow a bedrock outcrop has grooves in the otherwise scalloped marble, and some of the scallops have been flaked off (Figure 22). This is in a similar area to a large flake described by James and others (1982). The distance from the site to the nearest entrance of Creek Cave Overflow is about 50 m. Nearby, a couple of cave shields have come off the ceiling and the remains of one is in the gravel nearby. This area floods at times. However, judging by the patina on the remaining scallops, and grooves cutting through the scallops, it would seem that the scallops, then grooves and flake formation were due to earlier processes, and removal of the flakes was a more recent process. This area can get quite cold depending on the direction of the wind blowing in from the entrances. There is a short length of broken bench in this area that is difficult to see when buried

Figure 22. Bedrock with grooves, scallops and flakes, Creek Cave.

with flood debris. It may have been undermined in past floods.

In the western end of Chalkers Retreat is a broken and apparently bent speleothem with oval cross-section. Broken pieces lie nearby but since the area was subject to many historical visits, it could have been broken by people (but not bent). Nearby, high on a wall is a slightly bent "broomstick" stalagmite. A groove (or wall notch) in the lower part of the northern wall lines up with other grooves along the wall, suggesting something abraded the wall at a particular height (Figure 23). Some of the broken-topped stalagmites in this area have regrowth, although it is unclear whether the breakage was from people or not. Speleothem "dribbles" on the walls are a feature and are best viewed with side lighting. At first glance, they resemble veins or candle wax dribbles, but closer inspection shows that they appear to have been formed in fine layers. They generally lack conventional microgours, unlike the usual flowstone or shawls seen at Wombeyan Caves.

Figure 23. Wall notch, Chalkers Retreat.

Where the floor changes or there is a shelf, one sees a type of concrete-like coarse-grained flowstone which also lacks conventional microgours and appears to be associated with the "dribbles" and stalagmite breakage (Figure 24). Below a scalloped ceiling channel in the north-east area, grooves in the bedrock have apparently obliterated scallops in some areas but not others. One pendant appears almost cut through (Figure 25). We perceived a fairly large temperature difference between the humid eastern part and the cooler western part of Chalkers Retreat, which has a connection to the vertical Lots O Numbers Cave as well as the various other entrances of Fig Tree Cave.

Figure 24. Broken stalagmite stumps, concrete-like flowstone and dribbles, Chalkers Retreat.

Figure 25. Cut bedrock pendant, Chalkers Retreat.

Upper Marble Way (map, Figure 26) follows a ceiling canyon above the creek along a cantilever walkway. Broken stalagmites can be seen near the illuminated stalactite cluster near the junction of Upper Marble Way with the north-trending Belfry and the Drawing Room. Small flat-topped stalagmites lie below the illuminated stalactite cluster which also has broken tips and regrowth. Judging by apparent regrowth, the breakages appear to have occurred a long time ago. The surface texture of some of the speleothems appears unusual. Regrowth appears as "normal" calcite, covering an earlier growth of finer "dribbles" and crenulations. For convenience, we identified particular stalagmite sites with letters A, B, etc. On the opposite (south) side of the path, the showcave

