3.3 Wombeyan Caves

Introduction

Wombeyan Caves are located about 130 km to the south-west of Sydney (Figures 1.3 and 3.76). They are accessible by road from Mittagong or Goulburn and Taralga in the Southern Highlands (CMA Map 1976). Wombeyan Caves have been known to settlers since 1828 and developed for tourism since at least 1879 (Dyson et al. 1982). Wombeyan Caves Reserve is managed by the Jenolan Caves Reserve Trust (the same body which manages Jenolan Caves) and is a popular area for camping, walking and tourism. The surrounding area is agricultural but much of it is steep and left in a natural state. For most of the karst area, the vegetation is eucalypt woodland and grassland. Vegetation along creeks is dominated by *Casuarina* sp. Within the Caves Reserve are a number of marble quarries (ML2, ML3, ML4). The creamy white marble was quarried by Melocco Bros. for building stone. A quarry run by Steetly Industries crushes marble for industrial products.

Geological Setting

Regional Geology

Wombeyan Caves is about 19 km west of the western edge of the Sydney Basin. About 5 km to the west of Wombeyan Caves is a narrow belt of folded Ordovician sediments of the Triangle Group, trending N-S (Figure 3.75). These sediments are unconformably overlain further to the west by sandstones of the Upper Devonian Lambie Group which have developed in a syncline, forming a wide N-S trending belt (Cookbundoon Synclinorium). Silurian sediments, including a small amount of limestone, crop out about 20 km to the SE of Wombeyan Caves, SSW of Bullio. Sediments of the Upper Silurian Cobra Formation (Taralga Group) crop out 10 km to the north of Wombeyan Caves in Murruin Creek and Limestone Creek. The Wombeyan Limestone (Brunker & Offenberg 1970) crops out in an irregular area trending roughly NE-SW and is completely surrounded by effusive igneous rocks of the Lower - Middle Devonian Bindook Porphyry Complex (Scheibner 1973). In most places the limestone is highly marmorised to a creamy white, yellow and blue-grey saccharoidal marble, dolomitised in places. Metamorphism has recrystallised the fossil content and made dating the Wombeyan marble difficult but it has been correlated with the Upper Silurian Cobra Formation,and had developed in a stable, shallow, marine environment on the Capertee Rise (Scheibner 1973). The marble has been intruded by Devonian Columba Granite and gabbro. Granite intrusions (Dg and Cg) crop out about 15 to 20 km to the east and SE of Wombeyan Caves. Permian sediments of the Sydney Basin (Snapper Point Formation and Illawarra Coal Measures) crop out 19 km to the east (Bullio), SE and NE of Wombeyan Caves. Scheibner noted Permian deposits about 14 km south of Wombeyan Caves, surrounded by Lambie Group conglomerates, and suggested they correlated with the Tallong conglomerate.

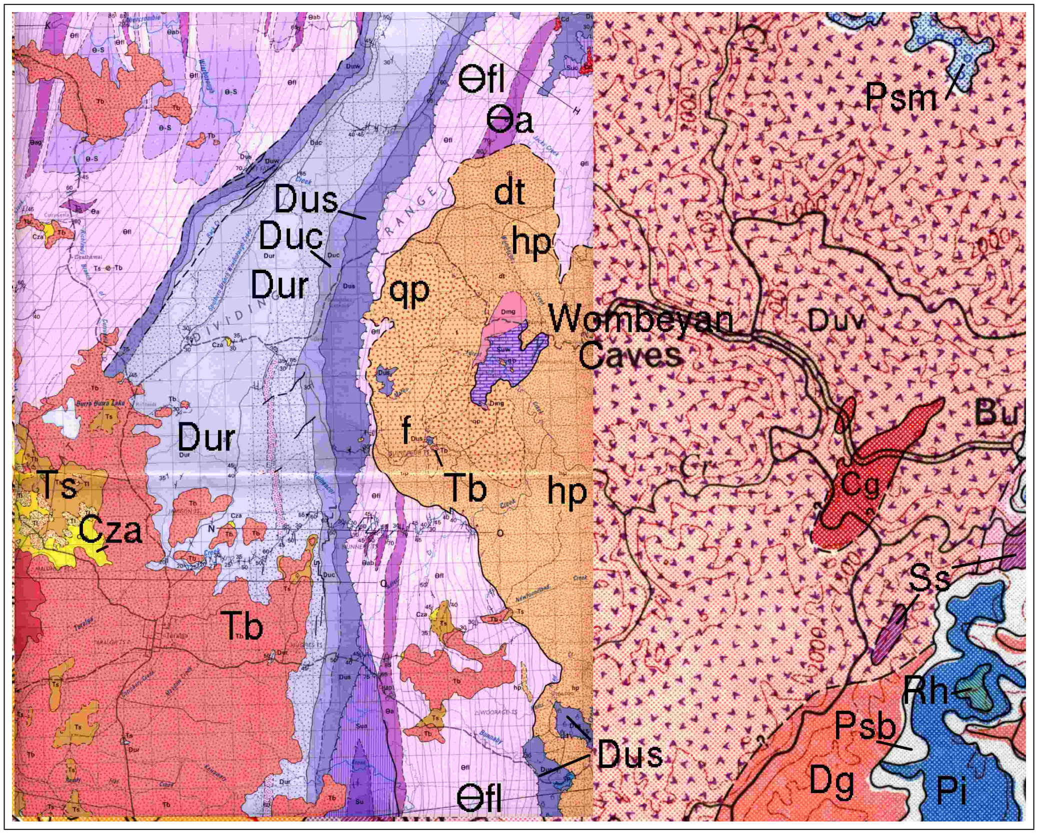


Figure 3.75: Geological Map of Wombeyan Caves region showing geological outcrops mentioned in text. LH side of area map is from Scheibner (1973). RH side of area map is from Brunker & Rose (1967). Width of image: approximately 40 km. Key: Cza - Quaternary alluvium (gravel, sand, silt & clay). Ts - Tertiary sediments. Tv - Tertiary volcanics (basalt, dolerite, microsyenite, trachyte & tinguaite). Rh - Triassic, Hawkesbury Sandstone (quartz sandstone with some shale). Pi - Permian, Illawarra Coal Measures (Sydney Basin). Psb - Permian, Berry Siltstone (Sydney Basin) (siltstone, sandstone & shale). Psm - Permian, Snapper Point formation (quartz sandstone, conglomerate, sandstone, siltstone, silty sandstone). Cg - Carboniferous (granite & granodiorite). Dmg - Early to Middle Devonian, Columba granite. Dg - Devonian, granite, tonalite & granodiorite. Dur - Latest Devonian to Earliest Carboniferous Lambie Group, Tarlo Formation (red sandstone, lithic sandstone, red, purple, green & grey shales, mudstone, quartzite). Duv - (undifferentiated) Lower - Middle Devonian, Bindook Porphyry, porphyry, dacite, tuff. dt, hp, f, qp: Part of Bindook Porphyry (dacitic and crystal tuff, hypersthene porphyry, felsite, quartz porphyry). Duc, Dus - Late Devonian Lambie Group, Cookbundoon Sandstone, Strathaird Formation (sandstone, shale, breccia, conglomerate, arkose, phyllitic slate, marine fossils). Ss - Silurian (sediments, volcanics & limestone). Θfl - Late Ordovician, Triangle Group Burra Burra Creek Formation (flysch, quartz greywacke, slates, carbonaceous slate, tuffs). Θa - Late Ordovician, Triangle Group, Bubalahla Formation (chert, radiolarian chert, slates, quartz greywacke & tuffs).

