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P.J. Ackroyd Oolites

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  -report of the 1973 Niugini Speleological Research Expedition to the Muller Range.
- **A Bibliography of The Jenolan Caves. Part One: Speleological Literature** J.R. Dunkley, 1976.
  -a detailed reference list.
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Cover: Oolites in a cave at New Guinea Ridge, VIC. © P. J. Ackroyd

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Vadose weathering of sulfides and limestone cave development —evidence from eastern Australia.

. . . . R. Armstrong L. Osborne

Abstract

Many significant limestone caves in eastern Australia are associated with sulfide deposits and other ore bodies. These deposits have a variety of origins and include hydrothermal ore bodies, palaeokarst-hosted Mississippi Valley deposits, sulfides emplaced by basinal fluids, skarns and volcaniclastic ore bodies. The sulfides weather on exposure to oxygen-rich vadose seepage water, lowering the water pH and releasing sulfate and magnesium which can lead to the deposition of gypsum and aragonite speleothems. Oxidation of ore minerals in veins and boxwork leads to the growth of secondary minerals which result in breakdown of limestone by crystal wedging. Removal of weathered ores and ore-bearing palaeokarst sediments in the vadose zone is, in places, an important mechanism for the formation of large caverns in limestones, in some cases resulting in the exhumation of Palaeozoic caves which had been filled with sulfide-bearing palaeokarst sediments.

Introduction

Although Australia's longest and most extensive cave systems are developed in the Tertiary limestones of the Nullarbor Plain, significant caves are developed in the impounded karsts formed on the lower Palaeozoic limestones of the Tasman Fold Belt in eastern Australia.

Research over the past twelve years has shown that many of these caves, including the best known and most extensive limestone cave systems in southeastern Australia, Jenolan Caves in New South Wales and Exit Cave in Tasmania, are associated with palaeokarst deposits resulting from repeated exposure of the limestones to subaerial conditions (Osborne 1984, 1991, 1994a; Osborne & Branagan 1988). These and a number of other large cave systems with significant mineral decoration in both New South Wales (Bungonia, Colong) and Tasmania (Mole Creek) are developed in limestones adjacent to or overlain by the unconformable base of Permo-Triassic basinal sediments.

Osborne (1993c) argued that removal of weathered pyrite-bearing palaeokarst deposits in the vadose zone is a significant cave-forming process at Jenolan Caves, resulting in the exhumation of karst conduits initially formed during Permo-Carboniferous times and Osborne (1984) suggested that the pyrite and dolomite in these palaeokarst deposits was emplaced by basinal fluids originating in the overlying Permo-Triassic Basins

Many other limestone cave systems in eastern Australia occur in close proximity to small, usually uneconomic, ore bodies. It is proposed that this association between extensive, highly decorated cave systems and sulfide mineralisation is not accidental, but is an important causal factor in vadose cave development and secondary mineralisation.

A	Abercrombie Caves	I	Jenolan Caves
B	Bendithera Caves	J	Mitta Mitta River
C	Buchan Caves	K	Mt Etna
D	Bungonia Caves	L	Mole Creek
E	Colong Caves	M	Wombeyan Caves
F	Cooleman Plain	N	Wyanbene Cave
G	Exit Cave, Ida Bay	O	Yarrangobilly Caves
H	Florentine Valley		

Figure 1. Eastern Australia showing cave localities mentioned in the text.

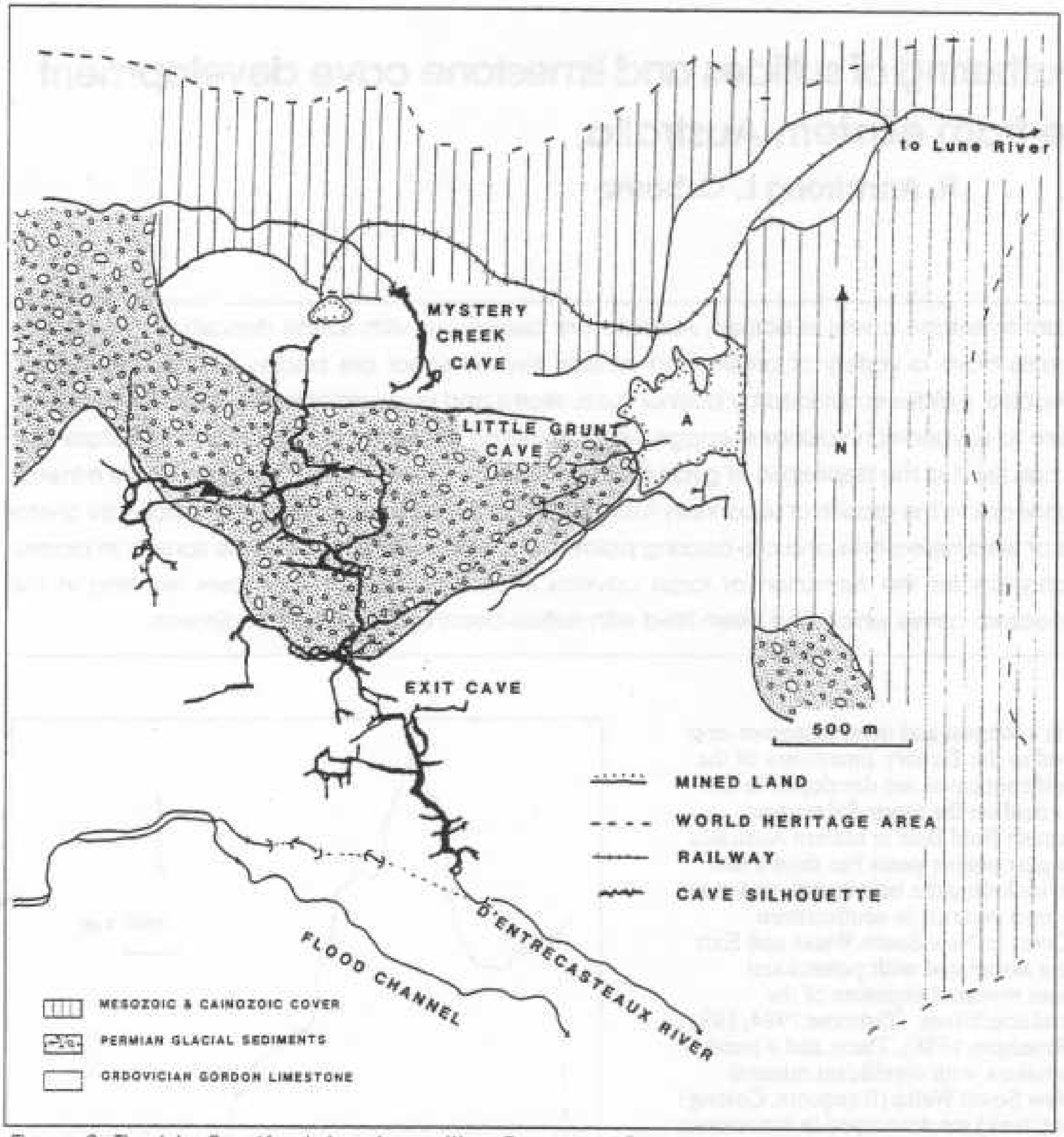

Figure 2 The Ida Bay Karst showing exiting Cave and Permian basinal cover. 'A' is Lune River Quarry

Limestone caves and sulfides

Evidence from the literature, from ongoing detailed field work, and from reconnaissance field work indicates that there is a significant relationship between sulfide mineralisation and vadose cave development processes at eight major cavernous karsts in eastern Australia. Ore deposits are found adjacent to a number of other cavernous karsts where cave/ore body relationships have yet to be investigated.

Abercrombie Caves, New South Wales

Abercrombie Caves are located 10 km south of Trunkey in the western margin of the central highlands plateau of New South Wales. (Figure 1, A). The main karst feature at Abercrombie is The Great Arch, a through cave some 180 metres long through which Grove Creek flows. The caves are developed in a regionally metamorphosed marble, part of the Upper Silurian Kildrummie Formation. Approximately 1 km south of the Arch is the Mt Gray Gold Mine which was worked without success between 1888 and 1898. Geochemical prospecting in the late 1970s and early 1980s indicted the presence of low grade lead, copper and zinc anomalies in the vicinity of the Arch.

Osborne (1991a) reported that thinly bedded units in the marble were preferentially eroded in the caves, resulting in the development of high bedding-controlled rifts which formed where the cave intersected the thin beds, but not in the more massive parts of the marble. This was attributed to the weathering of chlorite and pyrite, possibly from the derived from mineralisation, in the thinly bedded units.

Buchan Caves, Victoria

Buchan Caves (Figure 1, C) are the most extensive system of caves developed in lower Palaeozoic limestones in Victoria and is that State's premier show cave system.

Arne *et al.* (1994) have described a six small lead-zinc sulfide deposits hosted by the limestone of the Lower Devonian Buchan Group in which the caves have developed and noted the possibility of a genetic relationship between at least some of the cave development and the mineralisation. Late Tertiary cave systems which had been described by Webb *et al.* (1992) were found to be closely associated with mineralised strata at the four main deposits and this was taken by Arne *et al.* to suggest that the presence of sulfide minerals may have been conducive to cave formation.

Bungonia Caves, New South Wales

At Bungonia Caves, New South Wales (Figure 1, D) some of the deepest caves on the Australian mainland are developed in a plateau of steeply dipping Silurian limestone adjacent to a 285 m deep limestone gorge. The limestone is overlain unconformably by a thin cover of laterised Tertiary sands and Permian siliceous sandstones. Morphologically the caves consist of high-level phreatic passages which may date from the late Cretaceous and a low level phreatic system probably of early Tertiary age which were overprinted in the Latest Tertiary by vadose shafts and canyons (Osborne, 1993a). There is little breakdown and there are few speleothems at Bungonia Caves.

Osborne (1987) described laminated carbonate, quartz wake and spiculitic palaeokarst deposits, considered to be Permian in age, at Bungonia Caves. Re-examination of this material, and examination of specimens collected by Bauer (1994), has shown that limonite pseudomorphs after pyrite and dolomite are common replacement deposits in the palaeokarst sediments.

Where pyrite-bearing dolomitic palaeokarst sediments intersect the ancient high-level phreatic caves at Bungonia, passageways are constricted, indicating that these sediments are less soluble than the enclosing limestone when subjected to phreatic solution. Where pyrite-bearing clastic palaeokarst sediments are exposed in large moist caves, however, they are significantly weathered due to oxidation of pyrite and tend to be much weaker than the surrounding limestone. This has resulted in stoping of palaeokarst sediments from vertical clefts in Grill Cave, one of the five largest caves at Bungonia.

Exit Cave, Tasmania

Exit Cave at Ida Bay in the Western Tasmania World Heritage Area (Figure 1, G), one of the longest and largest limestone caves in Australia, consists of over 19 km of passage, much of which is more than 30 m high and wide (Houshold & Spate 1990). The cave is developed in horizontally-bedded limestone of the Ordovician Gordon Limestone Group which is unconformably overlain by Permian glacial and marine sediments of the Parmeener Supergroup. In many parts of the cave limestone is being broken down by gypsum wedging and gypsum speleothems, not common in east Australian caves, are a notable feature of the cave.

Recent work in association with I. Cooper has recognised palaeokarst-hosted pyrite, associated with limonite and dolomite, in the Gordon Limestone at Lune River Quarry, which adjoins Exit Cave. The palaeokarst features exposed in the quarry which host the pyrite include graded-bedded fissure fills, diamictites, breccias (Figure 3), mega breccias, crystal-lined cavities and doline fills with dish-shaped bedding. Water sinks from the quarry into the Exit Cave system (Figure 2).

Figure 3 Pyrite in palaeokarst breccia, Lune River Quarry, Tasmania. Thin section. Transmitted light, Crossed nicols. Pyrite forms opaque masses around large original clasts. Long axis of central pyrite mass is 5 mm.

Jenolan Caves, New South Wales

Jenolan Caves, 100 km west of Sydney (Figure 1.I), is Australia's best known show cave locality. The show caves are a complex system of over 20 km of passageway developed on a number of levels (Figure 4). They consist of phreatic conduits, active and abandoned stream passages and large chambers at several levels. Two other significant caves, Mammoth Cave with approximately 4 km of passageway and Wiburds Lake Cave with 2 km of passageway are developed upstream of the show cave system. The caves are developed largely along strike in the steeply dipping Late Silurian Jenolan Caves Limestone. Jenolan Caves are renown for their speleothems, in particular red-coloured calcite flowstones and aragonite helictites. Gypsum speleothems are present, but not abundant.

Jenolan Caves are situated close to the western margin of the Permo-Triassic Sydney Basin and remnants of gravels of assumed Permian age occur within 3 km of the caves. Work by Doughety (1994) has identified cemented Permian gravels at a low level within the valley of Camp Creek which is captured underground by the caves.

Laminated carbonate and dolomitic palaeokarst deposits, of probable Permian age, were described at Jenolan by Osborne (1991). Osborne (1993c) recognised that these deposits were resistant to solution below the water table, but were weathering in the vadose zone due to the oxidation of pyrite. Removal of weathered pyrite bearing deposits is exhuming cave passages that formed during Permo-Carboniferous times. Osborne (1995) found that secondary pyrite also occurred in cave-filling gravels at Jenolan which unconformably overlie laminated carbonate and dolomitic palaeokarst deposits, concluding that there were two phases of Late Palaeozoic karstification at Jenolan, one of probable Late Carboniferous age and the other of probable Latest Carboniferous to earliest Permian age.