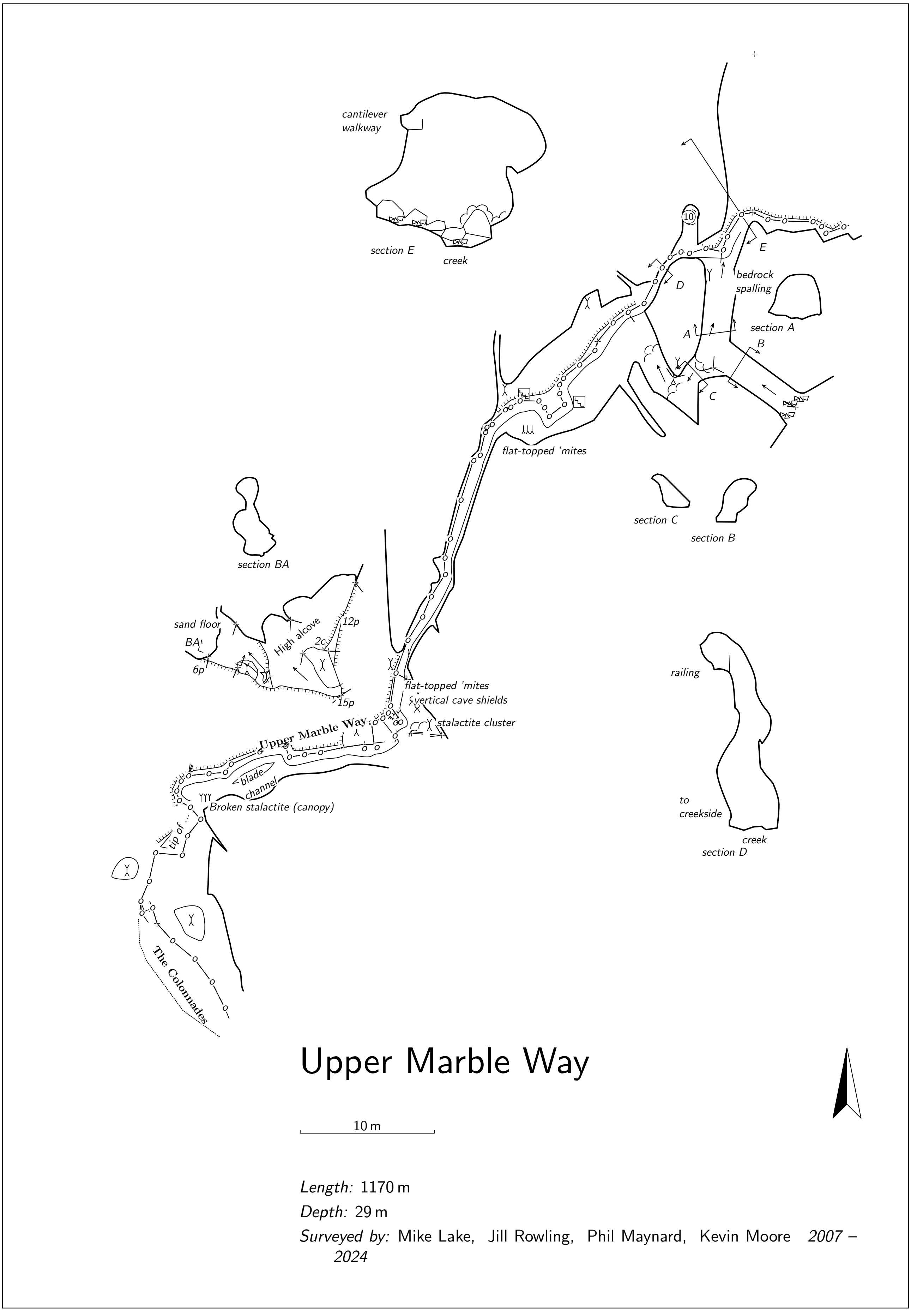

Figure 26. Plan of Upper Marble Way by the author. 10 m scalebar.

handrail has been installed over a broken stalagmite with regrowth. Another, site "B", is on the SE side of the path at the bottom of the steps, and another one, site "E", a little further to the northeast. Near E is a broken bedrock pendant and a deposit of flowstone resembling concrete. The area between B and E was potentially open to flood debris from the Belfry, although the creek is considerably lower down (about 10 m below). The positions of the tops of both stalagmites were surveyed, and the inclination was only 3° (the top of B is slightly lower – see Table 1). In the ceiling of this area is a sheared-off bedrock pendant, 4.4 m above a rocky surface which could be the missing piece. Above this again, the ceiling is scalloped but an area below that is devoid of scallops and instead has a smooth surface with broad horizontal grooves (Figure 27). The reddish material near the ceiling in the middle of the photo appears to be a flowstone, possibly the same material as occurs in the Drawing Room and apparently eroded by the same process that removed the scallops which are otherwise readily seen at this level.

Figure 27. Grooved ceiling canyon, Upper Marble Way.

A disc shape on the ceiling is most likely the site of a broken cave shield. Nearby are smaller intact shields, a sideways-flattened stalactite and a very thin, curved column with a surface texture of "dribbles". Further NE along the track there is another group of broken speleothems (Figures 28, 29). Here, some of the broken bits are loose but others are naturally cemented near to where they came from. The force which broke them appears to have come from upstream, but was not enough to wash away the broken pieces. This group includes a broken stalactite cemented to the floor, and broken-topped stalagmites. One stalagmite still has the top nearby and is bottle-shaped from overgrowth. Some of the breaks show uneven parting (Figure 28). A partially toppled stalagmite has been covered with considerable flowstone (Figure 29) and has regrown

Figure 28. Broken stalagmite (detail), Upper Marble Way.

Figure 29. Broken stalagmites and dribbles, Upper Marble Way.

in place. Also, in this figure one can see vein-shaped "dribbles" and a conventional microgour flowstone coating some of the speleothems. One cemented stalactite (Figure 30) looks very similar to the cryogenic ridges described by Onac and others (2023).

Further northeast are more broken-topped stalagmites, "dribbles" and angular cuts in the bedrock. These cuts are deeper than exfoliation, and occur along parts of the southern wall of Upper Marble Way (Figure 31). They are typically about 10 – 20 cm high and 10 – 30 cm long, possibly 5 cm deep. Spoon-shaped grooves in otherwise normally eroded cave walls might have been caused by something rubbing across the wall. This is not the same as polishing (e.g. by rock wallabies or people) and is mostly found in inaccessible areas such as near the ceiling and can occur in the same area as angular bedrock cuts and apparent cryogenic ridges.

Closer to the exit gate, the platey exfoliation of the bedrock, noted by James and others (1982) was verified along the north-eastern wall of a short, steep tubular passage in bedrock, linking the upper Marble Way path to a daylight hole in the southwest

Site in Fig Tree Cave	From	To	Inclination	Notes
Colonnades	Flat-topped south stalagmite	Flat-topped northern stalagmites	0°	Three in a row close together, 14th September 2024. Figure 11.
Chalkers Retreat – cloister / vestry near section 12	Top of flat-topped south stalagmite	Top of flat-topped northern stalagmite	5°	Survey book p. 118, 22nd June, 2024. Includes regrowth.
Chalkers Retreat as above	Top of flat-topped south stalagmite	Top of flat-topped northern stalagmite	3° to 5°	Survey book p. 118, 22nd June, 2024. Excludes regrowth.
Upper Marble Way near the Stalactite Cluster	Flat-topped northern stalagmite E	Flat-topped stalagmite B, at bottom of steps SE of path	-3°	Survey book p. 109, March 23-24, 2024. About 5 m apart.

Table 1. Surveyed inclinations between flat-topped stalagmite groups, accurate to half a degree in inclination.