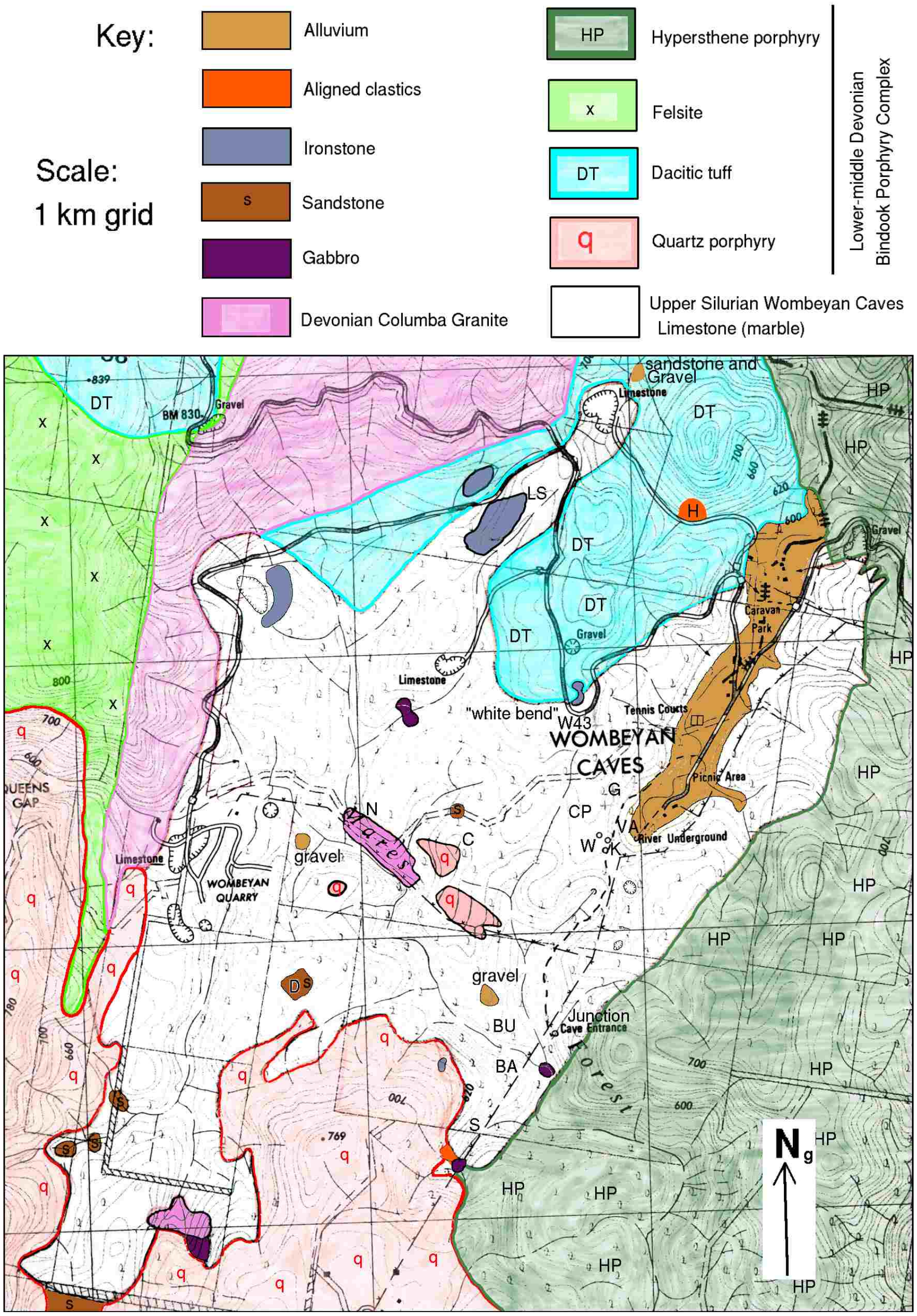
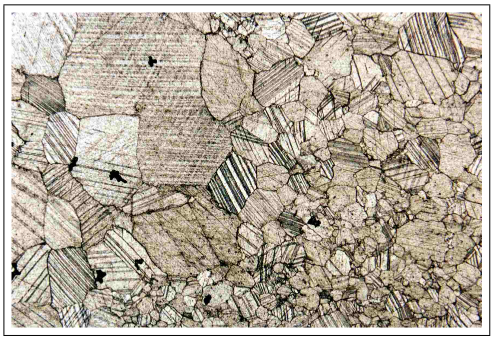
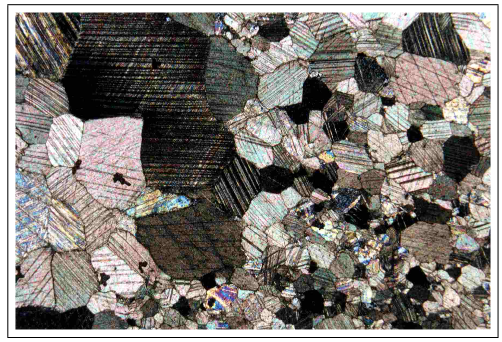


Figure 3.76: Map of Wombeyan Caves area showing geological features. Key to caves and other features mentioned in the text: BA - Basin Cave, BU - Bullio Cave, C - sample point near centre of park, CP - Cow Pit, D - Durins Tower Cave, FT - Fig Tree Cave, G - Guineacor Cave, H - Hockey Gully K - Kooringa Cave, LS - Lone Shoe Cave, S - Sigma Cave, VA - Victoria Arch, W43 - Cave W43, W - Wollondilly Cave. Based on Richlands topographic map 8829-II-N 1:25,000, overlaid with geological boundaries by Scheibner (1973), Osborne (1993) and this study.



W121/5 N35941 PPL, x13. Near Guineacor Cave.



W121/5 N35941 XN, x13.

Figure 3.77: Wombeyan marble.

Tertiary (Miocene is suggested by Scheibner) basalt flows unconformably overly the Ordovician and Silurian sediments about 10 km to the south and SW, and also 2 km to the SW at Mt Guineacor (Phipps 1950, Osborne 1993*b*). Most of the flows follow the region's older valleys and drainage lines. Quaternary sands and gravels are found near most of the streams of the region, and are also preserved within cave sediments at Wombeyan Caves.

Local Geology

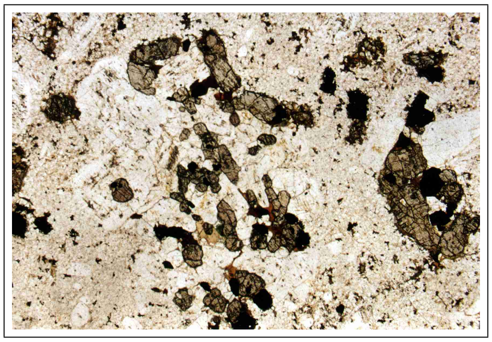
The local geological area around Wombeyan Caves comprises the region in Figure 3.76.

Wombeyan marble

The main body of the Wombeyan marble is a creamy coloured saccharoidal marble with yellow veining; other colours include white, blue-grey and yellow (Figure 3.77). Some small parts of the deposit are unaltered limestone such as the downstream area in Sigma Cave (Rowling 1999*a*). Osborne (1993*b*) noted the north-eastern margin of the marble was faulted, and dips to the west. Veins in the marble include a variety of calcium silicates including melilite. Wollastonite also occurs in the marble and may be recrystallised from silicic bioclasts in the original limestone.