Aragonitic speleothems at Jenolan Caves are almost always developed on a dolomitic palaeokarst substrate while pyrite-bearing palaeokarst deposits are closely related to red calcite and sulfate speleothems.

Recent work has shown that secondary pyrite is a common constituent of the both laminated carbonate and clastic palaeokarst deposits at Jenolan Caves. Where modern cave passages are entirely developed in palaeokarst deposits, the passages widen in cross-section at levels where they intersect pyrite rich beds. The process of vadose cave exhumation proposed by Osborne (1993c) has now been found to be very wide-spread and it is now clear that rather than modern caves accidentally intersecting and exposing palaeokarst features, a considerable proportion of the cavities forming the Jenolan Show Cave System are ancient caves (of Permo-Carboniferous age) from which sulfide-bearing palaeokarst deposits have been removed by weathering in the vadose zone.

Wombeyan Caves, New South Wales

Wombeyan Caves (Figure 1 M), 120 km south west of Sydney, are developed in massive crystalline marble believed to be Silurian in age. Osborne (1993b) described how the caves intersected Lower Middle Devonian volcaniclastic palaeokarst deposits, and more recent palaeokarst deposits composed of crystal breccias and ferruginous sandstones. Pyrite is a common constituent of the volcaniclastics and, in places large secondary pyrite cubes occur within the marble.

Pyrite-bearing volcaniclastic palaeokarst deposits have exercised considerable control over the development of two caves, Sigma Cave and Bouverie Cave. In Sigma Cave dyke-like bodies of pyrite-bearing

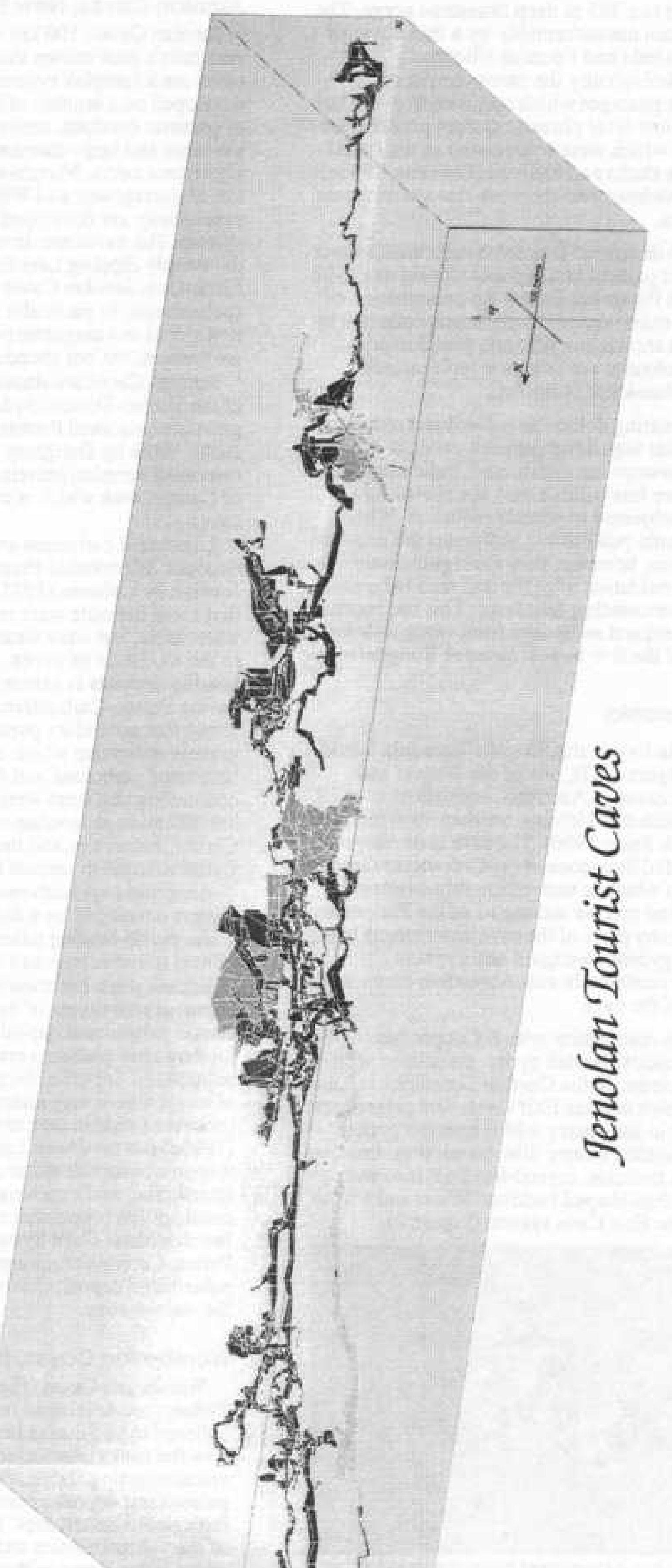

Figure 4 The Jenolan caves System

volcaniclastics act as constrictions in phreatic passages and control breakdown. Similar dyke-like bodies of pyrite-bearing volcaniclastics have controlled the development of the large breakdown zone near the entrance to Bouverie Cave.

Wyanbene Cave, New South Wales

Wyanbene Cave, is the largest of nine caves located 50 km south of Braidwood in southern New South Wales (Figure 1, N), developed in the Silurian Wyanbene Limestone adjacent to the unconformable contact between the limestone and clastics of the Late Devonian Minuma Range Group. The unconformable contact is erosional and there is evidence for exposure and palaeokarst development at the contact. A number of small abandoned mines, which have been worked for silver with little success, occur near hematite rich gossans close to the caves.

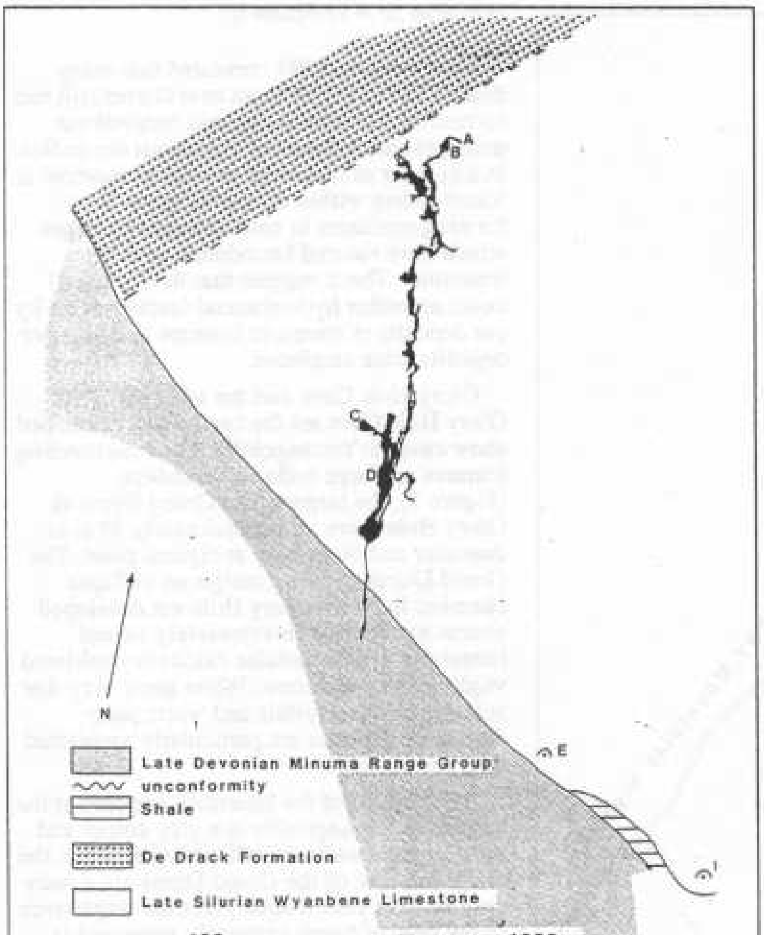

Figure 5 Wyanbene Cave showing relationship between cave and Late Devonian siliceous sediments.

A Cave Entrance
B Cave Entrance
C Gunbarrel Aven
D Caesars Hall
E Clarkes Cave
F Goat Cave
Cave map after Webb & Brush (1978), geology after Lishmund et al. (1986). Control of the overlay is poor, however field measurements confirm that the rock at the surface above the Gunbarrel Aven is limestone

Rowling (1995) provided a good introduction to the cave and its environs and described elements of its geology and mineralogy. Wyanbene Cave (Figure 5) is approximately 2 km long and consists for most of its length of a small north-south trending streamway, above which the cave opens up into a number of elongate chambers. Towards the southern end of the cave a large chamber, Caesars Hall, 100 m long, up to 30 m wide and 30 m high, and a cylindrical blind shaft, the Gunbarrel Aven, claimed to be 105 m high, are developed. South of Caesars Hall the cave contracts to a narrow high rift, developed along a single major joint.

The main control over cave development cave is a north south trending joint set, filled with sulfide-bearing palaeokarst sediments, remnants of which are found in Caesars Hall and at the ends of some of the small chambers. The cave also intersects crackle breccia, numerous veins and boxwork. East-west striking veins have in places deflected cave development.

Jennings (1971) considered that the Gunbarrel Aven was roofed with Upper Devonian sandstone, and had developed as a result of acidic water entering the limestone from overlying jointed sandstone, while Rowling (1995) noted the presence of a red, fine-grained volcaniclastic boulder and fragments of quartz sandstone and conglomerate at the base of the aven. Recent field work has shown the roof of the aven is not overlain by Devonian sandstone and that the northern edge of the Upper Devonian cover corresponds to the southern end of Caesars Hall (Figure 5) where the cave narrows to take the form of a single solution-enlarged joint. This suggests that the siliceous cover has inhibited cave development by restricting access of oxygenated vadose water to the limestone.

Rowling (1995) concluded that the development of Wyanbene Cave had been *extensively affected by north striking joints coupled with chemical reactions around east-west striking zones of hydrothermally deposited materials* [Rowling, 1995 p 34].

Yarrangobilly Caves, New South Wales

Yarrangobilly Caves are situated in a deeply incised valley on the western side of the Snowy Mountains in southern New South Wales (Figure 1 O). Extensive caves are developed here in the Late Silurian Yarrangobilly Limestone including four major show caves and Eagles Nest Cave which is one of the deepest caves on the Australian mainland. The limestone outcrop is approximately 3 km long and 500 m wide (Figure 6). The show caves are located at the southern end of the outcrop. Towards the northern end of the outcrop is a skarn body known as Garnet Hill and early maps of the area (e.g. Trickett, 1919) indicate the presence of copper ore scattered over the surface of the limestone.

Mining for copper, gold and lead in quartz veins and gossans was carried out at ten localities in the Yarrangobilly Limestone between 1905 and 1914. Small shafts and excavations yielded primary chalcopyrite, galena, pyrite and magnetite and secondary chalcocite, malachite and native copper. Degeling (1982) suggested that the deposits were the result of low-temperature hydrothermal fluids circulating through the limestone after cessation of the volcanism which produced the

Goobarragandra Beds, which underlie the Yarrangobilly Limestone.

The first indication that mineralisation had an influence on vadose karst processes at Yarrangobilly arose in 1986 when a major sinkhole failure occurred in the Snowy Mountains Highway which crosses the limestone 500 metres south of Garnet Hill. Examination of the cavity revealed by the collapse showed that although most of the failure was due to removal of poorly consolidated sediments filling the cavity, the bedrock wall of the cavity was itself fairly weak and began to fail as the supporting sediments were removed. The bedrock in this cavity was found not to be composed of massive limestone, but of lithified vadose cave deposit consisting of flowstone and porous cavity fill (clay pellets) cut by two generations of quartz and ferruginous veins and containing large euhedral secondary quartz crystals growing from the matrix.