Figure 30. Broken speleothem with possible cryogenic ridges near light fitting, Upper Marble Way.

side of Victoria Arch. A darker colour on the walls near the plates is thought to be due to algae, as this area is in twilight, being dimly lit from its proximity to Victoria Arch. The plates themselves appear rather delicate, only about 1 cm thick and ranging from hand-sized to about a metre in length. They occur on the passage's eastern wall and are composed of marble (Figure 32, Figure 26 section B).

As one exits the Fig Tree showcave and walks eastwards past the gate, light from the south side doline of Victoria Arch highlights additional

Figure 31. Bedrock wedges and dribbles near hand rail, Upper Marble Way.

Figure 32. Platey exfoliation, Upper Marble Way.

features. Elongated cut-off holes similar to phreatic tubes can be seen high in the south-western and north-eastern parts of Victoria Arch. Upper level tubes have an unusually elongated shape (inverted tear-drop) and their walls lack scallops (Figure 33).

Figure 33. Elongated holes, Victoria Arch.

Near the tube entrances, the volume of cave behind the tube does not appear to be great. Horizontal grooves occur in the bedrock. One is at around the same level as the aforementioned exfoliated bedrock and may be related to the passage with a similar feature. Another horizontal groove at the far north-eastern end of Victoria Arch appears to be roughly on the same level, although it curves upwards a little at its northern end and has a vertical slot partway along (Figure 34). At the northern end of the Arch, at a similar level to the platform built in 2024, is another notch with horizontal grooves (Figure 35). None of these high level Arch notches have scallops, although scallops are certainly plentiful in the lower passages of the Arch.

Figure 34. Grooves, northeast Victoria Arch.

Figure 35. Grooves, north Victoria Arch.

Discussion

Past climate and cave cold trap calculations

To estimate the current range of Wombeyan cave temperatures, a lapse rate of 6.5° Celsius per 1000 m was used based on the published mean temperatures for nearby Taralga (see Table 2). This data suggests a current mean minimum temperature at Wombeyan Caves of about 2.2°C which is not cold enough to significantly alter long-term speleothem development. However, where there is strong airflow, it is certainly possible for the air temperature in particularly draughty parts of Fig Tree Cave to get below zero temporarily. Ice expansion would break small water-filled speleothems such as straw stalactites in these areas. However, during the last glacial maximum (LGM) of the Pleistocene, winter temperatures could be on average some 8 Celsius degrees colder than at present (Barrows and others 2021). During that time, global sea levels were on average some 122 m lower than today, which would effectively put Wombeyan that much higher in altitude. The following methods used estimate the in-cave temperatures during the LGM:

1) Using the lapse rate, calculate the mean cave temperature ranges based on present ranges at the closest known weather station;

2) A simple subtraction of 8 Celsius degrees to estimate the expected range during Pleistocene glacial times.

On this basis, the mean annual temperature (underground rock temperature) in Fig Tree Cave would have been about 7°C during LGM, and the cold traps would be from -0.1° to -5.8° Celsius

(Table 2). Clearly the cave's geometry will dictate the actual temperatures possible.

Cave sumps, well away from diurnal temperature variations, would be expected to remain relatively constant at 7°C. Cold traps and chimneys then become significant in the caves. For example, if the valley's winter mean air temperature was -5.7°C during the LGM, then the chimney effect in a multi-entranced cave like Fig Tree Cave could result in cave cold traps remaining below freezing during the cooler months. This could have become significant if it was coupled with an increase in snow melt as suggested by Barrows and others (2021), as the mean annual temperature would have been positive. So, deep within most caves would have been ice-free; but in a cave's cold traps, pools of water could freeze over, incoming dripwater could form icicles (like the world's current ice showcaves for example Figure 1) and condensate from the sumps (discussed below) could freeze onto surfaces. The overall effect could be ice build-up in some areas which could take centuries to melt out, as presently occurs in Dobŝinska Cave, Slovakia (Zelinka 2008). The effect of summer / winter temperature variations would melt ice surfaces near boundary areas, resulting in local expansions and contractions of the ice and apply significant force to anything encased within it, as discussed below.

Sources of moisture, warm and cold air

Referring to the cave model (Figure 3), most of the broken speleothems and speleogens are located at a level about 20 – 30 m above the current cave sump. As discussed by Halbert & Michie (1982) and modelled by Gabrovšek (2023), cave sumps are a source of relatively stable, warm humid air. During winter nights, dense cold air can descend shafts and displace warm humid air upwards from lower in a cave. At Wombeyan, this can result in areas of condensation at cold traps. If one extrapolates the modern temperatures back to Pleistocene glacial times, as in Table 2, it seems plausible that there could be ice build-up in areas where condensation would have occurred, assuming a similar cave geometry. Another source of moisture is groundwater dripping from stalactites, discussed later. The two sources of water (condensate vs. groundwater) would have different chemical composition, with condensate tending to be corrosive to speleothems (James and others 2004, p. 42), while groundwater would tend to precipitate speleothems.