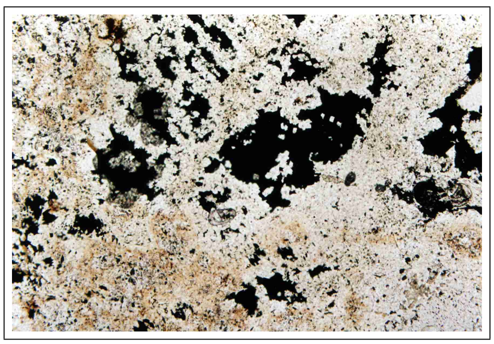
Bindook Porphyry

In all directions, the boundaries of the marble are overlain unconformably by silicic rocks of the Lower - Middle Devonian Bindook Porphyry Complex. The material comprises tuffs, ignimbrites and lavas. The Bindook Porphyry Complex near Wombeyan Caves was subdivided by Phipps (1950), and discussed by Scheibner (1973). In some places, the volcanic material has covered an ancient palaeokarst surface (Osborne 1993*b*). The eastern boundary of the marble is covered by (effusive) **hypersthene porphyry** and is faulted in places. The boundary between the marble and the porphyry is partly faulted and partly unconformable.

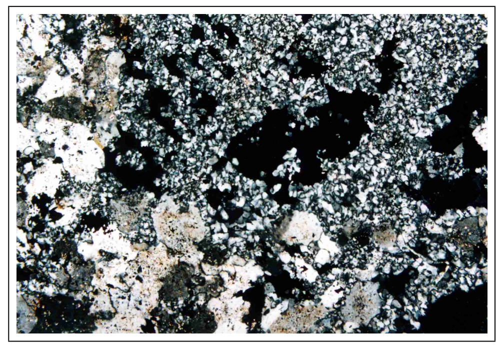


TS WOM-4 N36886 PPL x13. Hypersthene porphyry.

TS WOM-4 N36886 XN x13. Hypersthene porphyry with clotted phenocrysts.

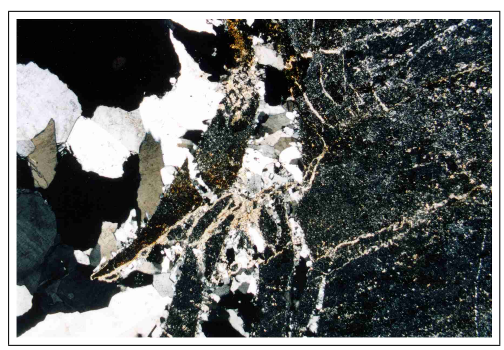


TS WOM-5 N36887 PPL x50. Vesicular phonolite with dark possible spinel. From centre of park.



TS WOM-5 N36887 XN x50. Vesicular phonolite with melilite.

TS WOM-6 N36887 PPL x13. Tuff/phonolite from centre of park.



TS WOM-6 N36887 XN x13. Tuff/phonolite with vein of melilite and nepheline, some fracturing and stylolites.

Figure 3.78: Thin Sections, effusive igneous rocks around Wombeyan Caves.

Sample WOM-4 is from about 250 m E of Victoria Arch. Thin Section N36886 (Figure 3.78) indicated a clotted phenocryst texture comprising about 20% pyroxenes (possibly olivine, orthopyroxene and hypersthene), 5% opaques including pyrite. Larger quartz phenocrysts had inclusions, stressed patterns and embayed edges. Feldspars included microcline, zoned albite and partially redissolved plagioclase. Many phenocrysts have glassy, zoned edges. A small amount of biotite may be present. The groundmass was a finer version of the same minerals.

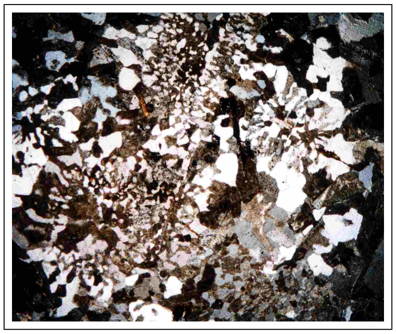
To the north-east, **dacitic crystal tuff** crops out in the area from "White Bend" northwards, and also in the north-west. The deposit in a quarry near "White Bend" is highly fractured and altered. Sample WOM-7, thin section N36889, has quartz phenocrysts in a matrix of quartz and altered feldspar with some possible welded or flow patterns reminiscent of an ignimbrite (Figure 3.79). Darker xenoliths occur in some hand specimens. **Felsite** occurs to the west of the Wombeyan marble. There are similarities between the White Bend material and the felsites in Phipps (1950).

To the south and south-west of the Wombeyan marble, **quartz porphyry** crops out (Scheibner 1973). This same material crops out in the centre of the park (Figure 3.76) as an effusive cover over the marble. Near the centre of the park, there are several other different igneous outcrops: a red and black scoriacous to rhyolitic to frothy phonolite with drusy crystalline vesicles, comprising melilite and opaques that are suspected spinels (sample WOM-5, thin section N36887, Figure 3.78). About 100 m to the SE of this is a weathered yellow tuffaceous rock. Sample WOM-6, thin section N36887 (Figure 3.78) from this area is a tuff / phonolite in which some of the quartz phenocrysts are shattered, embayed or have sieve textures. The material has stylolites, and has been permeated by veins of melilite and nepheline (black on XN). Quartz porphyry also occurs in the south east (discussed later in relation to Sigma Cave).

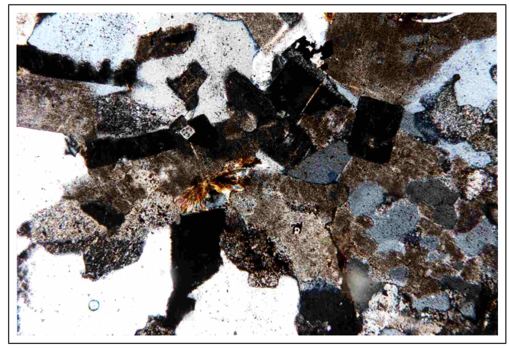
Intrusives

To the north-west is an outcrop of (intrusive) Late Devonian **Columba Granite** (Scheibner 1973). In the field this is a pink to red granite with black, brown and gold biotite grains and flakes. Weathered surfaces are rust-coloured. The grain size varies up to about 10 mm diameter. Its thin section texture shows approximately equal quantities of embayed quartz and feldspars with smaller quantities of biotite in a granophyric texture (Figure 3.79, Sample WOM-1, Thin Section N36850). Sample WOM-1 is from Wombeyan Creek; Sample WOM-8 is from the road cutting NW of Wombeyan Caves. XRD analysis of sample WOM-1 showed major sanidine, quartz, microcline, orthoclase, albite and anorthite with minor diopside, vesuvianite, metaschoepite and biotite. Some of the minor minerals are a source of Mg. Columba Granite also crops out in a small area near the south-west edge of the marble outcrop, and near the centre of the park (Osborne 1993*b*).