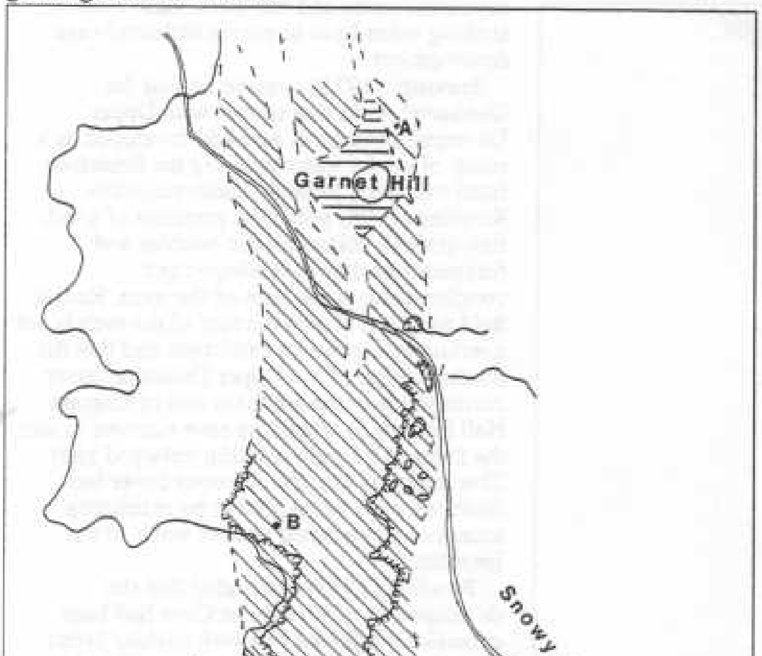

Figure 6 The Yarrangobilly Limestone
A Feature illustrated in Figure 7
B Yarrangobilly Copper Mine
C Glory Hole Caves

Figure 7 Remnant of gossanous deposit sitting within a doline at A in Figure 6

Field work in 1994 revealed that many dolines and cave entrances near Garnet Hill had formed by the weathering and removal via underground drainage of gossanous ore bodies. In a number of instances gossanous material is found sitting within dolines (Figure 7) or forming remnants in cave entrance passages which have sutured boundaries with the limestone. These suggest that the (original) caves are either hydrothermal features filled by ore deposits or meteoric features in which ore deposits were emplaced.

Glory Hole Cave and the adjacent North Glory Hole Cave are the two largest developed show caves at Yarrangobilly. Their outstanding features are large collapse chambers (Figure 7), the largest, The Grand Dome in Glory Hole Cave, is approximately 30 m in diameter and 50 m high at highest point. The Grand Dome and the contiguous collapse chamber in North Glory Hole are developed almost exclusively in extensively veined limestone which contains calcite crystal-lined vughs up to 1 m across. White pasty very fine acicular calcite crystals and white pasty carbonate deposits are particularly associated with these vughs.

While most of the limestone exposed at the surface at Yarrangobilly is a grey colour and most of cave walls are off-white in colour, the walls and roof of the Grand Dome are a rusty yellow. This yellow rock gives the impression in the field of being extremely weak and is actively breaking down. Samples of the yellow coloured rock, however, are composed almost entirely of strong, dense massive limestone. The yellow colour being a coating only a few millimetres thick representing the weathered remnants of veins.

Other Karst Areas associated with Sulfide-bearing Palaeokarst or Ore Bodies

In addition to the eight localities discussed above, six other cavernous karst localities in eastern Australia have so far been identified that contain sulfide bearing palaeokarst deposits or where sulfide ore bodies occur in close proximity to caves. Relationships between these deposits and the cave development has yet to be investigated.

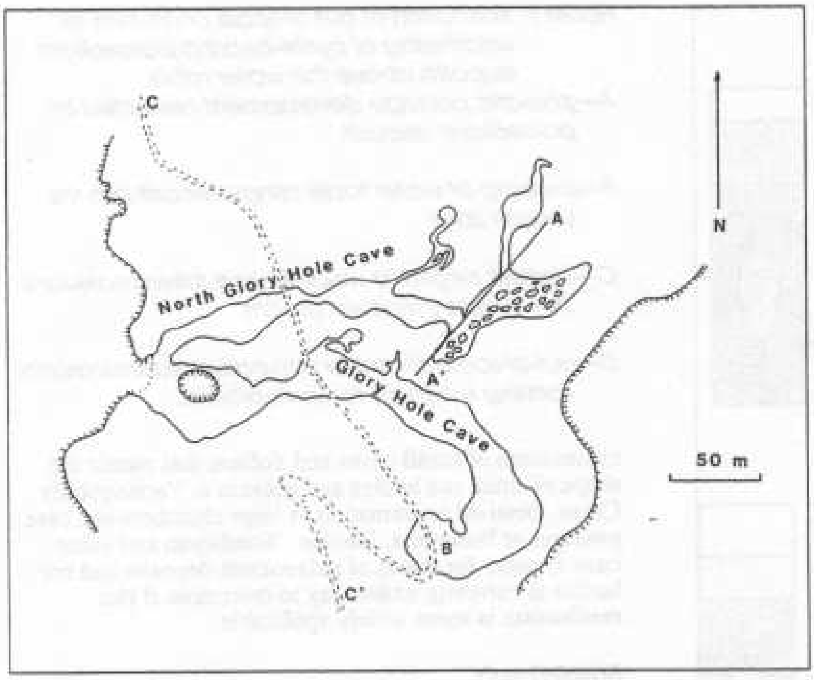

Figure 8 Glory Hole and North Glory Hole Caves, Yarrangobilly Caves, New South Wales.

A-A' Joint fissure-vein along which large calcite lined vughs have formed and which has controlled. Intense breakdown has occurred to the east of this structure.
B The Grand Dome
C-C' Cave access road
Cave plan after Trickett (1914).

At Bendithera in south eastern New South Wales (Figure 1, B) Lishmund et al. (1986) recorded silver-lead-zinc mineralisation in the Silurian Bendithera Limestone in which a number of caves are developed. One mine shaft, abandoned in the 1890s, occurs within 200 metres of a cave entrance.

Colong Cave, located SW of Sydney and at the western margin of the Sydney Basin (Figure 1, E) was for many years considered to be the longest single cave in New South Wales. The cave is approximately 1 km from end to end and consists of 6 km of passages at a variety of levels. Osborne (1985) noted that the cave was developed N-S along strike and spread out E-W where it became blocked by E-W trending dykes. Although there has been no detailed study of palaeokarst deposits exposed the cave, or their relationship to cave development, reconnaissance sampling has shown the presence of secondary dolomite and pyrite in carbonate palaeokarst deposits intersected by the cave.

At Cooleman Plain in the Snowy Mountains of New South Wales (Figure 1, F) significant caves are developed in the Silurian Cooleman Limestone. Gilligan (1973) proposed that the Mount Black lead-zinc deposit at Cooleman Plain, hosted by the Cooleman Limestone and adjacent to Cooleman Caves, had similarities with typical Mississippi Valley-type ore deposits. Ashley and Creelman (1975) examined that the Mount Black deposit and concluded that it had developed by sulfides replacing a palaeokarst breccia.

At Mt Etna in central Queensland (Figure 1, K) two hundred caves are developed in limestone of early Devonian age. Large caves in the area include Johansens Cave, the second longest cave in Queensland, with 5.5 km of passageway and Olsens Tourist Cave with 1.6 km of passageway (Matthews,1985).

Pyrite-bearing breccias are exposed in limestone quarries at Mt Etna. Pyrite bearing andesitic dykes, first described by Shannon (1970), are intersected by, and have controlled the development of a number of caves in the area. Gypsum crystals have formed on the surface of one of these bodies in Olsens Cave and there appears to be a relationship between these bodies and bedrock breakdown in sections of Olsens Cave.

Near the Mitta Mitta River in eastern Victoria, (Figure 1, J) Whitelaw (1954) noted the presence of caves in close proximity to copper deposits in small bodies of limestone.

Sulfides, palaeokarst and cave processes

The evidence from the localities discussed above indicates that four processes; cavern formation by vadose stoping, breakdown, formation of avens, and deposition of speleothems can be either caused, or strongly influenced, by the weathering of sulfides, ore minerals, dolomite and hydrothermally altered limestone in the vadose zone. It also suggests that overlying sedimentary basins and siliceous cover can play an important role in the genesis of complex limestone cave systems with extensive speleothem development.

Initial and substantial cave development in all the limestone cave localities examined has clearly been the result of phreatic (and in some instances possibly hydrothermal phreatic) solution, and there is some evidence from Bungonia and Jenolan that sulfides, dolomite and other ore minerals inhibit phreatic solution by their low solubility in poorly oxygenated waters.

Weathering of sulfides, ore minerals, dolomite and hydrothermally altered limestone has a significant influence on the development of limestone caves following exposure to fresh oxygenated water in the vadose zone.

Cavern Formation by Vadose Stoping of Ore and Palaeokarst

Vadose stoping involves the weathering, collapse and later removal by cave streams, of ore and palaeokarst bodies within cavernous limestone which become unstable on exposure to oxygenated vadose waters. Osborne (1993c) observed that this process was taking place at Jenolan Caves where masses of weathered pyrite bearing palaeokarst deposits were falling from the cave roof, disintegrating and then being carried away by the cave stream.

Many eastern Australian cave systems feature large chambers, which appear to be out of scale both with the size of cave passages connecting to them, and the size of the presently active streamways in the caves. The process of cavern formation by weathering of pyrite-bearing palaeokarst or other ore bodies in the limestone is illustrated in Figure 9. There is clear evidence for this process at Wyanbene Cave and it is indicated in Oolite Chamber of Mammoth Cave at Jenolan Caves.

Vadose stoping is clearly not restricted to the excavation of large chambers and appears to be the major process at Jenolan Caves by which palaeokarst deposits are exhumed from cave passages of all dimensions. Vadose stoping also appears to be responsible for the

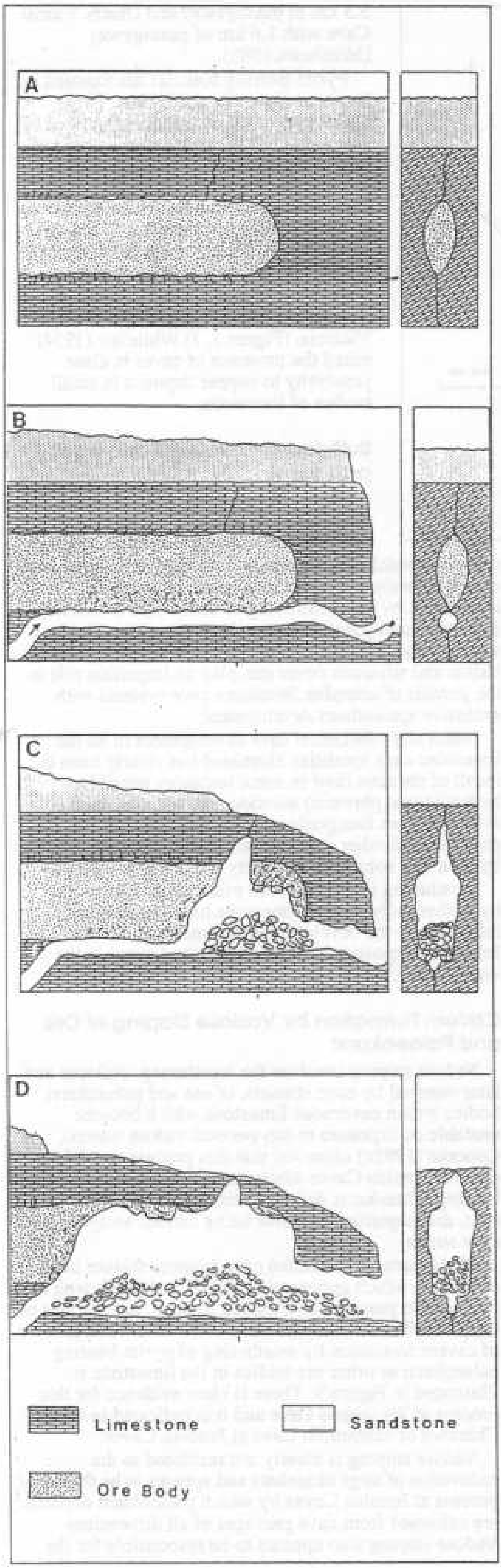

Figure 9 Formation of out-of-scale chambers by weathering of pyrite-bearing palaeokarst deposits above the water table.
A—phreatic passage development deflected by palaeokarst deposit.

B—lowering of water table brings deposit into the vadose zone

C—deposit begins to weather and fallen material is removed by modern stream.

D—out-of-scale chamber with palaeokarst remnants forming substrate for speleothems.

exhumation of small caves and dolines that mimic the shape of small ore bodies and gossans at Yarrangobilly Caves. Detailed examination of large chambers and cave passages at Bungonia, Jenolan, Wombeyan and other cave systems for traces of palaeokarst deposits and ore bodies is currently under way to determine if this mechanism is more widely applicable.

Breakdown

Large chambers which have not formed by direct removal of ore or palaeokarst bodies can be formed by principally by breakdown, modified by breakdown or have breakdown zones at their margins. In many cases cave breakdown can be explained by parting along joints/ bedding planes, roofs failing in tension or failure along discontinuities in the bedrock, such as dykes. In other cases it is clear that there is a genetic relationship between breakdown and ore, palaeokarst bodies, and hydrothermally altered bedrock.

Weathering of sulfides in the vadose zone can lead to the growth of gypsum crystals and thus result in crystal wedging. White (1988) described how crystal wedging by deposition of gypsum in joints and bedding planes could result in breakdown. Where this process has been observed, rock in breakdown zones is often shattered, giving the impression that it has literally been blown apart.

Growth of gypsum crystals, derived from weathered pyrite is responsible for the development of large breakdown zones in Exit Cave Tasmania. In Wyanbene Cave a large breakdown zone occurs at the northern end of Caesars Hall. This breakdown is occurring as a result of a boxwork of mineralised veins weathering, expanding and breaking apart the rock. These veins were probably fed from the main ore body whose removal was responsible for the formation of Caesars Hall.