Site	Taralga	Hockey Gully	Bullio Cave cold trap	Victoria Arch saddle	Camping Ground, and Wombeyan Ck in Fig Tree Cave
Values for each site, where known					
Present altitude, m AMSL (approximates are from topographic map)	845	650	620 m approx.	620 mm approx.	620 mm approx.
Tmax mean maximum temperature, °C	26.2		20		
Tmin mean minimum temperature, °C	0.7		7.9		
Estimates below for present, derived from lapse rate of -6.5°C/1000 m, using Taralga values					
Tmax mean maximum temperature, °C		27.47	27.66	27.66	27.79
Tmin mean minimum temperature, °C		1.97	2.16	2.16	2.29
Rock temperature, °C (average annual temperature of site)	13.45	14.72	14.91	14.91	15.04
Temperature estimates below for the Last Glacial Maximum (LGM) – see text for explanation					
LGMTmax (Tmax - 8), °C	18.2	19.47	12	19.66	19.79
LGMTmin (Tmin - 8), °C	-7.3	-6.03	-0.1	-5.84	-5.71
LGM rock temperature, °C (LGM average annual temperature of site)	5.45	6.72	5.95	6.91	7.04

Table 2. Present values for site elevation and mean temperatures compared with calculated temperature estimates for the same sites during the last glacial maximum. Site height estimates are based on the topographic map, +/- 10 metres for the approximate site heights.

Bedrock exfoliation, scallop removal and grooves in the rock

Platey exfoliation, as seen near Upper Marble Way of Fig Tree Cave, and in Creek Cave, resembles an unloading effect as if the wall had been subject to pressure. The plates themselves are quite delicate and unlikely to survive much water or debris flow since their formation. Consider a marble tube in a cold trap during the last glacial maximum, ice filled, undergoing repetitive expansion and contraction as the temperature varies about the freezing point (as per Spötl and others 2023). The forces will be even all round, and as Hueckel (2016) indicated, most likely making noises as the Wombeyan marble is compressed towards its maximum strength, due to growth of cracks, fractures and plastic deformation. After the ice retreated, simple unloading will gradually form concentric rock flakes and plates. The same processes may have removed the scallops by local ice expansion, causing exfoliation, but many of the plates in Creek Cave have since been removed by floods. Only the colour of the patina shows us where the plates once were. Note this process has not occurred everywhere in the cave, but only where there are other apparent ice-influenced features.

Grooved rock surfaces as seen in Victoria Arch could be the result of ice very slowly flowing past, with entrapped rock debris creating grooves. That is, the ice itself did not abrade the bedrock, but rock debris spalled from the wall near the cave's entrances became entrapped in ice. Very slow movements of the ice and rock deposit would then erode the sides of the Arch. Another possibility is an ice-covered pool of water in the Arch, but in that case one expects the grooves to line up across the passage, which they do not. This aspect needs further investigation.

Angular cuts in the bedrock as seen in Victoria Arch, Creek Cave, the Drawing Room and Chalkers Retreat could be caused by a similar process but with a more directed force rather than an evenly-spread force. For example, the crack in the bedrock to the right of the fractured speleothem in Figure 12, where a thick block of ice may have formed on the top of a lake, undergoing temperature variations near the freezing point.

Spoon-shaped grooves in cave walls could be caused by a flow of ice gradually moving across that part of the wall. Embedded calcite grit (cryogenic calcite) could assist the ice to erode and polish the wall.

Breakage of the "large broken stalactite" – a theoretical approach

Speleothem breakage is commonly dismissed with a handwaving argument when no other information has come to light. In the case of the "large broken stalactite", ideas have been suggested such as flood events, earthquakes or just being too heavy. Let us consider how the speleothem could have been damaged by examining the forces needed to break it, and compare that with forces expected from 1) being "too heavy", 2) an earthquake, 3) a log propelled by a flood, 4) a mass-flow event and 5) by ice expansion.

Assumptions: We do not have exact values for the strength of Wombeyan stalactites and in any case they are likely to be variable in strength as they are all different shapes and have different growth histories, but as they are made of calcite they are unlikely to be greatly different from the European examples. We assume a calcite speleothem may break with about 1 to 5 MPa under tension (Spötl and others 2023). This is 1 MN to 5 MN / m^2. The face of the detached piece was estimated earlier to be about 5 square metres of calcite, so the amount of force required to pull it apart would be 5 MN to 25 MN. If force is applied as a cantilever, the force required to break the speleothem is similar to that under tension, as it is unconfined. If the force is applied to the side of the speleothem, the area is the full length 3.9 m long by 1.8 m width. Ribbing tends to make this shape somewhat resilient to crack propagation, and the calcite crystals are usually arranged with their C axes pointing outwards. This should give the canopy similar structural properties to marble bedrock.

Case 1: Could it break under its own weight?

As an exercise, let us consider the mass of the stalactite and what force is needed to break it. Compare the mass of the broken part to the mass of the entire speleothem. Calcite density is 2.71 g/cm^3 or 2.71 tonnes per cubic metre. From the dimensions given earlier, the broken lower bit could be a considered a cylinder with an oval cross-sectional area of π x 1.18 x 1.4 m and length of 1.7 m, so its volume would be (multiply all above times 0.8 for fluting) 7.05 m^3 and its mass would be 19 tonnes.

The mass of the original (reconstructed) canopy, assuming similar oval cross section:

0.8 x 3.859 x π x 1.18 x 1.4 x 2.71 tonnes = 43 tonnes.

The weight of the (now-broken) lower part when originally attached to the upper part would be usually (under static conditions) 9.8 ms^{-2} x 19000 kg = 186200 N which is significantly less than that required to fracture the stalactite (5 MN). Thus, it is not plausible that it broke from being too large.

Case 2: Could the damage be from an earth-quake?