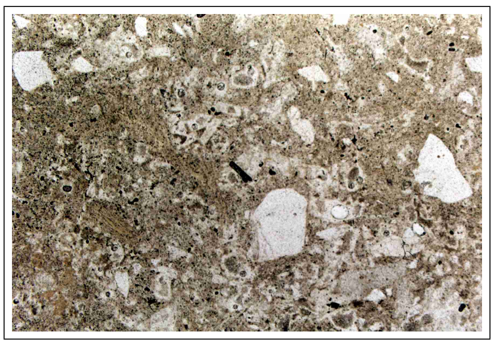
Gabbro crops out in small circular areas. One outcrop is near the south-west edge of the marble outcrop, close to Columba Granite. Another fairly olivine-rich gabbro occurs in the middle of the marble, south of Glass Cave and about 250 m south west of a marble quarry (sample WOM-9, thin section N36890, Figure 3.79). Field specimens are dark green to black on fresh surfaces, and weather to a grey-green and brown. This study noted two outcrops of gabbro in the south east of the marble, near Sigma Cave around the junction of Sigma creek and south Sigma



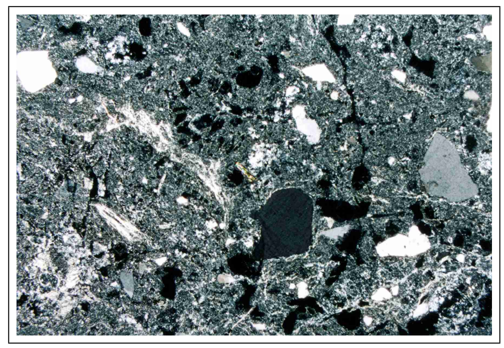
TS WOM-1 N36850 XN x13. Columba Granite. Granophyric texture.



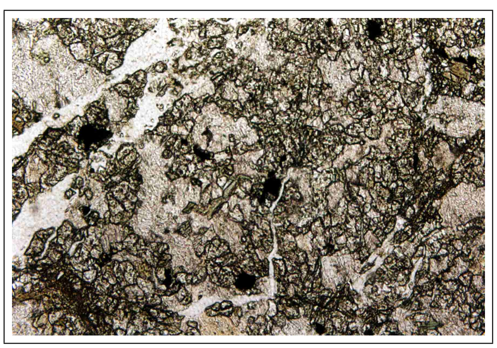
TS WOM-1 N36850 XN x50. Columba Granite. Quartz, diopside / vesuvianite, biotite and possibly wollastonite.



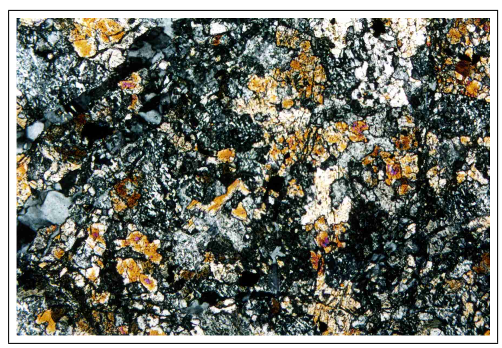
TS WOM-7 N36889 PPL x13. Dacitic tuff near White Bend. Ignimbrite texture.



TS WOM-7 N36889 XN x13. Dacitic tuff. Ignimbrite texture.



TS WOM-9 N36890 PPL x50. Gabbro, south of Glass Cave.



TS WOM-9 N36890 XN x50. Gabbro, south of Glass Cave.

Figure 3.79: Thin Sections, igneous rocks around Wombeyan Caves.

creek. This is discussed in more detail later (see Sigma Cave). Gabbro also occurs as boulders in Mares Forest Creek at the junction of Wombeyan Creek. Hand specimens were observed to be high in biotite and albite.

Filled joints and grikes

Filled joints are a feature of the marble (Osborne 1993*b*). In some areas, pyroclastic material has filled grikes. In other areas, such as in Junction Cave and Sigma Cave, Osborne showed that the "dykes" were filled joints, e.g. sample Σ2 which has formed a carbonated arenite (Figure 3.80). Near Igneous Fingers Spring is a small outcrop of a greenish, tough, fine-grained rock, which has been identified by this study as chert or siltstone and not an igneous rock as it is mainly silica with fine veins, no flow structures and no contact metamorphism. It is most likely a filled joint (Figure 3.80, Sample WOM-2, TS N35936).

Sandstones and ironstones

Sandstone occurs in the area as roughly circular deposits at high levels (Osborne 1993*b*). These are horizontally bedded; some are possibly filled dolines on an earlier karst surface and others are remnant surface deposits.

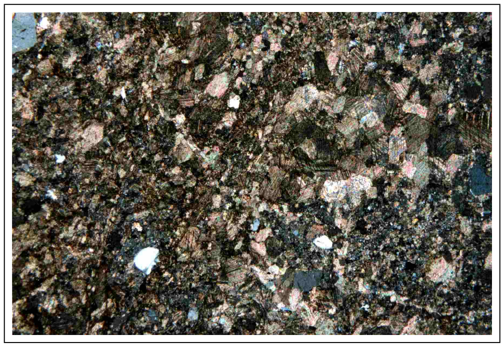
Scheibner (1973) mentioned the ironstone at Wombeyan. Osborne found that sandstones and conglomerates at high levels graded to ironstones, forming a continuous deposit and ascribed this to a more extensive cover of sediment over an existing karst surface. He noted more pure ironstones in the north of the marble deposit close to its edge, and in one case overlying the Columba Granite. They were considered to be an in-situ weathering product of the granites and volcanics. The age of the sandstones was suggested as either Permo-Triassic or Latest Cretaceous to Early Tertiary. Iron deposits occur near the north of the marble near Lone Shoe Cave. A small deposit of iron (goethite) occurs near the southern edge of the marble, between Basin Cave and Durins Tower Cave. The iron deposits occur as concretions of massive, ochreous or crystalline goethite adjacent to the marble (Figure 3.81). These have been interpreted as gossans and have slowly developed near the contact between the overlying volcanics and the marble.

Gravels and mass-flow deposits

North west of Hockey Gully are large boulders of rounded, cemented gravels. Clasts include quartz and are cemented with iron-rich sandstones. These are similar to the Permian gravel deposits at Jenolan Caves.

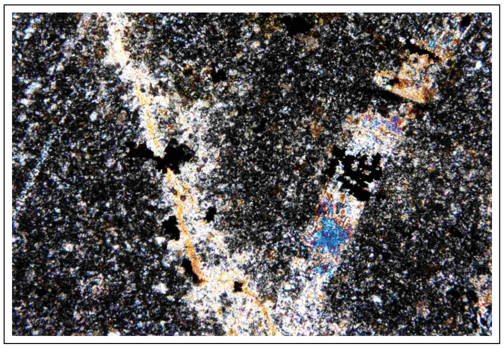
To the south of Mares Forest Creek at Wombeyan Caves is a prominent hill, mostly quartz porphyry. Its eastern side is partially mantled by a mass-flow deposit which also occurs in the caves near this hill, in particular, Basin, Bullio and Sigma caves. The gravels of this deposit comprise mechanically reworked and weathered porphyries (both felsic and mafic).

TS Σ2 x13 PPL. Embayed quartz and other fragments altered to carbonate. Ohno Drop, Sigma Cave.



Carbonated arenite, TS Σ2 x13 XN.

TS WOM-2 N35936 XN x13. Fine cherty siltstone, Igneous Fingers Spring.



TS WOM-2 N35936 XN x50. Fine cherty siltstone, Igneous Fingers Spring.

Figure 3.80: Thin Sections, filled joints.