In addition to the weathering of sulfides, hydrothermally altered limestones are frequently unstable in the vadose zone. Unlike massive limestones which dissolve at exposed surfaces while their interior remains mechanically strong, hydrothermally altered limestones are frequently veined and contain minerals other than sulfides which weather and destroy the mechanical strength of the rock. This process is well illustrated at Yarrangobilly Caves where the large breakdown chambers in Glory Hole and North Glory Hole Caves are the product of hydrothermally veined limestone disintegrating on exposure to the vadose environment and in Castle Cave where stoping of hydrothermally altered breccia appears to be the dominant mechanism of chamber formation. Samples from Niggli Chamber in Niggli Cave, Florentine Valley Tasmania (Figure 1, H), currently the deepest known cave in Australia, suggest that disintegration of dolomitic breccia has played an important role in its development.

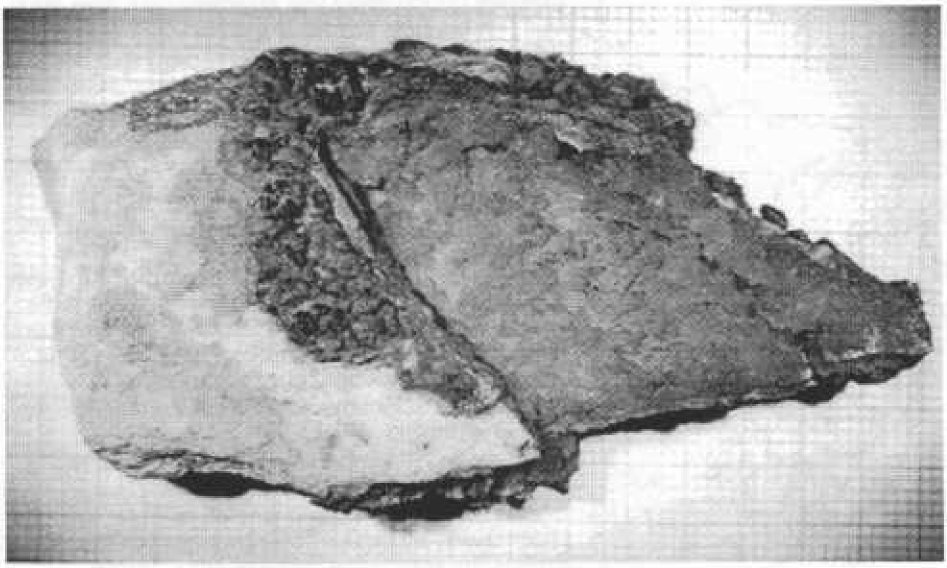

Figure 10 Gypsum speleothem growing from pyrite -bearing palaeokarst substrate, Jenolan Caves. Australian Museum Mineral Specimen D 12021. 10 mm grid.

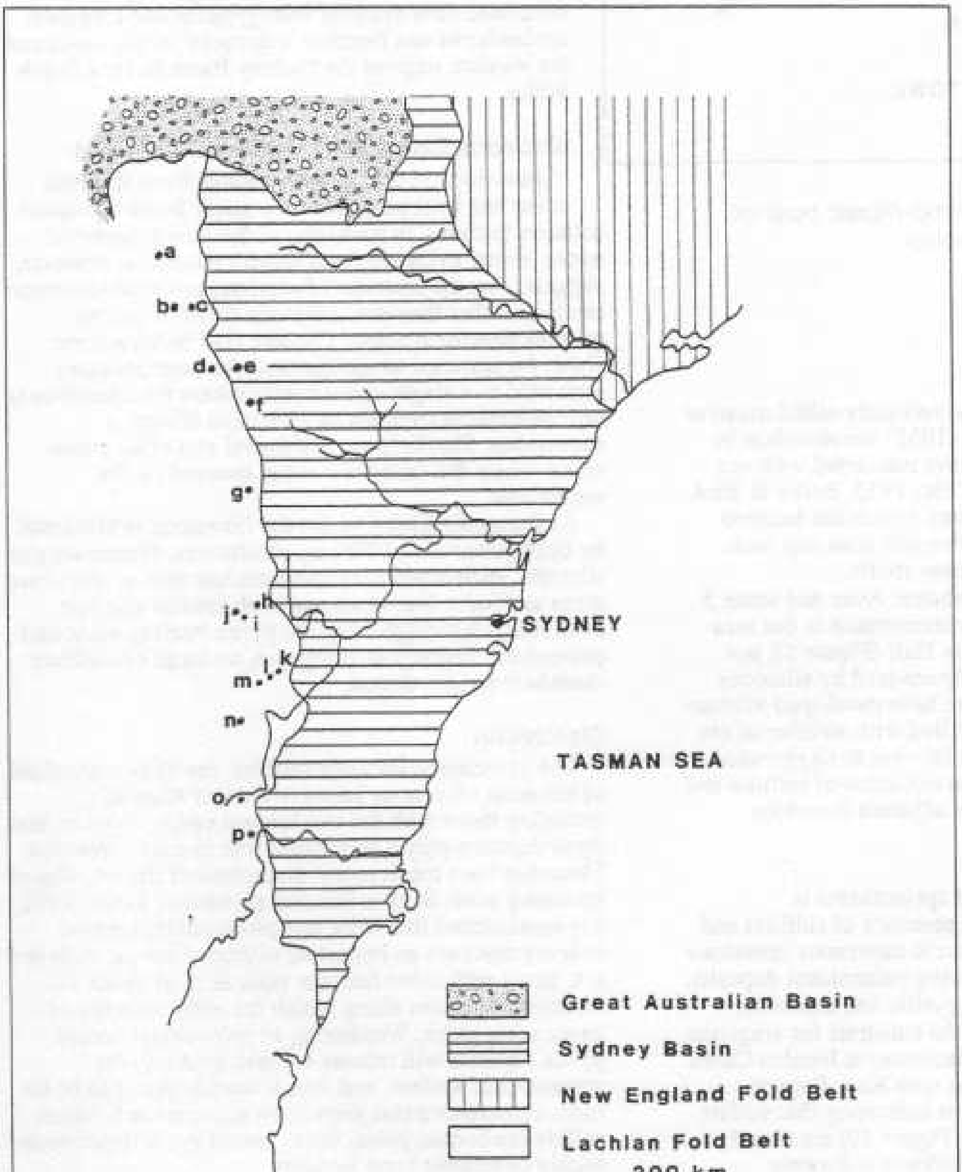

Figure 11 Karst areas near the margin of the Sydney Basin in New South Wales.

a Gulgong
b Mt Frome
c Havilah
d Cudgegong
e Kandos
f Brogans Creek
g Portland
h Jenolan
i Tuglow
j Jaunter
k Church Creek
l Billys Creek
m Colong
n Wombeyan
o Canyonleigh
p Bungonia

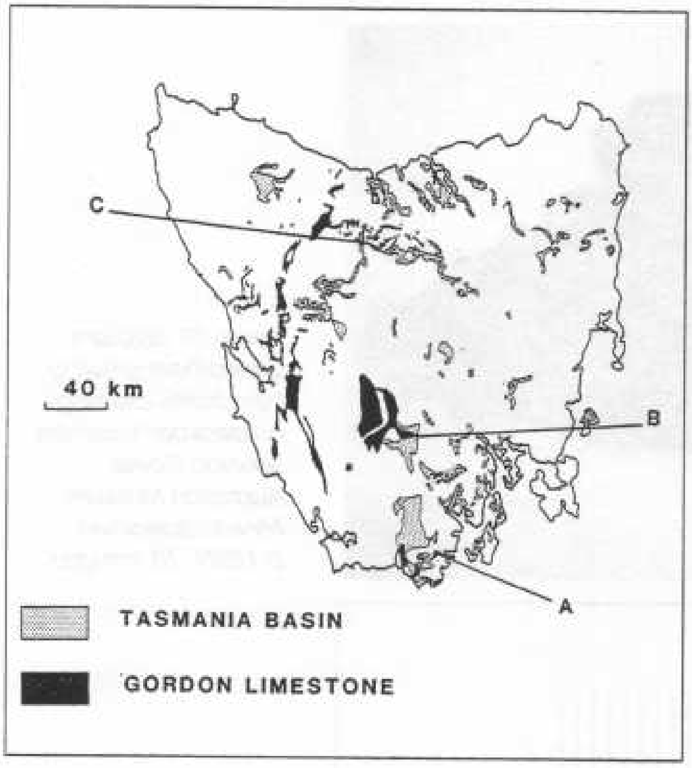

Figure 12 Karst areas and Permo-Triassic basinal sediments in Tasmania
A Ida Bay
B Florentine Valley
C Mole Creek

Development of Avens

Blind vertical shafts in caves, variously called *avens* or simply *vertical shafts* by Pohl (1955) are abundant in some limestone caves which have interacted with ore bodies. The traditional view (Pohl, 1955, Burke & Bird, 1966) has been that vadose water, which has become aggressive through contact with a siliceous cap rock, seeps down joints and forms these shafts.

At Wyanbene Cave, the Gunbarrel Aven and some 5 other vertical blind shafts are concentrated in the area adjacent to and north of Caesars Hall (Figure 5), not where the limestone is currently covered by siliceous rocks. The Gunbarrel appears to have developed in close relationship to a vertical joint filled with weathered ore material. Exposure of such a joint-vein to oxygenated vadose water would result in the oxidation of sulfides and thus strong acid solution of the adjacent limestone.

Speleothem Mineralogy

The mineralogy and form of speleothems is significantly influenced by the presence of sulfides and other ore minerals in or adjacent to cavernous limestone and of pyrite and dolomite bearing palaeokarst deposits.

Osborne (1993c) noted that pyritic and dolomitic palaeokarst sediments formed the substrate for aragonite helictites and red-coloured speleothems at Jenolan Caves. Work in progress in association with Ross Pogson (Australian Museum, Sydney) is indicating that sulfate speleothems at Jenolan Caves (Figure 10) are closely associated with dolomitic palaeokarst sediments containing weathered pyrite. This relationship has also been observed at Exit Cave, Tasmania, and in Olsens Caves near Mt Etna, Queensland.

Aragonite quill anthodites at Wyanbene Cave were described in detail by Webb & Brush (1978), but they did not examine the substrate from which they were growing. Rowling (1995) noted that aragonite (*var.* floss ferri) and gypsum (*var.* transistor gypsum, Hill & Forti, 1986) at Wyanbene Cave was associated with bands of *oxide material* (weathered pyrite-bearing palaeokarst ore) in north-south striking joints . At Yarrangobilly Caves development of pustular speleothems, fine acicular calcite and calcite paste is closely associated with veins and large calcite-filled vughs.

Sedimentary Basins and Caves

The longest cave systems in eastern Australia, and those with the most extensive deposits of aragonite and gypsum, Jenolan in New South Wales; Exit Cave, Florentine Valley and Mole Creek (Figure 1, K) in Tasmania occur close to the margins of, or in limestones overlain by, remnants of Permo-Triassic basinal sediments (Figures 11 & 12).

Osborne (1994a) suggested that the pyrite and dolomite in the palaeokarst deposits in these limestones were emplaced at relatively low temperatures by basinal fluids from above. This would explain the association between large, highly decorated cave systems with gypsum and aragonite speleothems and Permian 'cap rocks' in Tasmania and the western edge of the Sydney Basin in New South Wales.

Siliceous Cover and Vadose Processes

Introduction of aggressive water from siliceous cover has been proposed as a major factor in vadose solution in caves, in particular in the development of avens. Initial evidence from eastern Australia, however, suggests that the presence of siliceous cover on limestone inhibits, rather than promotes, the types of vadose process described above. Caesars Hall in Wyanbene Cave, for instance terminates and the cave becomes restricted to a single opened joint where the limestone is unconformably overlain by Devonian siliceous sandstones. Similarly the Gunbarrel and other avens occur where the limestone is not covered by the sandstones.

At Bungonia Caves where the limestone is blanketed by both Permian and Tertiary sandstones, ferricretes and silcretes, speleothems are less abundant than at other cave areas in similar limestone and with similar climatic conditions. Although there are pyrite bearing veins and palaeokarst deposits at Bungonia, no large breakdown chambers are developed.

Discussion

The association between sulfides, ore bodies and eight of the most cavernous karsts in eastern Australia, including those with the two longest caves, suggests that these deposits play a significant role in cave formation. There has been much recent discussion of the role played by strong acids in cave forming processes. Lowe (1992) has summarised this work and proposed that pyrite bearing strata are an important source of strong acids and act, along with other features such as sand layers as *inception horizons* along which the early solution of caves takes place. Weathering of palaeokarst hosted pyrite deposits will release sulfuric acid into the groundwater system, and thus it would appear to be no mere coincidence that there is an association between sulfide ore bodies, palaeokarst-hosted pyrite deposits and highly cavernous karst systems.

Large, highly decorated cave systems in eastern Australia have developed in limestones adjacent to ore bodies or where dolomite and pyrite have been emplaced in palaeokarst deposits. The importance of these deposits does not appear to be as inception horizons for phreatic development, since they appear to act as aquicludes to phreatic flow, but rather their role in later stage cave processes such as exhumation of palaeokarst, breakdown and speleothem deposition.