A massive earthquake could break the stalactite but one would also expect there to be some considerable rock movement, damage along existing joints and cracked flowstone which is not found in that area. At least one known near-vertical fault can be seen striking roughly eastwards near the western entrance of Creek Cave. A bench has collapsed in Creek Cave Overflow, but it is localised and appears to have been undermined. Also, there are plenty of delicate speleothems in the cave which have not been damaged. Other large speleothems such as the fallen stalactite in the Opera House should have shattered, but it appears relatively intact, so something cushioned its fall. Generally, earthquakes are only felt strongly on the surface and are not felt deep underground. If there was ground movement, one expects it would topple large stalagmites, breaking them from their bases. Some have a strong lean but this could also be from other causes such as substrate movement. Most other breakages seen are part-way down the speleothem. If there was movement along the known fault, one would expect the "large broken stalactite" to be damaged near its attachment point, which is intact (Figure 14).

Using the values from Case 1, the lower 19 tonne portion of the stalactite would have to oscillate considerably to break off from the rest of the canopy. It is plausible that there was an earthquake. However, there would need to be a lot more damage to the cave for the earthquake concept to be more convincing.

Case 3: Was it struck by a log in a flood?

Consider a horizontal force applied to the lower end of the original canopy, forming a cantilever. If a log came down the creek during flood, could it break the drapery? Typical floods rush in the confined space below at around 2 m/s. When floating logs interact with objects, they tend to move about in the channel. Consider the force F applied to the end of the stalactite by a log of mass ***m*** travelling a 2 m/s striking the stalactite during a flood. Let us assume that the stalactite can flex a little, and the floating log takes 0.1 seconds to come to a complete standstill. The deceleration a of the log is 2 m/s per 0.1 s, so a = 2 / 0.1 ms^{-2} = 20 ms^{-2}. Then the force applied, using F = ***m***a = 1000 kg x 20N = 20 kN. This is significantly less than the force needed to break the canopy, although it could break something smaller such as the tips. If we decrease the hypothetical stopping time, it is still hard to get close to the 5 MN needed to break the "large broken stalactite" within the confines of the canyon and the setting. The scenario is therefore implausible.

Case 4: Was it damaged by a mass-flow event?

Consider a hypothetical major flood event creating a mass-flow of mud, water and sediments rushing past the "large broken stalactite". Most of the hypothetical slurry goes past without interacting, but the part impacting the stalactite applies a force from its deceleration over the impacted area. Such an event would have left material behind, yet there is nothing obvious at the site which would suggest such dense material flowed down this part of the canyon. The scenario is thus implausible.

Case 5: Was it damaged by ice expansion?

As noted earlier, a simple flow of ice will not crack the speleothem. But thermal expansion cycling around freeze / thaw temperatures in a confined space will easily reach the pressures described above if the speleothem is completely encased in ice.

Let us assume the site is a cold trap during the last glacial maximum. Refer to Table 2 for expected temperatures. In this situation, ground temperatures are still high enough for groundwater to be liquid, but the site air temperature is well below freezing, so water dripping onto the canopy will quickly freeze. Ice will build up over the original intact canopy, possibly filling all the space above and around the canopy as shown in Figure 36. Assume there is considerable thickness of ice buildup compared to the diameter of the speleothem, and the ice is in contact with the speleothem surface and the walls. Now allow the mean temperature to vary above around the ice freezing point which allows ice to expand and contract more than the calcite, due to their differing thermal coefficients of expansion. This will stress the speleothem in directions in which the ice can move: downwards, sideways, both upstream and downstream. The forces applied are from stress proportional to the temperature and ice thickness, as well as the overall mass of the speleothem (discussed in the Case 1 scenario). Repeated thermal cycles will crack the speleothem and eventually break it.

Perhaps the lower stalactite tips broke first, being thinner and weaker. Once the larger piece was broken, it could slowly sink into ice and sediment, then all the ice eventually melted leaving just the sediment and the lower portion of the speleothem in its current position. So this scenario is plausible.

Other broken speleothems and speleogens

Other broken canopies and stalactites (Figure 13) were seen in the ceiling a few metres to the west of the “large broken stalactite”. The largest is broken 5.9 m down from the ceiling channel which is relatively flat-topped, and it is interesting to compare this with the “large broken stalactite” which has broken 5.8 m down from the ceiling channel. This is a similar level to the other areas of Upper Marble Way with broken speleothems and speleogens. This type of clustered breakage was noted by Spötl and others (2023). The broken stalactite or shield in the Opera House has not shattered where it fell, but may have also come down onto a cushioning pile of ice. The toppled stalagmites in Bush Rangers Hall may have been assisted by ice expansion. The fracture seen in a calcite column in Bush Rangers Hall lines up with a wall notch nearby (Figure 12) and the various breakages in the Colonnades, suggesting a common cause such as a frozen pool of ice at the same level, together with ice build-up on speleothems.

Some of the broken stalagmites along Upper Marble Way are broken about half way along, and are not chamfered along the typical calcite cleavage as would be expected from a knock, but rather they are parted in steps as though pulled apart, with the steps most likely associated with a dusty layer where calcite deposition was not continuous, for example, Figure 28. Others have broken with a typical chamfer but have considerable regrowth suggesting the break happened long before the showcave was developed.

Fractured and broken speleogens may have been damaged by a mechanism similar to that of the stalactites. For example, the rock pendants damaged in the northern end of the Opera House, the Drawing Room, Chalkers Retreat and Upper Marble Way.