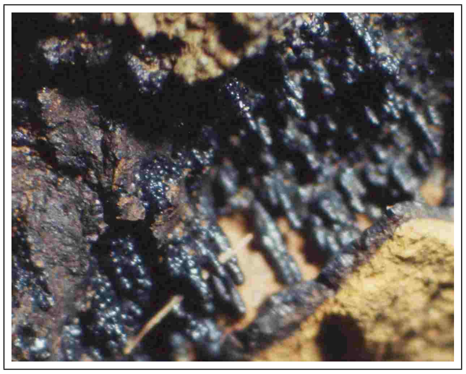


Figure 3.81: Goethite from the track near Lone Shoe Cave. Left: goethite crystal aggregate, x2.5. Right: stalactitic goethite in vugh, x8 approx.

Bone Breccia

The Broom bone breccia is an area of phosphatic sediment around a knoll to the west of Wollondilly Cave (Figure 3.76) identified by Broom in 1894 (Broom 1896) and discussed in Hope (1982) for its Pleistocene fossil fauna. Steep-sided dolines trapped several different mammal species such as *Burramys parvus* and *thylacine* (from the Broom deposit), and *Zygomaturus* and *Palorchestes* (from the Wombeyan Quarry deposit). Some caves at Wombeyan today have a pit-trap shape.

Geomorphological Setting

Wombeyan Caves are located in a broad basin surrounded by steep hills. The region is drained by Wombeyan Creek and Mares Forest Creek, thence Wollondilly River and is part of the Sydney catchment area. Tributaries of Mares Forest Creek include the ephemeral Wombeyan Creek, Gap Creek and several unnamed creeks. At a major bend in Mares Forest Creek, near the south-eastern corner of the marble outcrop, another intermittent creek joins from the south. This unnamed creek is referred-to in this document as Sigma creek for convenience. The northern part of Wombeyan Creek flows over dacite and hypersthene porphyry, and sinks near its contact with the marble. Its valley is blind, terminating at Victoria Arch. Floodwater from Wombeyan Creek flows though Victoria Arch, Creek Cave and the normally dry Wombeyan Creek south of Victoria Arch. Water from Wombeyan Creek resurges in Creek Cave (part of the show cave complex) for a short distance and continues underground, partially through phreatic tubes and partially vadose cave passages. It resurges in the Junction show cave and intermittently in the Junction Cave efflux. It joins Mares Forest Creek via underground conduits and intermittently flows to the southern end of Wombeyan Creek via the Junction Cave efflux. Scalloping on the walls of Grants Cave indicate that in the past, it has been both an efflux and an influx, taking flood water from Wombeyan Creek into the Junction Cave creek or vice-versa. The water flowing through Junction Cave is not aggressive to the marble. Instead it appears to be saturated to supersaturated with HCO_3 and deposits calcite gours in Junction cave and efflux.

Mares Forest Creek flows through marble gorges up to 50 m deep. Several caves efflux into the gorge. According to James, Jennings, Martyn & Halbert (1982), one of the underground creeks seen in Bouverie Cave has been dye traced to a creek in Bullio Cave. This involves the underground creek crossing a minor (surface) hydrological divide.

Aligned, angular gravels cover part of the marble. Deposits are located in Hockey Gully to the north of Wombeyan Caves. Gillieson & Spate (1993) suggested they were caused by cold-climate processes. Gravels similar to these crop out in Sigma creek. Osborne (1993*b*) described benches north of Victoria Arch and ascribed a Pleistocene age to them. Osborne noted a bench south of Sigma Cave at the 680 m level. A similar bench occurs to the west of Sigma creek. The present Sigma creek has cut through the eastern side of this bench, forming a short canyon. Scheibner (1973) noted many streams in the area were rejuvenated and had cut steep valley walls.

Geological and Karst History

During the Silurian (Ludlovian), limestone was deposited in a shallow marine environment. A karst surface existed during the Early Devonian and was buried by volcaniclastics during the Early to Mid Devonian. The oldest volcaniclastics filled submerged fissures, grikes and other karst features with sediment composed of particles of quartz porphyry. Marmorisation is suggested by Osborne (1993*b*) to have been caused by emplacement of the Late Devonian Columba Granite intrusions and other small mafic intrusions such as gabbro. Caves may have been present during the Carboniferous, with rockpiles and cave sediments, later to be relithified as coarse breccias. Crackle breccias, crystal lined vughs and porous fills appear to pre-date the caves. At some stage, rounded gravels and cobbles were deposited over the surface which was later eroded. A karst surface was again present during either Permo-Triassic or Latest Cretaceous to Early Tertiary. Sediment was deposited again over the landscape forming sandstones and angular conglomerates, some filling caves. Vulcanism during the Miocene deposited basalt about 2 km away and possibly closer. Iron oxides were deposited through some of the sandstone and gravels, possibly as a result of weathering of ferromagnesian minerals from the sandstones or from local thermal waters. A karst surface was again present during the Pleistocene, when some solufluction occurred, filling some of the caves with angular clasts of quartz porphyry, now loosely cemented. Latter stages of cold climate may have been responsible for the present rounded hills, lack of soil cover, erosion of the Broom deposit and unroofing of some caves such as Blackberry Hole and Cow Pit. The present landscape has many loose scree slopes, especially in the area south of Mares Forest Creek.

Introduction to Caves

There are 275 caves recorded for Wombeyan in the 1985 Karst Index database (Australian Speleological Federation 2002) with least another 185 speleological features (not all are caves) recorded by cavers. There are six well-decorated show caves and three ex-show caves. About 15 caves at Wombeyan could be described as “extensive”. Caves are scattered all over the karst, possibly because of the varied exposure the marble has had over time. The show caves are the largest and best decorated caves, and are mostly located on the eastern side of the area near Victoria Arch. Caves are generally aligned with major joint sets running roughly NNE and minor sets running NNW. The marble is heavily jointed in local areas, with a variety of joint angles influencing cave development.

Coarse and Crackle Breccias

Coarse and crackle breccias (Osborne 1993*b*) are a feature of many caves at Wombeyan. Coarse breccias may be a cemented rockpile, whereas crackle breccias resemble a mosaic of light coloured marble fragments cemented with dark red to brown and black calcite. In crackle breccias, there is no rotation of the marble fragments and the marble appears to have been invaded along cracks, possibly by thermal waters.

Crystal Vughs

Deep reddish brown crystal vughs occur in several caves at Wombeyan, such as Sigma Cave, Creek Cave, Mares Forest Creek Cave and Wollondilly Cave (Mulwaree Cave tour). Crystal vughs in caves are often associated with crackle breccia (Osborne 1993*b*). They appear to be calcite, and may be replacements after ferroan dolomite as some surfaces resemble that of dolomite with dark zonings extending into the marble bedrock. This feature of Wombeyan Caves needs further work. It is interesting to compare these vughs with similar pink crystal vughs at Mammoth Cave, Jenolan (Section 3.2).

Crystal Veins

Crystal veins occur in many caves at Wombeyan (Osborne 1993*b*), appearing as dark brown lines or veins in the creamy marble. The colour varies from light tan to black, from red to deep reddish brown. They are mainly calcite, and the dark colour seems to be mostly manganese oxides and goethite. Manganocalcite was noted in a crystal vein in Sigma Cave (sample Σ 8). Some of these veins are shallow and do not penetrate the bedrock very far. They may be a feature which was part palaeokarst and has been re-excavated by the present cave, which seems to be the case of the veins in "Alpha Amble" of Sigma Cave.