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References

ARNE, D.C., CROMIE, P.W., WEBB, J.A. and RICHARDS, J.R., 1994, The genesis of Pb-Zn sulphide occurrences in the Lower Devonian Buchan Group, Victoria. *Aust. J. Earth Science*. 41 (2):75-90.

ASHLEY, P.M. and CREELMAN, R.A., 1975, The Mount Black lead-zinc deposit, a probable Mississippi Valley-type sulfide occurrence at Cooleman Plains, southern New South Wales. *J. geol. Soc. Aust.* 22(4):423-433.

BAUER, J., 1994, The Siluro-Devonian Bungonia Group, southern highlands, N.S.W. *Helictite*. 32(2):25-34.

BURKE, A.R. and BIRD, P.F., 1966. A new mechanism for the formation of vertical shafts in Carboniferous Limestone. *Nature*. 210:831-832.

DEGELING, P.R., 1982, *Wagga Wagga 1:250 000 Metallogenic Map Mine Data Sheets and Metallogenic Study*. Department of Mineral Resources, New South Wales, Sydney, 425-426.

DOUGHTY, D.G. 1994, The stratigraphy and structure of the southern limestone area, Jenolan Caves NSW. Broadway. University of Technology, Sydney. B.Appl. Sc.Thesis (unpbl).

GILLIGAN, L.B., 1973, Possible Mississippi Valley-type deposits at Cooleman, southeastern New South Wales. *Quarterly Notes geol. Surv. New South Wales*. 10:1-10.

HILL, C.A. and FORTI, F., 1986. *Cave Minerals of the World*. National Speleological Society, USA.

HOUSHOLD, I. and SPATE A., 1990, the Ida Bay karst study, geomorphology and hydrology of the Ida Bay karst area. Report to the World Heritage Planning Team, Department of Parks, Wildlife and Heritage, Tasmania, unpublished, 63p.

JENNINGS, J.N., 1971, *Karst, An introduction to systematic geomorphology, Volume seven*. Australian National University Press, Canberra, 151.

LISHMUND, S.R., DAWOOD, A.D., & LANGLEY, W.V., 1986. The limestone deposits of New South Wales. Geological Survey of New South Wales, *Mineral Resources of New South Wales*. 25, Second Edition.

LOWE, D.J. 1992, A historical review of concepts of speleogenesis. *Cave Science, Trans. Brit. Cave Res. Assn*. 19 (3):63-90.

MATTHEWS, P.G. 1985, *Australian Karst Index 1985*: Melbourne, Australian Speleological Federation, 73 p.

OSBORNE, R.A.L., 1984, Multiple karstification in the Lachlan Fold Belt in New South Wales: Reconnaissance evidence. *Jour. Proc. Roy. Soc. New South Wales*. 117: 15 -34.

OSBORNE, R.A.L., 1985, Letter: Dykes and cave development at Colong Caves, New South Wales. *Helictite*. 23 (1):33-35.

OSBORNE, R.A.L.,1991a, A geological review of Abercrombie Caves. *Helictite*. 29 (1): 8-18.

OSBORNE, R.A.L., 1991b, Palaeokarst deposits at Jenolan Caves, New South Wales. *Jour. Proc. Roy. Soc. New South Wales*. 123: 59-73.

OSBORNE, R.A.L.,1993a, A new history of cave development at Bungonia, N.S.W. *Australian Geographer*. 24 (1):62-74.

OSBORNE, R.A.L., 1993b, The history of Karstification at Wombeyan Caves, New South Wales. Australia, as revealed by Palaeokarst Deposits. *Cave Science*. 20 (1): 1-8.

OSBORNE, R.A.L., 1993c, Geological Note: Cave formation by exhumation of Palaeozoic palaeokarst deposits at Jenolan Caves, New South Wales. *Aust. J. Earth Science*, 40 (6):591-593.

OSBORNE, R.A.L., 1994a, Caves, dolomite, pyrite, aragonite & gypsum: The karst legacy of the Sydney and Tasmania Basins.Twenty Eight Newcastle Symposium on Advances in the Study of the Sydney Basin, University of Newcastle Department of Geology Publication. 606: 322-324.

OSBORNE, R.A.L., 1995, Evidence for two phases of Late Palaeozoic karstification, cave development and sediment filling in south-eastern Australia. *Cave and Karst Science*. 22 (1):39-44.

OSBORNE, R.A.L. and BRANAGAN, D.F., 1988, Karst Landscapes of New South Wales, Australia. *Earth-Science Reviews*. 25: 467-480.

POHL, E.R., 1955. Vertical shafts in limestone caves. *Occasional Paper, National Speleological Society*. 2.

ROWLING, J., 1995. Investigations of the Wyanbene Caves area. *Helictite*. 33(1):29-33.

SOLOMON, M., GROVES, D.I., and KLOMINSKY, J., 1972, Metallogenic provinces and districts in the Tasman Orogenic Zone of eastern Australia. *Proc. Australas. Inst. Min. Metall*. 242:9-24.

TRICKETT, O., 1914, Limestone Caves. *Annual Report of the Department of Mines, New South Wales*. 1913: plan 3.

TRICKETT, O., 1919, The Yarrangobilly Caves Limestone (map) *in* J.E. Carne & L.J. Jones, The Limestone Deposits of New South Wales. *Mineral Resources of New South Wales*. 25: 200.

WEBB, J.A. and BRUSH J.B., 1978. Quill anthodites in Wyanbene Cave, upper Shoalhaven district, New South Wales. *Helictite*. 16(1):33-39.

WEBB, J.A., FINLAYSON, B.L., FABEL, D. and ELLAWAY, M. 1991. The geomorphology of the Buchan karst: Implications for the landscape history of the Southeastern Highlands of Australia. *Special Publication of the Geological Society of Australia*. 18:210-234.

WHITE, W.B. 1988. *Geomorphology and Hydrology of Karst terrains*. Oxford University Press, New York.464 p.

WHITELAW, H.S. 1954. Some limestone and marble deposits in East Gippsland. *Mining and Geological Journal* (Victorian Department of Mines) 5 (3):1-11.

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The Stromatolites of the Cenote Lakes of the Lower South East of South Australia

. . . . .Mia E. Thurgate

Abstract

Actively-forming, lithified stromatolites composed primarily of calcite occur in cenote (sinkhole) lakes near Mount Gambier, in the Lower South-East of South Australia. The stromatolites display a high diversity in their external morphology, with 14 different forms or 'types' identified to date. Columnar growth forms are most common, and both branching and non-branching examples are common. An examination of the associated microbial communities from sites supporting stromatolites suggests that each cenote supports its own unique flora. Three genus of diatom, *Achnanthes, Cymbella, Gomphonema,* and three genus of cyanobacteria, *Schizothrix, Lyngbya, Phormidium,* are the most likely to be responsible for stromatolite development.

Actively-forming stromatolites have also been recorded from the volcanic Blue Lake, near the city of Mount Gambier, and from three saline to hypersaline coastal lakes near the township of Robe. These occurrences, in combination with those of the cenote lakes, may support as many as 23 stromatolite types in total. This high level of stromatolite biodiversity is unprecedented within the Australian context, and for this reason Lower South East of South Australia is considered to be one of the most important areas of stromatolite development on the continent.

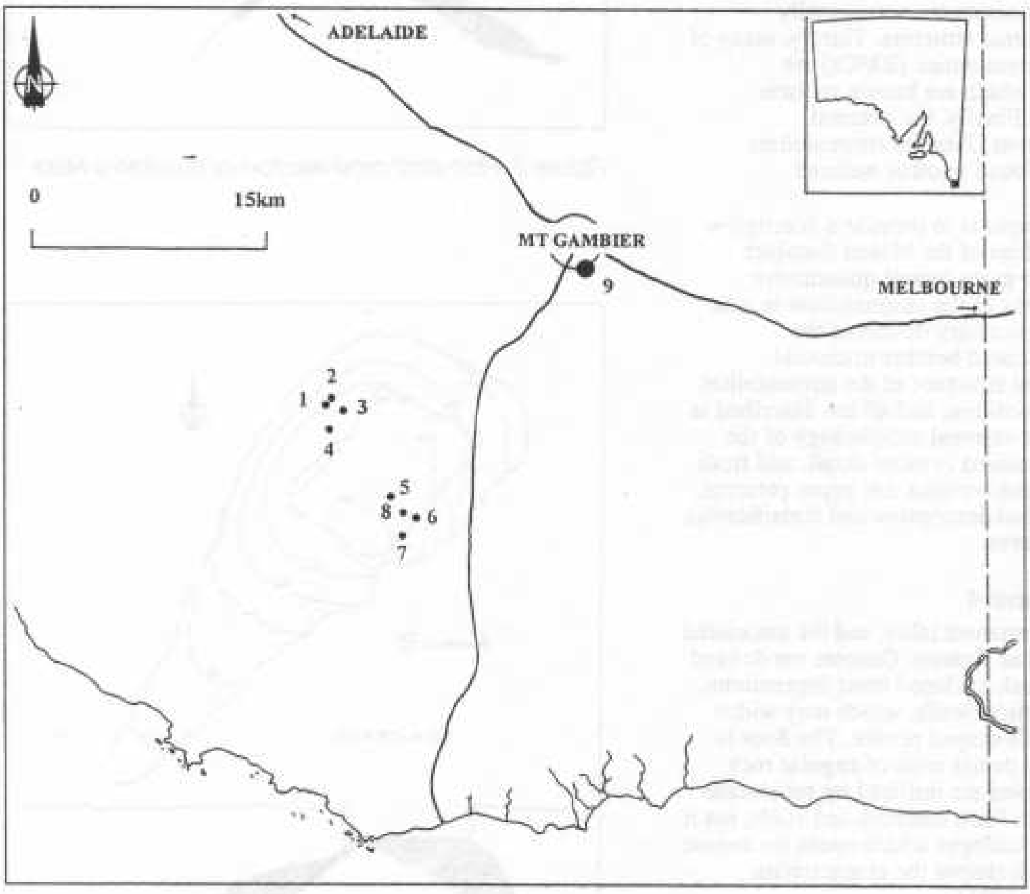

Figure 1. Location of sites containing actively forming stromatolites
1 Black Hole
2 Woolwash Cave
3 Ten Eighty
4 The Sisters
5 Little Blue
6 Ela Elap
7 Gouldens Hole
8 One Tree
9 Blue Lake

Introduction

Actively-forming, lithified stromatolites are present in freshwater cenote (sinkhole) lakes near Mount Gambier, in the Lower South-East of South Australia. There is much debate concerning the definition of stromatolites, but for the purposes of this paper, a number of basic characteristics are recognised. Stromatolites are lithified, laminated, organosedimentary deposits which are formed by complex ecological associations of algae, bacteria and other the microbes (benthic microbial communities) which trap and bind detritus and/or induce the precipitation of chemical sediments (Burne & Moore 1987; Winsborough & Golubic 1987).

Stromatolites have so far been found in eight cenote lakes: Gouldens Hole, The Black Hole, Woolwash Cave, One Tree Sinkhole, Little Blue Lake, Ela Elap, Ten-Eighty Sinkhole and The Sisters, the locations of which are shown in Figure 1. Typically, the stromatolites can be recognised *in situ* as erect columnar projections which are attached to the cenote walls. The actively-forming stromatolites are generally arranged in bands which extend around the entire circumference of the cenote lake, and they range from the water surface to depths of between 10 to 25 m. Bands of inactive, exposed stromatolites occur above the water line, but will not be considered here.

Individuals are arranged in such a way that they are offset from their neighbours to minimise shading. On sheer wall sections, the stromatolites are vertically aligned, while in shaded alcoves and beneath overhangs, they range towards the horizontal, so that the active surfaces always point towards the direction of the surface and the source of sunlight. This deliberate arrangement of individual columns, in particular the growth response to reduced light levels, was the first clue as to the identity of the stromatolites.

Subsequent observations have revealed a number of other features which support the stromatolite hypothesis. Firstly, all collected samples have an internal structure which is dominated by poorly formed, fine laminations. Secondly, all collected samples have an external coating of living benthic microbial organisms including a wide range of algae and cyanobacteria (blue-green algae), and the remains of these organisms are occasionally preserved within the internal structure. Thirdly, many of the benthic microbial communities (BMCs) are dominated by microbes which are known to form stromatolites elsewhere. Finally, the external morphologies of the Mount Gambier stromatolites closely resemble those found in other wetland environments.

The purpose of this paper is to provide a descriptive account of the stromatolites of the Mount Gambier cenotes as a precursor to more formal quantitative studies. Brief observations of the stromatolites *in situ*, have so far provided preliminary details of the composition of the associated benthic microbial communities, the internal structure of the stromatolites and their chemical composition, and all are described in the following paper. The external morphology of the stromatolites has been studied in more detail, and from these morphological characteristics this paper presents, for the first time, a detailed description and classification of these interesting features.

The Cenote Environment

The study sites are permanent lakes, and the associated landforms are classified as cenotes. Cenotes are defined as water-filled, cylindrical, enclosed karst depressions, with vertical or near-vertical walls, which may widen towards the base to a bell-shaped profile. The floor is typically covered with a debris cone of angular rock fragments and silt. Cenotes are initiated by subsurface solution processes which form conduits and voids, but it is continued subsurface collapse which opens the cenote to the surface, and which shapes the characteristic vertical walls (Thurgate 1995).