Although the main break of the “large broken stalactite” was likely to have occurred during the LGM, the straw regrowth of a “few hundred years” (James and others 2004) may be correct; perhaps the straw stalactites do regrow, only to be broken during the next cold period. A “few hundred years” could even be the “Little Ice Age” of the 16th – 19th centuries. A drop of only one degree Celsius could lower the Wombeyan average minimum temperature, and frosty winter nights may have been more frequent then. Straw stalactites growing in a cold trap would then be a temporary feature, and perhaps the loose straw seen on the stalagmite boss came down during a recent frosty night.

Throughout the cave, many broken-off pieces of stalagmite or stalactite are cemented to flowstone in dry areas. This does not indicate how the breakage occurred, but it does indicate that the breakage occurred long before the showcave was developed, and there was no great flood of water or debris through the area immediately post-breakage, otherwise the pieces would have been washed away.

Bent speleothems

Bent columns, curved stalagmites and stalactites could be caused by growth around tree roots or by wind deflection, even rockpile movements. However if they occur in the same area as other potential ice-related features, then pressure from ice expansion could also apply. The geometry could be checked to be more certain, and each speleothem will be different. It is possible for marble to be bent under constant pressure if it is confined, as per Hueckel (2016). Another consideration regarding bent stalactites that resemble tree roots: if the speleothem was formed during mid-Pleistocene, when there was a lack of trees as per Barrows and others (2021), then it is less likely that tree roots caused these bends. More work is needed in this area.

Cave welts in the Drawing Room

Welts are a feature of most columns in the Drawing Room (Figure 7). Hill and Forti (1997, p. 99) noted that they develop similarly to a cave shield, where a slowly opening crack guides carbonate solutions to the outside of the crack, allowing calcite to precipitate around the edges. In the case of the Drawing Room welts, the upper side has a deposit resembling concrete, and the lower side is more stalactitic. This suggests the material on the upper side may be deposited from material dribbling down to the welt, and the lower cascade of stalactites may be from excess material coming out of the welt's crack. The ceiling is bedrock, and the floor is a sediment of unknown depth. A common structural change has allowed welts to develop only on the columns, but not single-ended speleothems such as stalagmites. This could arise from heaving of the substrate, temporarily compressing the columns which will then slightly bend. Continued compression will crack the centre of the column where the bend is greatest, and a slow subsidence back will expose the cracks in the columns, allowing the welts to form. If instead, the substrate had subsided first, the columns would then be subject to tension. This would typically have eventually detached them from one of their end points such as the ceiling, and one would expect a set of helictites (for example) to develop at the top of the columns. This has not occurred, so it is more likely that the substrate heaved first. If the substrate had been wet, then froze sufficiently, this could temporarily cause heaving. The process may be similar to that described by Lundberg and McFarlane (2012) in Kents Cavern where periglacial conditions and air flow in the cave led to lowered temperatures, substrate frost heaving and flowstone cracking.

Cryogenic ridges

The ridged surface of some stalagmites in the Drawing Room, and at least one of the small, toppled speleothems in Upper Marble Way, look like cryogenic ridges. Further work could be done in this area, in particular stable isotopic analysis to clarify the temperatures of deposition, as there are similarities with tropical deposits such as moonmilk (B. Onac pers. comm. to the author, 29 and 30 October 2024).

The current temperature regime may support a small amount of cryogenic calcite formation during the coldest month (July). Some of the ridges could be associated with substrate cracking, so could result in small stegamites. The area can get quite cold at times and this aspect should be investigated.

Are the ridges caused by tree roots? This is more problematical to disprove, but we could not see the remains of tree roots. Usually if they had been present, there would be dark organic remnants and these areas seem quite devoid of such material. Tree roots do exist in the northwest of Chalkers Retreat, near its connection with Lots O Numbers Cave, above. Cryogenic ridges should be considered where speleothems are claimed to be from tree roots, but no actual organic material is found. If they are cryogenic ridges, they should have hairline gaps longitudinally down the ridges. If tree roots are suspected, one should be able to see actual tree roots in the area. Most tree roots do not descend deeply into bedrock; they follow the water lines. Also, tree roots tend to be larger towards the tree, whereas the fine gaps in cryogenic ridges are generally more irregular in width. Note also the previous comments about the lack of trees during the mid-Pleistocene, if the speleothem developed during that time.

"Dribble" speleothems and concrete-like flowstone

At Wombeyan Caves, the surface texture of many active calcite speleothems is usually of the fine microgour style, and smooth textures are sometimes due to moonmilk. "Dribbles" of presumed fine grained calcite deposited on stalagmites or walls do not appear to have been described, at least not at Wombeyan. Since we have only found them in areas with other possible ice features, it is thought that they are related to colder depositional temperatures. In the same areas we found coarse-grained concrete-like flowstone deposits which appeared to be related to the "dribble" features. Whether they are from fine or coarse CCC (Munroe and others 2021) is unknown. More work is needed to clarify what they are. What we know so far about them is that they occur in areas of the cave with other suspected cryogenic activity. They are on mostly vertical to near-vertical surfaces. They appear to be comprised of fine layers of calcite with a chalky appearance; their edges are slightly undercut and uneven; they generally have a sinuous shape. They may have a deposit of concrete-like flowstone at their lower end, and their upper end may be indistinctly developed on the bedrock. They may branch and re-join. Their surface may have a very fine microgour pattern, much finer than "normal" microgour flowstone.