Gravel and cobbles

In both Fig Tree Cave and Wollondilly Cave, perched gravel and cobble deposits in the upper chambers of the caves are interpreted as older stream passages. The material resembles weathered Columba Granite and hypersthene porphyry, similar to that presently found in Wombeyan Creek and in the floodway of Creek Cave.

A different type of gravel deposit can be seen in Bullio, Basin and Sigma caves. Osborne (1993*b*) noted oriented allochthonous clastics in the upper levels of Basin Cave and Bullio Cave. These are angular clasts, often aligned in one direction, and interpreted as Pleistocene mass movements. This material can also be found on the nearby hillsides above Basin and Sigma caves and is similar to aligned angular deposits in Hockey Gully to the north. Mass-movement deposits are identified in Figure 3.76.

Caves Chosen

The caves chosen for this study were Sigma Cave, Wollondilly Cave and a steep sided doline called Cow Pit. Other caves examined were Guineacor, Kooringa and cave W43.

Why Were These Caves Chosen?

Sigma and Wollondilly Caves were chosen as aragonite had been reported from those caves. In the case of Sigma Cave, the aragonite area was found during a survey of the cave. Aragonite had been reported from Wollondilly Cave by cave guides (Terry Matts and Steve Reilly, pers. comm.). Cow Pit was chosen as it contains some aragonite-like wall speleothems, and is a different (more open) environment compared to Sigma or Wollondilly. Other caves were not chosen due to their apparent lack of aragonite, although some have aragonite-like speleothems. At Basin Cave, there is a curious stalagmite high on a wall niche near The Ballroom. This is almost entirely covered in coralloid forms and looks like a paramorph after an aragonite “Furze Bush”. The nearby walls contain deposits of black and white minerals resembling phosphates, although gypsum also occurs in the cave (most likely associated with bat guano). Basin Cave may have a very small amount of aragonite in the form of helictites in a muddy area north of “The Circular Walk”. Guineacor Cave was examined as unusual helictites had been seen in it, but little aragonite was found. A sample from W-43 (Big Crystal Squeeze Cave, also known as CO_2 Pit) was examined and contains a small amount of aragonite. This cave has some unusual square-shaped calcite speleothems but has a high level of foul air, preventing long term study.

Cave Observations at Wombeyan: Sigma Cave

Location

Sigma Cave is located in the south-east of the marble outcrop, south of Mares Forest Creek and close to its easterly edge. (Figures 3.76 and 3.85. The cave lies under a steep grassy hillside with an open woodland of blackthorn (*Bursaria spinosa*), eucalyptus (possibly *E. viminalis*), Kurrajong (*Brachychiton populneum*) and river reed (*Lomandra* sp.). A small intermittent unnamed creek runs along the eastern side of the cave. For the purposes of this study, this is called “Sigma creek”. To the south of the cave, another unnamed side creek in a steep gully flows eastwards and joins Sigma creek in a thicket. This other creek will be referred to as “south Sigma creek”, as it lies above and to the south of the cave. The vegetation in the thicket consists of blackthorn, clematis, *Acacia falcata*, stinging nettle (*Urticaria* sp.), a eucalyptus and a lush plant that resembles a pilea. Most of these plants prefer alkaline soils. The thickets delineate changes in underlying rock chemistry and do not occur in the valley east of Sigma creek, which is open woodland. Sigma creek is steep in places, with short waterfalls and mostly stable banks formed variously of quartz porphyry scree, marble and gabbro. South Sigma creek is very steep, with numerous short waterfalls and unstable scree banks.

Valley, Sigma creek.

Typical vegetation in the steep sloped thicket.

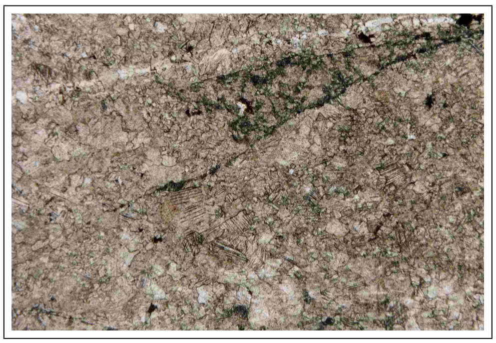
Figure 3.82: The Sigma Cave area.

Geological Setting

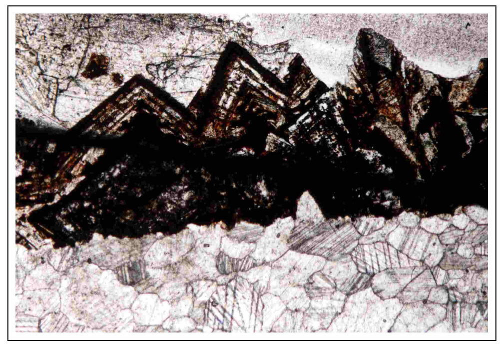
Not all of the bedrock is exposed around Sigma Cave; some of it is covered by scree. Sigma Cave lies close to the most south-easterly edge of the Wombeyan marble outcrop.

Carbonates

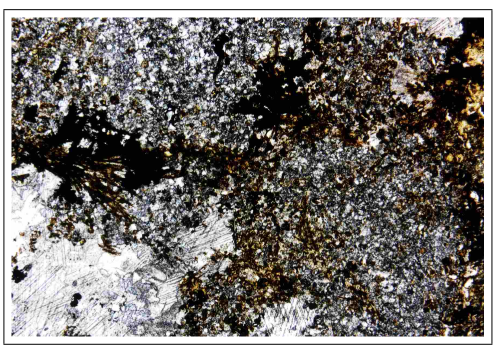
The rock around Sigma Cave is a cream coloured saccharoidal marble (Figure 3.83, TS Σ3) with occasional inclusions of wollastonite. It weathers to characteristic karstic shapes such as rillenkarren. The marble grain size varies from about 1 mm to about 5 mm, possibly depending on the original (pre-metamorphic) limestone texture. Marble near Sigma creek varies from high purity to veined to siliceous. Reddish veins appear to be altered dolomite. (Figure 3.83, TS W161-5a). To the east of Sigma Creek, the marble is impure, with boulders grading to a yellow and red limy rock with a high proportion of calcium silicates and ferromagnesian minerals (Figure 3.83, W161-6b). These rocks tend to weather like granite, with onion-skin flakes and may be metamorphosed impure limestone. A small amount of dolomite is associated with melilite veins (Figure 3.83, TS W161-6a). Marble may occur south of south Sigma creek, in a steep, narrow strip between the quartz-rich scree from the hill to the west, and the gabbro and porphyry to the east, based on vegetation types (no outcrop).



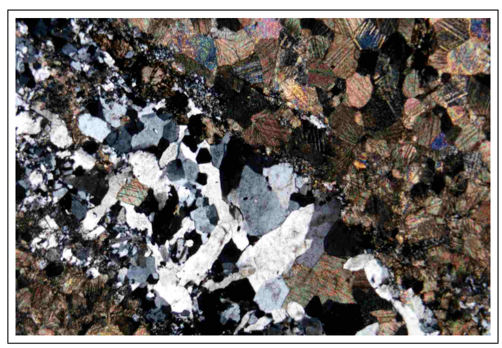
TS Σ3 PPL x13. Wombeyan marble near Sigma Cave with possible remnant bioclast.



TS W161/5a N35934 PPL x25. Wombeyan marble near Sigma creek with red vein (possibly altered ferroan dolomite).