Gouldens Hole and The Black Hole have been the focal sites of the most detailed observations to date, and illustrate the main features of a typical cenote. Gouldens Hole (Figure 2) is a cylindrical feature of about 30 m in diameter, with sheer walls extending 9 m from the top to the water surface. On the south-eastern side, the walls have been breached by the construction of an artificial ramp which leads to the lake. The area below the ramp is

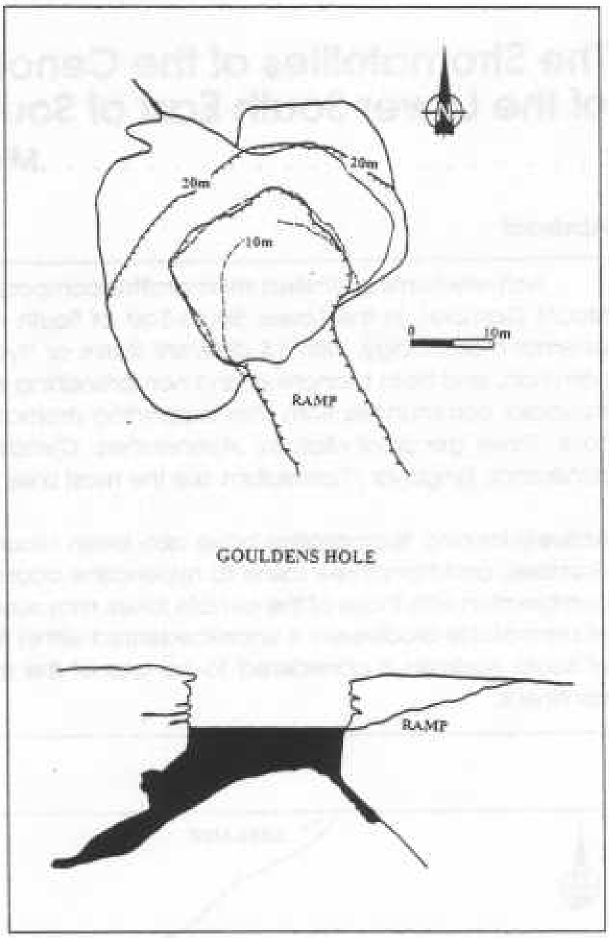

Figure 2 Plan and cross section of Gouldens Hole

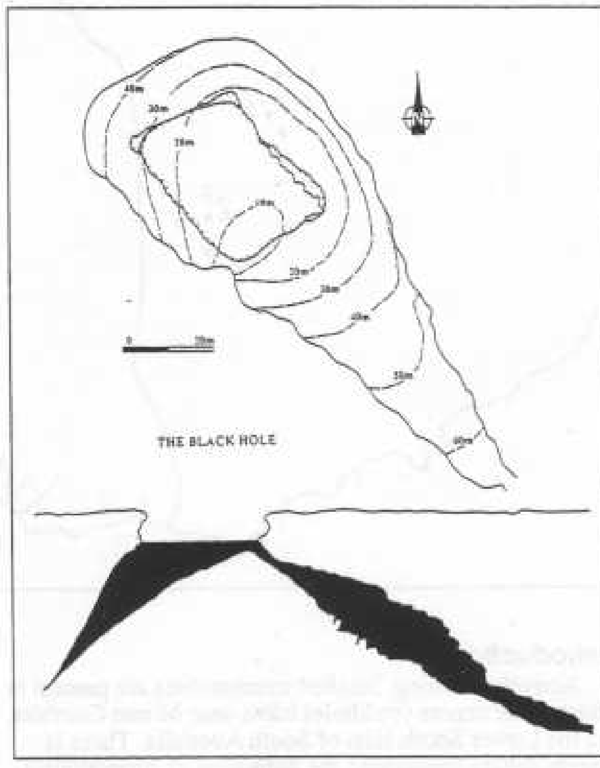

Figure 3 Plan and cross section of Black Hole

covered by a rubble mound, and is only 3 m deep. Beneath the rubble mound is the characteristic debris cone, and this feature slopes steeply to down to 20 to 26 m, where it meets with the lower sections of the walls.

The Black Hole is the largest cenote in the Mount Gambier area (Figure 3). It has a rectangular surface opening, measuring 65 m in length and 45 m in width. The sheer walls of the feature drop 12 m to the water table, at which point the walls open out to the typical cylindrical shape. The shallowest point lies to the south, where the top of the debris cone is reached at 6 m below the water surface. The northern, eastern and western sections slope steeply down to depths of up to 45 m. To the south and south-east, the cenote narrows and continues as an elongated tunnel which slopes steeply to depths in excess of 60 m.

There has been no regular, long-term water quality monitoring in any cenote to date. Short-term and sporadic sampling indicates that the cenote lakes are characterised by low-salinity waters enriched in calcium and bicarbonate with a high total alkalinity. Thermal and chemical stratification are dominant features of these lakes during the summer months (Horne 1987; Thurgate 1995). During stratification, water temperatures range from 22°C at the surface to 14°C below the thermocline, although there is some variation between sites. During the rest of the year, water temperatures at all sites are a constant 14-15°C.

pH values are around neutral to alkaline, with an annual mean of 7.2 to7.6 at most cenote lakes. The cenote waters are typically saturated with respect to carbonate minerals. Based on a single sampling period, saturation indices calculated for Gouldens Hole (using WATEQ), were 0.24 for aragonite, 0.52 for calcite and 0.5 for dolomite. These conditions favour the chemical precipitation of carbonate minerals, particularly calcite and dolomite, and this has important implications for the development of the stromatolites.

Benthic Microbial Communities

Composition of BMCs

Samples of BMCs from stromatolites in five cenotes; Gouldens Hole, The Black Hole, The Sisters, Ela Elap and One Tree have been collected. Initial examination of BMCs indicates that at least 4 species of blue-green algae (Cyanophyta), 12 species of diatoms (Bacillariophyta), 5 species of green algae (Chlorophyta), one species of golden-brown algae (Chrysophyta) and 2 species of aquatic moss (Bryophyta) are present (pers. comm. J. John 1992). A summary of the species identified to date is given in Table 1. The results shown in this table suggest that each cenote has its own unique stromatolite flora.

The stromatolites of Gouldens Hole are dominated by the green algae *Chlorella* sp. and diatoms including *Rhoicosphenia curvata*. The Black Hole is unique in having a mucilage-embedded community of thin filamentous blue-green algae (*Phormidium* sp.), along with a crustose species of filamentous green algae (*Chaetophora* sp) and few diatoms. In other cenotes, diatoms dominate in species diversity and *Schizothrix*, a cyanobacteria with a mucilaginous (sticky) covering is a common component (pers. comm. J. John 1992).

Microbes That Construct Stromatolites

The mechanism by which these microbes construct the stromatolites, and indeed, the actual species responsible for stromatolite-building has not yet been determined. The literature suggests that in order for stromatolite development to take place, a number of conditions must be met. These include; a water chemistry favourable for calcification; a BMC capable of interacting with the host environment to form a stromatolite; a rate of sedimentation sufficient to produce a preservable structure, and which allows continued colonisation by the BMC, and; an ecological balance that ensures that pressure from grazing and burrowing fauna does not retard stromatolite development (Moore 1987; Walter 1976). Presumably these requirements are met in the cenotes.

Studies from elsewhere suggest that BMCs initiate stromatolite development by preferentially colonising natural surface irregularities, and that this may be supplemented by the actions of fauna, which by burrowing and grazing on the BMC form additional irregularities (Moore, Knott & Stanley 1984). The growth of the BMC can then be stimulated by environmental conditions which encourage the microbes to flourish and stabilise the substrate to which they are attached (Moore & Burne 1985). Once established, stromatolite development proceeds by the trapping and binding of suspended particles and/or by biologically influenced precipitation.

The process of sediment-trapping is most commonly associated with microbes that are either encased in sticky, mucilaginous sheaths, or which produce mucilaginous trails. The detritus sticks to these surfaces and eventually intertwines to form a cohesive mat (Burne & Moore 1987; Golubic 1976; Winsborough & Seeler 1984). In stromatolites where precipitation is the dominant process, photosynthetic components of the associated BMC alter the water chemistry in the immediate vicinity by removing carbon dioxide, causing a rise in pH and the precipitation of carbonate (Burne & Moore 1987).

It is assumed that the stromatolites in the cenotes are formed predominantly by precipitation. The cenote lakes are still-water environments and the stromatolites are attached to rock wall faces, and are well above the sediments of the debris cone. Trapping and binding is therefore not likely to be a dominant process. The saturation indices for carbonate minerals in Gouldens Hole would seem to support development by precipitation.

BMCs which produce stromatolites must have mechanisms that allow them to survive burial and encrustation by sediment. The main survival strategies reported in the literature are either upward growth or movement (Golubic 1976; Winsborough & Seeler 1984). Some microbes produce upright, radial filaments (e.g. *Rivularia*), while others produce a gelatinous stalk to elevate themselves above the sediment (e.g. *Cymbella*). Alternatively, some microbes are able to move above the sediment by gliding through their gelatinous sheaths (e.g. *Lyngbya* and *Phormidium*). Typically, it is the cyanobacteria and the diatoms which possess such characteristics.

By comparing the dominant microbes found in the cenote lakes to those reported in other studies, several genus are most likely to be responsible for building the stromatolites. *Phormidium*, a cyanophyte common in The Black Hole, has been associated with stromatolite building in freshwater environments (e.g. Golubic 1976; Winsborough & Seeler 1984; Parker & Wharton 1985).

Neither of the two species identified from Gouldens Hole can be identified as stromatolite builders. The dominant diatom *Rhoicosphenia* has not been recorded previously in association with stromatolite deposits. *Chlorella*, the dominant green algae does not possess any of the characteristics required to be a successful stromatolite builder.

ID Code[1]	Growth Form	Shape of Growth Form and Branching Characteristics	Maximum Observed Length	Sites Where Observed[2]
C1	Columnar	Flattened, broad, blade-shaped column with rounded tip. No branching.	4 m	GH, BH
C2	Columnar	Club-shaped column, with broad, flattened tip. No branching.	1.2 m	GH, EE, OT
C3	Columnar	Highly variable. Cylindrical to sub-cylindrical with rounded tip. No branching.	3 m	GH, SI, BH, WW
C4	Columnar	Flattened column with rounded tip. No branching.	50 cm	BH
C5	Columnar	Cylindrical with conical tip. No branching.	20 cm	GH, OT
CB1	Columnar	Cylindrical column with rounded tips on branches. Parallel branching.	6 m	GH, BH
CB2	Columnar	Flattened triangular to conical column with distinct striations on wall-facing side. Branches club-shaped, parallel, with distinct 'cauliflower' texture.	40 cm	GH, BH
CB3	Columnar	Cylindrical column with broad, flattened tips on slightly divergent branches. Crests of branch tips may have very small conical projections.	2 m	GH
CB4	Columnar	Flattened club-shaped columns with occasional niches and projections. Branches slightly divergent with flattened tips.	1.5 m	OT
CB5	Columnar	Circular to cylindrical columns with rounded tips. Branching and overall appearance similar to cave coral.	50 cm	GH
CB6	Columnar	Flattened, subspherical to club-shaped columns with moderately divergent branches which may be sub-cylindrical or conical.	4 m	GH
CB7	Columnar	Flattened, subspherical columns with slightly divergent branches which have a ridged, herringbone pattern along their length. Branches coalesce on the outward side, but on the inward size are erect and club-shaped.	1 m	GH, BH
D1	Domal	Flattened, subspherical, plate-shaped domes with rounded tip. No branching.	2 m	GH, EE
TB1	Tabular	Low, coalescent reefs which incorporate cylindrical, club-shaped and conical columns. Branching is present and highly variable in shape.	12 m (width)	GH

Table 1. Summary of stromatolite growth forms and external stromatolite morphology

[1] ID Code:

C = columnar, no branching; CB = columnar with well-developed branching; D = domal; TB = tabular

[2] Site Code:

GH = Gouldens Hole; BH = The Black Hole; EE = Ela Elap; OT = One Tree; SI = The Sisters