Large elongated holes in Victoria Arch

The elongated holes (inverted tear-drop shape) seen in Victoria Arch are usually described as abandoned phreatic tubes, which they may be. Normally, active phreatic tubes transition to vadose with a slot canyon or similar, and sometimes the other way around for vadose to phreatic, but the holes seen fairly high in Victoria Arch are either simply round, or have a ring of flaked bedrock near the outer edges, as though there was some pressure evenly distributed around the outer edges. Those with an inverted tear-drop shape could have been shaped by grit being moved along the lower part of the channel. Possibly during one of the past ice ages, there may have been a build-up of ice filling smaller phreatic tubes, wedging the outsides and enlarging them. In Slovakia, in 2013, the author saw ice in the lower slots of abandoned phreatic tubes in ice showcaves, and presumably expansion / contraction grinds grit along their lower edges, to be washed out in the thaw along with any CCC grit.

Implications for Pleistocene fauna

Fossil vertebrates at Wombeyan Caves include *Burramys parvus*, now only known from alpine regions (Hope 1982). Undated bones of megafauna and other material extracted from a nearby active quarry suggest a Pleistocene age for them, possibly 13 ka – 17 ka based on the faunal assemblage. This suggests the area may have had an alpine vegetation at the time, which agrees with other studies such as Barrows and others (2021). As the cave ice thawed seasonally, karst springs would have been available to fauna at the time in an otherwise relatively dry landscape. Further afield, the author has seen a large broken and re-cemented stalactite at Wellington Caves (also, incidentally, a Pleistocene megafauna site). Cave ice thaw typically lags surface snow melt as, for example, if compared with modern showcaves containing ice deposits. The opening times for modern “ice showcaves” in central Europe reflect this, where the showcaves are closed in autumn during their ice thaw. The period over which groundwater was available from snow and ice melting would be extended in areas where caves contained ice deposits compared with those which had no ice.

Other cave areas with naturally broken speleothems

Large broken speleothems have been recorded by various photographers in Eastern Australian caves at Jenolan, Yarrangobilly, Mole Creek, Wellington, Cliefden and Abercrombie. There may be many more sites within south-eastern Australia.

In south-east Asia, people have reported large broken speleothems in caves in Vietnam and Malaysia. Many of these caves appear to be good initial candidates for consideration as Pleistocene cold caves given their large size, the possibility of chimney effect and their location near mountainous areas.

Conclusions

It is suggested that Fig Tree Cave and Victoria Arch once had deposits of permanent ice, possibly during the Last Glacial Maximum of the Pleistocene, based on evidence for speleothem and speleogen damage by ice expansion and contraction as the temperature varied about the freezing point. Ice build-up could have been caused by cave geometry, promoting cold traps in specific areas of the caves, even though ice may not have been a permanent feature outside of the caves or even deep in the caves. Individual features such as speleothem breakage would not be conclusive evidence for past cold-climate processes, but a collection of many features all in the same localised area is more convincing. The presence of ice in the cave could also explain both the bedrock exfoliation and the “large broken stalactite” seen in the cave.

As other caves also have broken speleothems and features similar to those described here, it is suggested that the caves were particularly cold during winters of the last glacial period. At present, ice does not build up in the caves to any significant amount, but during past glacial periods, ice did build up, mainly from the chimney effect. The presence of suspected cryogenic speleothems and types of damage caused to parts of the cave may help us to gauge the significance of cooling in the area at the time. This could be used as a palaeoclimate proxy for the region, complementing the periglacial scree slope measurements by Gillieson and others (1985), studies of relict periglacial block deposits by Slee and others (2023) and regional climatic studies by Barrows and others (2021).

Most caves are very complex, and numeric modelling of air flow can become complicated. It should be possible to estimate a cave’s cold-trap Pleistocene temperatures by measuring its current cold-trap temperature ranges over a couple of years, then use the methods described here. If possible, there should be several points of temperature measurement as there can be differences with wind direction. Some assumptions may need to be made about the air flow with the past cave geometry compared with its current geometry (removal of sediments, or addition of gates and bridges, for example).

Further work

Better analysis of apparent cryogenic cave carbonates would include stable isotope studies to help determine the temperature during formation, and Scanning Electron Microscopy could help to distinguish moonmilk from other calcites or aragonite. X-ray Diffraction could be used to determine mineral species present. Monitoring of current temperatures around various sites in the caves would give insight into how variable the temperatures can be at present, and then extended to calculating what they could have been during past colder periods. Stratigraphy may help constrain the dates of the deposits and hence which cold periods could have been involved. Further work is needed to determine what the apparent calcite “dribbles” and concrete-like flowstones are. Similar features from other caves in the Wombeyan area will be documented, especially the show caves such as Kooringa Cave and Wollondilly Cave. The work will be extended to include Jenolan Caves and Yarrangobilly Caves as they are at higher altitudes than Wombeyan, and Abercrombie Caves which also have fractured stalagmites and sculpted bedrock forms. Large toppled and broken speleothems with upright regrowth have been reported from other caves in eastern Australia and elsewhere, and it would be interesting to see if the techniques described here could indicate where other caves may have contained permanent ice deposits during previous colder times.

Further work could be done on modelling breakage for particular stalactite geometries, including the welts in the Drawing Room, and modelling airflow within the cave system as per Gabrovšek (2023), as well as obtaining more temperature data for particular caves. Further investigation is needed on the grooves and other patterns in the Arch.

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References

Barrows, T.T., Mills, S.C., Fitzsimmons, K., Wasson, R. & Galloway, R. 2021 Low-altitude periglacial activity in southeastern Australia during the late Pleistocene. *Quaternary Research,* 107: 125-146. https://doi.org/10.1017/qua.2021.72

Bahrani, N., Valley, B., Kaiser, P.K. & Pierce, M. 2011 Evaluation of PFC2D grain-based model for simulation of confinement-dependent rock strength degradation and failure processes. *45th U.S. Rock Mechanics / Geomechanics Symposium, San Francisco, California, June 2011*. Paper Number: ARMA-11-156.