TS W161/6b N36086 PPL x13. Impure marble, Sigma creek. With wollastonite, dolomite and iron oxides.



TS W161/6a N35943 XN x13. Vein in Wombeyan marble contains melilite and minor dolomite. Sigma creek.

Figure 3.83: Thin Sections, carbonate rocks in the Sigma Cave area.

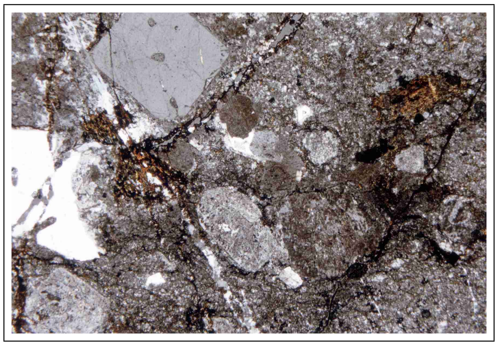
Porphyry scree and aligned gravels

The lush vegetated area on the surface between south Sigma creek and Ohno Drop in Sigma Cave is on a steep scree slope of aligned gravels and highly weathered boulders of slickensided quartz porphyry. The weathering of this material has contributed to the fine soil that supports the thickets. Samples W161/3a and W161/3b are of the porphyry, which has zones of ferromagnesian minerals. XRD of the weathered W161/3 material shows major quartz, albite, anorthite, with other minor feldspars (Figure 3.84, TS W161/3a).

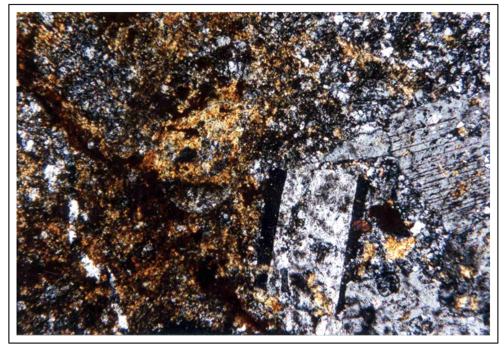
A similar material occurs in Sigma creek, east and below the scree slope (water-worn but not an outcrop: sample W161/4b). Sample W161/4b has quartz and pink (reflected light) ferrian vesuvianite phenocrysts in a fine matrix (Figure 3.84, W161/4b). This material may be related to the hypersthene porphyry to the east. Where the toe of the scree slope has been cut through by Sigma creek, the soil profile (approx. 2 m exposure) shows angular rock fragments, many aligned, similar to a mass-movement deposit.

Intrusives

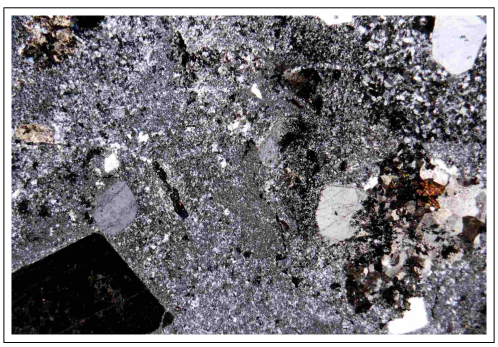
Near the junction of Sigma creek and south Sigma creek, gabbro crops out in a small, roughly circular area. Near Sigma creek, this is a dark green rock with a medium to low quartz content. Samples include W161/4a and W171/7a from Sigma creek. Specimens contain a high proportion of ferromagnesian minerals, albite and K-feldspars (Figure 3.84, TS W161/4a and W161/7a). This rock occurs in the most southern extent of Sigma Cave as dark rounded cobbles in small streamways; also in the bed of south Sigma creek. XRD of sample W161/4 showed major clinochlore, quartz, vesuvianite, albite and anorthite with minor uranium minerals, other feldspars, biotite, konyaite, sapphirine, baileychlore, and trace calcium silicates and rare earth minerals. Sample W161/7 contained similar minerals with more anorthoclase, chalcosiderite, eudialyte, wollastonite, and less uranium minerals. No age has been suggested for the gabbro.



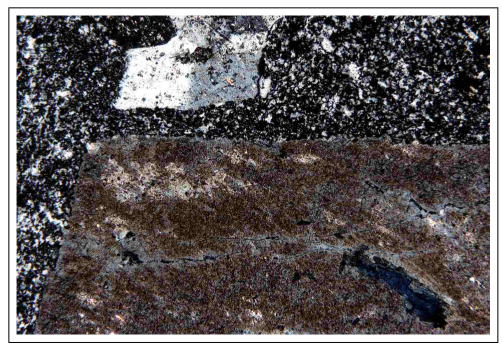
TS W161/3a N35931 XN x13. Quartz porphyry (weathered) from surface above Ohno Drop.



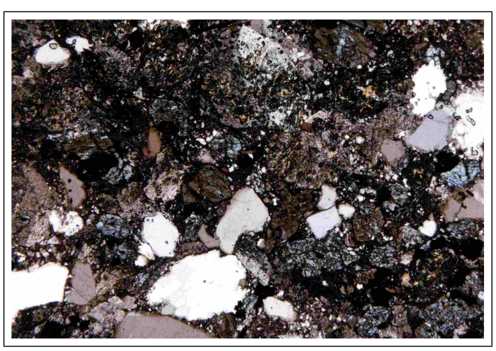
TS W161/3a N35931 XN x50. Albite and weathered ferromagnesian minerals suggests the rock may be related to the hypersthene porphyry.



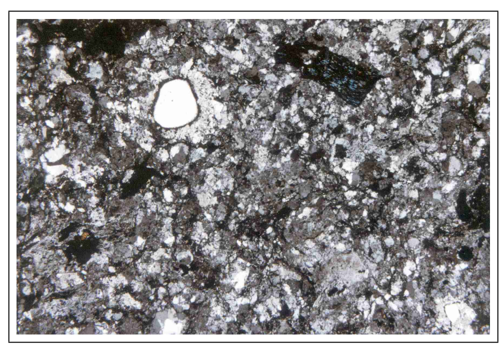
TS W161/4b N35933 XN x13. Phenocrysts include possible ferrian vesuvianite and quartz. Sigma Creek.



TS W161/4b N35933 XN x50. Possibly porphyritic ferrian vesuvianite with albite and sapphirine.



TS W161/4a N35932 XN x13. Gabbro with clinochlore and sapphirine, Sigma creek.



TS W161/7a N35935 XN x13. Hypersthene porphyry. Vesicles surrounded by aureoles. Blue phenocryst may be eudialyte or sapphirine. Sigma Creek.

Figure 3.84: Thin Sections, quartz - porphyry with possible ferrian vesuvianite, gabbro and hypersthene porphyry from surface near Sigma Cave and from Sigma creek east of Sigma Cave.