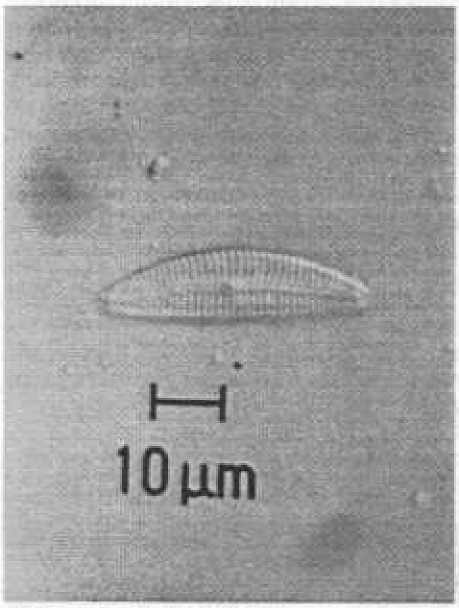

Plate 1 a Cymbella

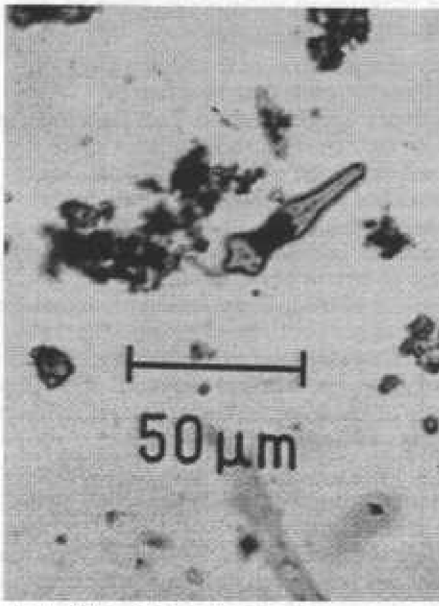

Plate 1 b Gomphonema

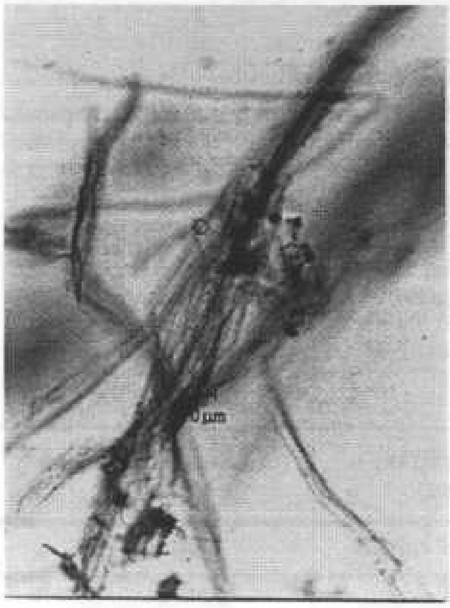

Plate 1 c Schizothrix

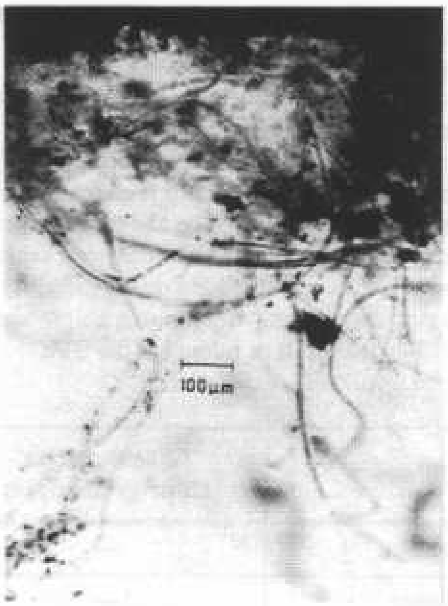

Plate 1 d Lyngbya

It seems most likely that either the stromatolite-building organisms from this site has either not been successfully collected or was missed in initial preparation and examination of BMC samples. Further work is obviously required to locate suitable microbes.

Comparisons of the BMC flora at the other three sites suggests that several diatoms and a number of cyanobacteria are primarily responsible for stromatolite development.

The diatoms *Achnanthes, Cymbella* (Plate 1) and *Gomphonema* (Plate 2), and the cyanobacteria *Schizothrix* (Plate 3) and *Lyngbya* (Plate 4) are known stromatolite-builders from wetland environments across the world (e.g. Winsborough & Golubic 1987; Gomes 1985; Wharton et al. 1982).

Physical and Chemical Characteristics of the Stromatolites

A preliminary classification of the Mount Gambier region stromatolites suggests that 14 different morphological 'types' may be present. This classification is based solely on the external characteristics of the stromatolites, and cannot be considered as final. Many published stromatolite classifications separate types according to a combination of both the external characteristics and the internal structure, the latter being influenced by the processes of the dominant microbes. A detailed examination of the internal structures across the morphological types has yet to be completed for the cenote examples. However, given that the same type of stromatolite may appear in different cenote lakes, but that the BMCs appear to be unique to each site, it is unlikely that internal details will adversely affect the classification.

The classification proposed here is weakened by the fact that many stromatolite morphologies are described from only a single specimen. Thus the level of variation within a type or class is not well known. It may be that further research will result in the merging of some classes. Conversely, systematic field sampling in as many sites as possible may well reveal the presence of even more classes. Either way, the range of stromatolite morphologies described herein is remarkably diverse.

External Stromatolite Morphology and Growth Forms

There is a high degree of variability in the external features of the stromatolites. The actively-forming stromatolites are generally olive green to pink in colour, although some of the deep water forms are a deep iron-red. The surfaces range in texture from completely smooth to pustular. Pitting of the surface is common, and is presumably caused by small animals and certain algae boring into the BMC. Structures such as cornices, peaks and projections are occasionally found on the margins, and in many cases, deep, lengthwise grooves are present, which are probably the result of folding of the BMC.

Table 2 presents a description of the growth forms and main external features of the stromatolites that have been identified so far, along with a list of sites where each form is known to occur. The fact that Gouldens and The Black Hole feature so frequently in this is due to sampling biases, and is not meant to imply a lesser diversity or absence of the same types at the other locations.

The classification (ID code) given in the last column of Table 2 is based on an alpha-numeric combination which identifies the growth form (C = columnar, D = domal or T = tabular), presence of branching (designated by a second letter 'B') and unique number code. The fourteen stromatolite types have been designated in this way. Columnar forms, which make up 12 of the 14 types, are the most diverse and the most abundant growth form. In some areas, tabular growths have coalesced with each other and with branching columns to form low reefs (Plate 2). Stromatolite domes are the only other growth form identified to date.

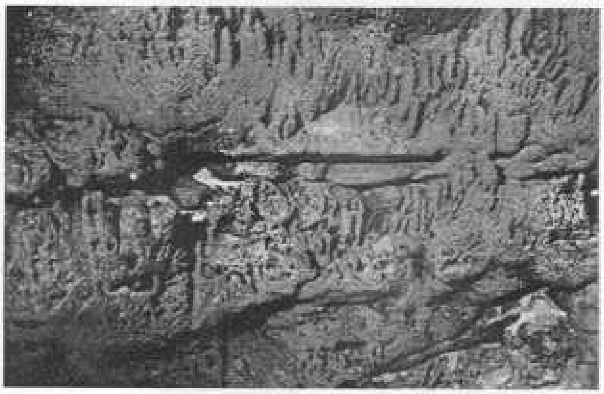

Plate 2. Tabular, reef-like structures, with coalesced columns and branches (TB1), along western wall of Gouldens Hole. Depth 10 m, average height 45 cm.

The columnar forms can be subdivided into non-branching (Plate 3) or branching (Plates 4 to 6). Column shapes are highly variable, but a common feature, particularly in vertical areas, is that many are

Site	Cyanobacteria (Blue-green algae)	Bacillariophyta (Diatoms)	Chlorophyta (Green algae)
Gouldens	—	Rhoicosphenia curvata	Chlorella sp.
Sisters	—	Achnanthes brevipes Frustulia sp.	Microspora sp.
Ela Elap	Schizothrix sp.	Nitzschia sp. Cymbella sp. Navicula sp.	Oedognomium sp.
One Tree	Schizothrix sp. Oscillatoria sp. Lyngbya sp.	Gomphonema acuminatum Cocconeis placentula Navicula sp. Nitzschia sp.	Cladophora sp.
Black Hole	Phormidium sp	—	Chaetophora sp.

Table 2. Dominant algae associated with stromatolites of the cenote lakes.
All identifications by Dr Jacob John, Curtin University. Several less common microbe species, Gyrosigma sp., Epithemia sorex, Amphora sp. and ?Pithium sp., were recorded by Dr John, but not assigned to a particular site.

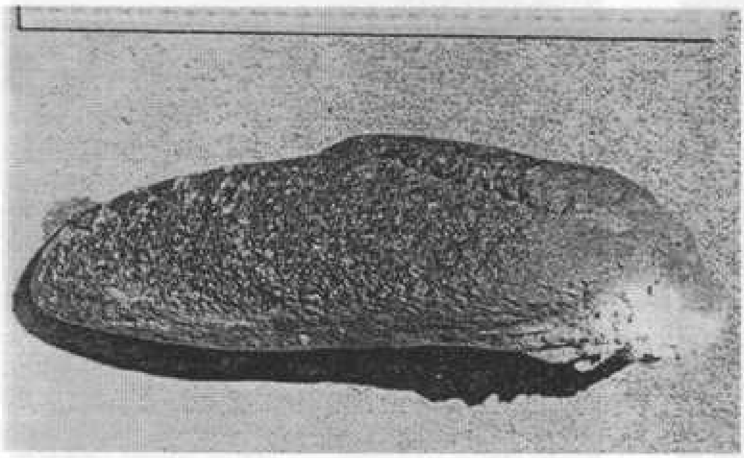

Plate 3. Flattened, broad blade-shaped column with no branching (C1), collected from 3 m at Gouldens Hole.

Plate 4. Flattened club-shaped column with branching and niche and projection structures on margin (CB4). Collected from 2 m at One Tree.

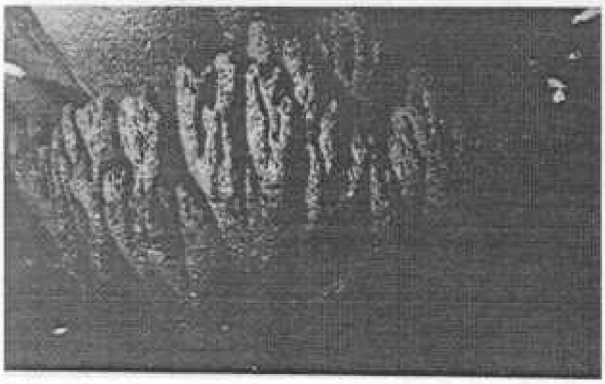

Plate 5. Flattened, club-shaped columns with highly divergent branching (CB6). Photographed in Gouldens Hole at a depth of 7 m. Average column length 75 cm.

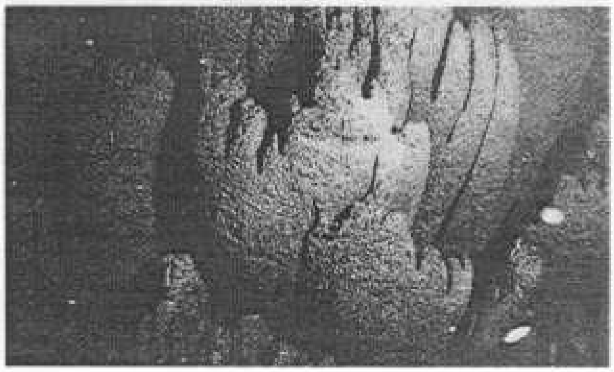

Plate 6. A variation on the CB6 form stromatolite shown in Plate 5, this example shows less well developed, parallel to slightly divergent branching on subspherical columns.

flattened along surfaces facing outwards from the cenote walls, presumably to maximise the surface area that receives sunlight. This would seem to be supported by the characteristics of the inward (wall-facing) surfaces, which typically are highly folded, providing an even greater surface area in situations of lower light intensity.

Distribution Patterns

The distribution patterns of the Mount Gambier stromatolites is not well understood, however, a few general trends have been noted. Generally, the larger forms (e.g. C1, C3, CB1 and CB6) are dominant in shallower waters, and appear to reach their maximum sizes in water depths of 4 to 6 m. They favour the well-lit, open areas and are generally aligned with the direction of the cenote wall (i.e. vertically). Occasionally, these larger forms are found in alcoves and overhanging areas, and when this is the case, their alignment tends towards the horizontal. However, it is the smaller stromatolite forms which are most abundant in the shaded areas, and in deeper waters (e.g. C4, C5, CB5). Generally, no stromatolites occur below a depth of 20 m, however, in Ela Elap, and isolated group of small branching columns are present at 30 m below the surface.

Internal Stromatolite Structure

The internal morphology of the stromatolites is highly variable. The internal cores of larger, shallow-water stromatolites may be dense and finely laminated or they may be friable and clotted in texture with poor lamination. Between the core and the outer layers, sediments are coarse and laminations range from clearly visible to indistinct. Often this mid-layer contains the remains of various molluscs. The outer layers, adjacent to the active surfaces are fine-grained, darker in appearance than the rest of the structure, and are well laminated. Laminations in the outer layer are finer than 1 mm and may alternate between dark and light layers.

The internal laminations in the larger stromatolites are commonly disrupted by small voids or fenestrae. These features are thought to be formed by (1) detachment of the surface layers of the BMC from underlying layers due to the generation of gas bubbles; (2) incomplete calcification of isolated parts of the BMC, or; (3) fauna living in the mat which have left cavities upon their death (Monty 1976). The presence of fenestrae within the internal stromatolite structure provides further evidence of biological involvement in the development of these features.