Gillieson, D., Spate, A. & Head, J. 1985 Evidence for cold climate processes at Wombeyan Caves, Southern Tablelands, New South Wales. *Search,* 16(1-2): 46-47.

Gabrovšek, F. 2023 How do caves breathe: The airflow patterns in karst underground. *PLoS ONE,* 18(4): e0283767. https://doi.org/10.1371/journal.pone.0283767

Halbert, E. & Michie, N. 1982 Climate above and below ground. [in] Dyson, H.J., Ellis, R. & James, J.M. (Eds), *Wombeyan Caves: Sydney Speleological Society Occasional Paper,* 8: 137-154.

Hill, C. & Forti, P. 1997 *Cave Minerals of the World.* Second Edition. National Speleological Society, Huntsville AL.

Hope, J. 1982 Fossil vertebrates from Wombeyan Caves. [in] Dyson, H.J., Ellis, R. & James, J.M.

(Eds), *Wombeyan Caves: Sydney Speleological Society Occasional Paper,* 8: 155-164.

Hueckel, T. 2016 Instability phenomena in geomechanics - A review from a multi-physics point of view (pp. 11-12) [in] Sulem, J., Stefanou, I., Papamichos, E. & Veveakis, M. (Eds) *ALERT Doctoral School 2016 Modelling of instabilities and bifurcation in geomechanics,* pp. 3-28.

James, J.M., Jennings, J.N. & Dyson, H.J. 1982 Mineral decoration and weathering of the caves. [in] Dyson, H.J., Ellis, R. & James, J.M. (Eds), *Wombeyan Caves: Sydney Speleological Society Occasional Paper,* 8: 121-136.

James, J., Barnes, C., & Warild, A. 2004 The magic of marble. [in] R. Ellis (Ed.), *Caves and karst of Wombeyan: Sydney Speleological Society Occasional Paper,* 13: 75-84.

Jennings, J.N., James, J. & Montgomery, N.R. 1982 The development of the landscape. [in] Dyson, H.J., Ellis, R. & James, J.M. (Eds), *Wombeyan Caves: Sydney Speleological Society Occasional Paper,* 8: 45-64.

Kempe, S. 2004 Natural speleothem damage in Postojnska Jama (Slovenia), caused by glacial cave ice? A first assessment. *Acta Carsologica,* 33(1): 265-289.

Kukuljan, L., Gabrovšek F. & Covington M.D. 2021 The relative importance of wind-driven and chimney effect cave ventilation: Observations in Postojna Cave (Slovenia). *International Journal of Speleology,* 50(3): 275-288. https://doi.org/10.5038/1827-806X.50.3.2392

Lundberg, J. & McFarlane, D. 2012 Gryogenic fracturing of calcite flowstone in caves: theoretical considerations and field observations in Kents Cavern, Devon, UK. *International Journal of Speleology,* 41(2): 307-316. http://dx.doi.org/10.5038/1827-806X.41.2.16

McDonald, J. & Drysdale, R. 2004 Palaeoclimate research in Wollondilly and Kooringa Caves. [in] R. Ellis (Ed.), *Caves and karst of Wombeyan: Sydney Speleological Society Occasional Paper,* 13: 75-84.

Munroe, J., Kimble, K., Spötl, C., Marks, G.S., McGee, D. & Herron, D. 2021 Cryogenic cave carbonate and implications for thawing permafrost at Winter Wonderland Cave, Utah, USA. *Nature Scientific Reports,* 11 (6430). https://doi.org/10.1038/s41598-021-85658-9

Onac, B.P., Cleary, D.M., Dumitru, O.A., Polyak, V.J., Povară, I., Wynn, J.G. & Asmerom, Y. 2023 Cryogenic ridges: a new speleothem type. *International Journal of Speleology,* 52(1): 1-8. https://doi.org/10.5038/1827-806X.52.1.2416

Sefton, A. & Sefton, I. 1982 The show caves. [in] Dyson, H.J., Ellis, R. & James, J.M. (Eds), *Wombeyan Caves: Sydney Speleological Society Occasional Paper,* 8: 13-44.

Slee, A., Barrows, T.T., Shulmeister, J., Gontz, A., Kiernan, K., Haworth, R., Clark, D., Fifield, L.K. 2023 The age and paleoclimate implications of relict periglacial block deposits on the New England Tablelands, Australia. *Quaternary Research,* 111: 121-137. doi:10.1017/qua.2022.32.

Spötl, C., Jarosch, A.H., Saxer, A., Koltai, G. & Zhang, H. 2023 Thermoelasticity of ice explains widespread damage in dripstone caves during glacial periods. *Nature Scientific Reports*, 13 (7407). https://www.nature.com/articles/s41598-023-34499-9.pdf

Thomas, O. & Pogson, D. 2012 *Goulburn 1:250 000 Geological Sheet* S1/55-12, 2nd edition, explanatory notes. Geological Survey of New South Wales.

Zelinka, J. 2008 Cave microclimate [in] Pavel, Bella (Ed.) *Caves of the World Heritage in Slovakia,* pp. 87-94. State Nature Conservancy of the Slovak Republic, Slovak Caves Administration, Liptovský Mikuláš.