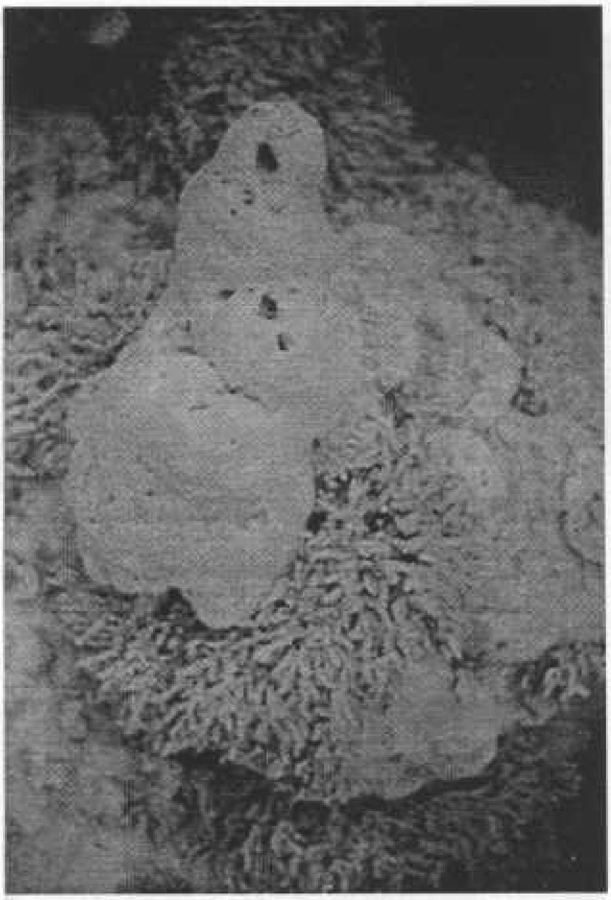

Plate 7. Conical stromatolite mound from the volcanic Blue Lake. Photographed at 12 m, approximate length 30 cm. Beaded structures at the base are calcite-encrusted Chara filaments.

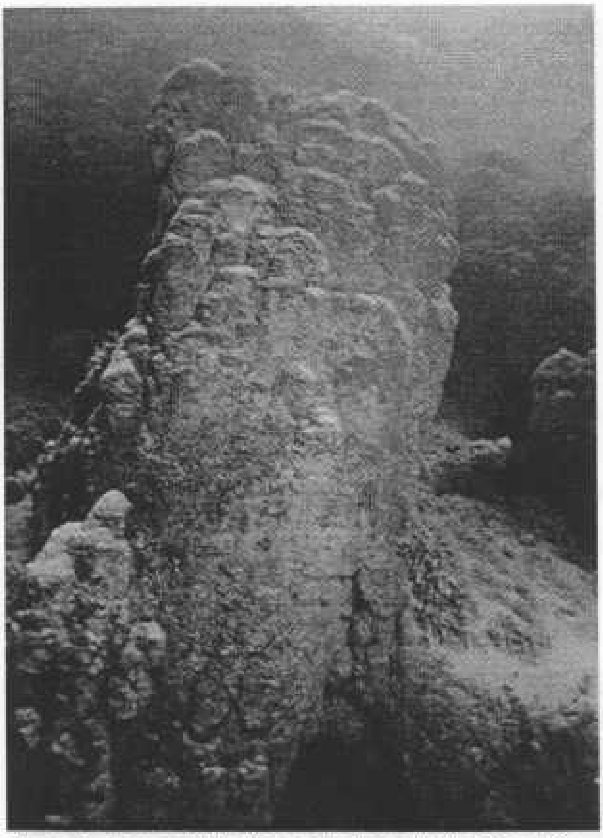

Plate 8. Large club-shaped stromatolite from the Blue Lake. Photographed at 6 m, approximate length is 3.5 m.

The smaller, deep-water stromatolites, in contrast, show little variation in internal structure, are dense throughout the structure, and have distinct, fine-grained laminations. Differences in internal texture have been related to the composition of the associated BMC. The distinct zones of differing texture and lamination properties in the larger, shallow-water stromatolites suggests that there have been significant changes in BMC species composition through time. In addition, while there is no evidence that different BMC communities are responsible for variations in external morphology, the contrasting internal characteristics of the shallow and deep-water stromatolites suggests that some differences may occur along a depth gradient.

Chemical Composition

The chemical composition of selected stromatolite samples has been determined by staining and x-ray analysis. All tested samples were found to be dominated by carbonate minerals, principally calcite. In stromatolites from sites which are dominated by diatoms (e. g. One Tree, Ela Elap), silica is also a major component. Some variation in chemical composition occurs within sites. For example, shallow-water stromatolites from Gouldens Hole were found to be composed of pure calcite, while in deeper waters the mineralogy was far more complex with silica, sulphur, manganese, potassium, iron and nickel also present. The presence of some of these minerals suggests that bacteria may be incorporated into deep-water BMCs.

Other Stromatolite Occurrences in the South East

The cenote lakes are not the only environments that support stromatolites in the Mount Gambier region. Actively-forming stromatolites have also been found in the freshwater, volcanic Blue Lake, which is part of the Mount Gambier volcanic Complex (Figure 1). While the origins of this lake are not directly related to karst processes, the crater rim sits on top of the Gambier Limestone, and the waters of the lake are derived directly from the same karst aquifer system that is exposed by the cenotes.

To date, five locations in the Blue Lake have been visited, and at least eight stromatolite growth forms are present (Thurgate 1992). This includes large reefs, conical towers (Plate 7), domes, extensive tabular deposits, and several columnar forms including large club-shaped columns (Plate 8) and small triangular columns with striated surfaces, similar to those described in Gouldens and The Black Hole (CB2). The BMCs of the Blue Lake stromatolites are dominated by a high diversity of diatoms including *Epithemia sorex*, *Amphora ovalis*, and *Achnathes brevipes*, the latter genus being a known stromatolite builder (Winsborough & Seeler 1984). The chemical composition of these structures is dominated by calcite, magnesium, silica and sulphur. The internal structure of these features is complex, and very different to the cenote examples.

The stromatolites of the Blue Lake are found on both vertical walls, as well as on the sediment-covered, sloping lake floor. The Blue Lake stromatolites are best developed at depths of 5-10 m below the surface of the lake, where a single structure may attain heights of up to

12 m. Generally the size and abundance of these stromatolites becomes increasingly less with depth, however, the clarity of the water and the seepage of carbonate-rich groundwater through even the deepest parts of the lake allow the development of moderately large structures to depths of up to 45 m.

Stromatolites and related organosedimentary deposits are also present in several hypersaline coastal lakes to the west of Mount Gambier and near the township of Robe. Stromatolites are present in Lake Hawdon South, but have never been formally described. In Lakes Fellmongery and Butler, Taylor (1975) described hard, pelletal aggregates of monohydrocalcite which are related to stromatolites. Taylor reported that these deposits were covered by a mucilaginous layer dominated by a BMC of *Oscillatoria*, *Schizothrix calcicola*, *Spirulina*, *Trichodesmium*, *Rivularia* and *Chlorella*. This list of microbes bears a resemblance to those described from some of the cenote stromatolites.

Conclusions

The Lower South East of South Australia is one of the most important areas of stromatolite development in Australia. Preliminary examinations of eight cenote lakes has revealed the presence of tens of thousands of actively-forming stromatolites. Based on an examination of the external morphology of the stromatolites 14 different 'types' have been identified. This classification has not yet been fully tested, but if shown to be accurate, then cenotes would support the most diverse communities of stromatolites reported from Australia so far.

In general, Australian environments which support actively-growing stromatolites are considered to exhibit a high diversity if between four to six morphologies are present (e.g. Grey et al. 1990). At Shark Bay in Western Australia, up to nine morphological types have been reported, and until now, this was considered to be the most diverse stromatolite environment on the continent (Hoffman 1976). In combination with the Blue Lake and Lake Hawdon South, the Lower South-East of South Australia contains a high diversity of aquatic environments with a combined total of 23 different stromatolite 'types'. Clearly this region is of national, if not international significance for the conservation of stromatolite biodiversity.

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References

BURNE, R.V. and MOORE, L.S. 1987 Microbialites: organosedimentary deposits of benthic microbial communities. *Palaios* 2:241-54.

GOLUBIC, S. 1976 Organisms that build stromatolites. In M.R. WALTER (ed) *Stromatolites*: 113-126. Elsevier Scientific Publishing, Amsterdam.

GOMES, N.A. d. N.C. 1985 Modern stromatolites in a karst structure from the Malmani Subgroup, Transvaal Sequence, South Africa. *Trans. Geol. Soc. S. Afr.* 88:1-9.

GREY, K., MOORE, L.S., BURNE, R.V., PIERSON, B.K. and BAULD, J. 1990 Lake Thetis, Western Australia: an example of saline lake sedimentation dominated by benthic microbial processes. *Mar. Freshw. Res.* 41:275-300.

HOFFMAN, P. 1976 Stromatolite morphogenesis in Shark Bay, Western Australia. In: M.R. WALTER (ed), *Stromatolites*: 261-271. Elsevier Scientific Publishing, Amsterdam.

HORNE, P. 1987 *Seasonal Temperature Changes in the Water-Filled Sinkholes of the Lower South East Region of South Australia*. Adelaide.

MONTY, C.L.V. 1976 The origin and development of cryptalgal fabrics. In: M. R. Walter (ed), *Stromatolites*: 193-249. Elsevier Scientific Publishing Company. Amsterdam.

MOORE, L.S. 1987 Water chemistry of the coastal saline lakes of the Clifton-Preston Lakeland System, South-Western Australia, and its influence on stromatolite formation. *Mar. Freshw. Res.* 38:647-60.

MOORE, L.S. and BURNE, R.V. 1985 The morphology and genesis of lacustrine stromatolites in South Australia and Western Australia. *Recent Sediments in Eastern Australia- Marine Through Terrestrial, Abstracts* 13:65-66. Geological Society of Australia.

MOORE, L.S., KNOTT, B. and STANLEY, N. 1984 The stromatolites of Lake Clifton, Western Australia. *Search* 14(11-12):309-14.

PARKER, B. C. and WHARTON, R.A. 1985 Physiological ecology of blue-green algal mats (modern stromatolites) in Antarctic oasis lakes. *Arch. Hydrobiol. Suppl. (Algological Studies 38/39)* 71(1/2):331-48.

TAYLOR, G.F. 1975 The occurrence of monohydrocalcite in two small lakes in the South-East of South Australia. *Am. Mineralogist* 60:690-697.

THURGATE, M.E. 1992 Some preliminary observations on the stromatolites of the Blue Lake, South Australia. *Proc. Tenth ASPAB Conference*. Australasian Society for Phycology and Aquatic Botany, Sydney.

THURGATE, M.E. 1995 Sinkholes, caves and spring lakes: An introduction to the unusual aquatic ecosystems of the Lower South East Of South Australia. *SAUSS Occ. Paper No. 1*. South Australian Underwater Speleological Society: Adelaide.

WALTER, M.R. (ed) 1976 *Stromatolites*. Elsevier Scientific Publishing Company: Amsterdam.

WHARTON J.R., R.A., PARKER, B.C., SIMMONS J.R., G.M., SEABURG, K.G. and LOVE, F.G. 1982 Biogenic calcite structures in Lake Fryxell, Antarctica. *Nature* 295:403-5.

WINSBOROUGH, B. M. and SEELER, J. S. 1984 The relationship of diatom epiflora to the growth of limnic stromatolites and microbial mats. In: M. Ricard (ed) *Proc. Eighth Int. Diatom Symp.* Koeltz Publishers, Paris.

WINSBOROUGH, B.M. and GOLUBIC, S. 1987 The role of diatoms in stromatolite growth: two examples from modern freshwater settings. *J. Phycol.* 23:195-201.

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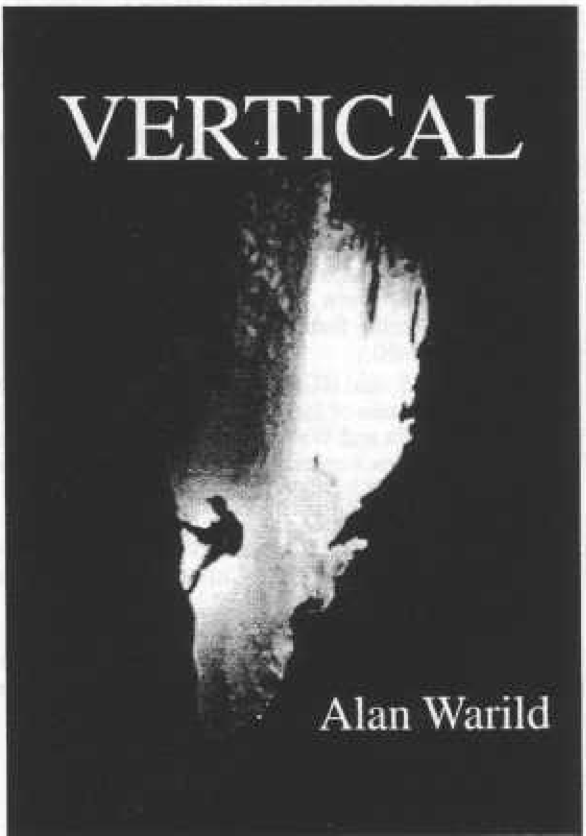
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WIGLEY, T.M.L. and WOOD, I.D., 1967 Meteorology of the Nullarbor Plain Caves. In: J.R. DUNKLEY and T.M.L. WIGLEY (eds), *Caves of the Nullarbor. A Review of Speleological Investigations in the Nullarbor Plain. Southern Austalia*: 32-34. Speleological Research Council, Sydney.

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