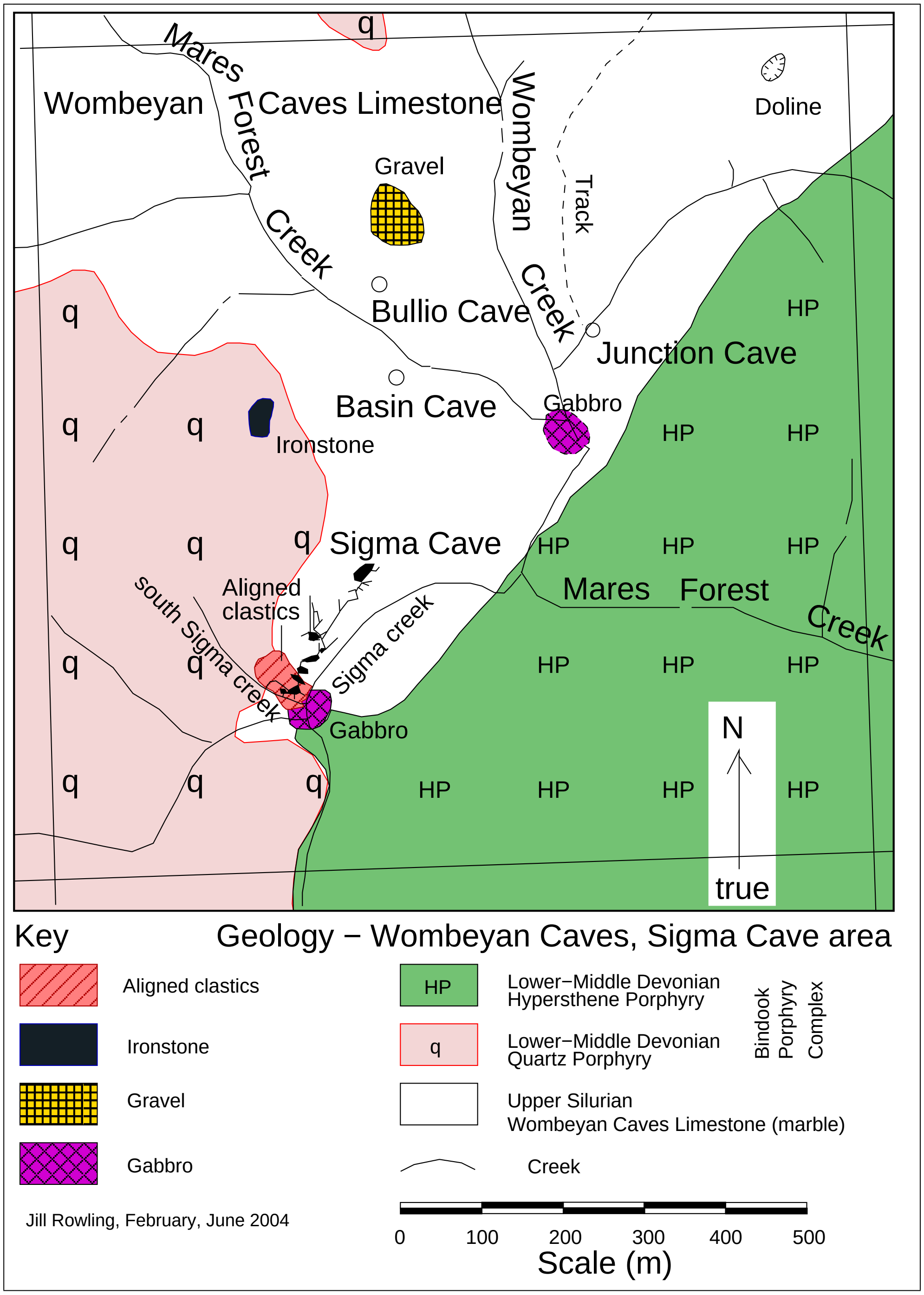


Figure 3.85: Geological map of the area near Sigma cave with Sigma Cave outline sketched.

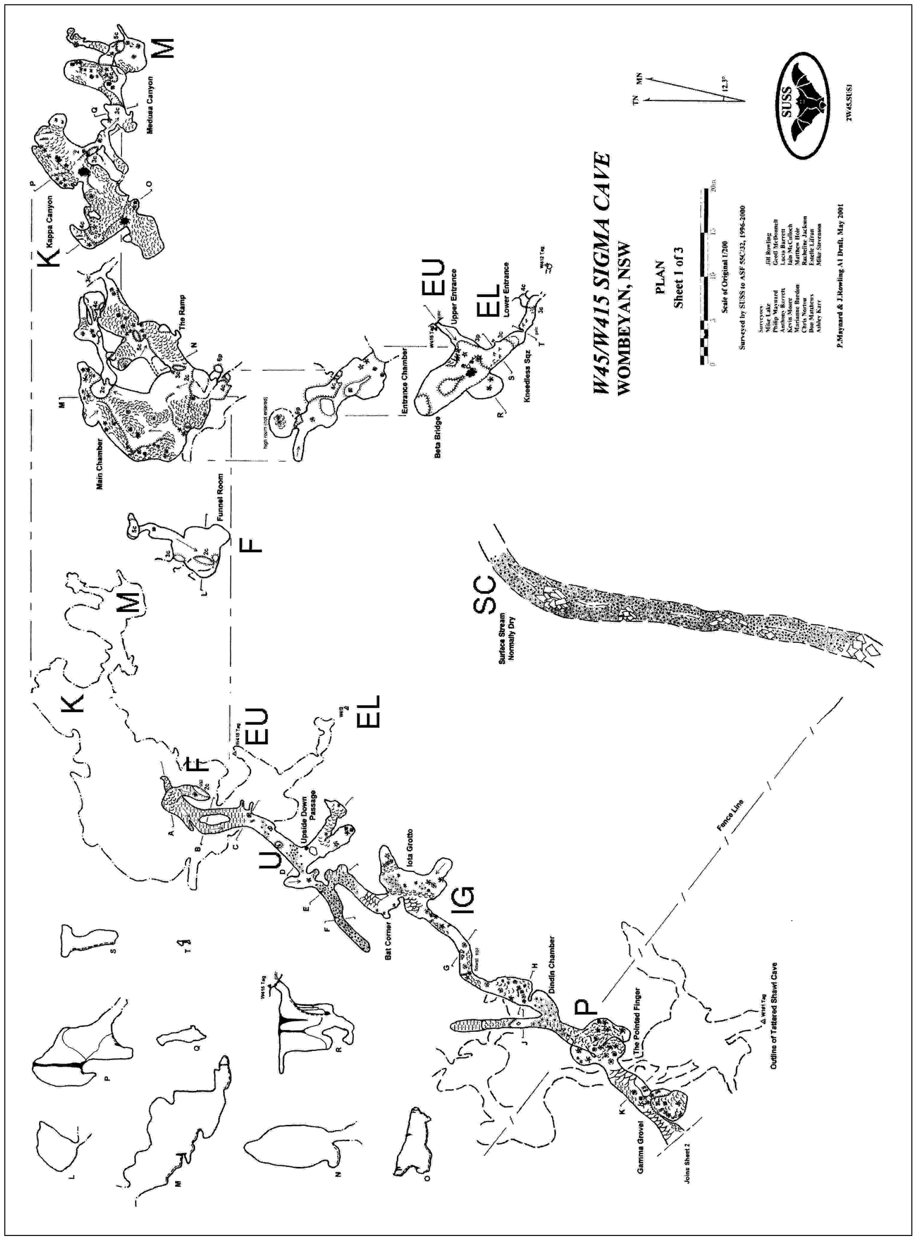


Figure 3.86: Map of Sigma Cave, northern region (plan view). Key: EU, EL: Upper and Lower Entrances; F: Funnel Room; IG: Iota Grotto; K: Kappa Canyon; M: Medusa; P: Pointed Finger Chamber; SC: Sigma creek; U: Upside Down Passage. Based on Sydney University Speleological Society map 2W45.SUS1 by Phil Maynard and Jill Rowling, 2001.

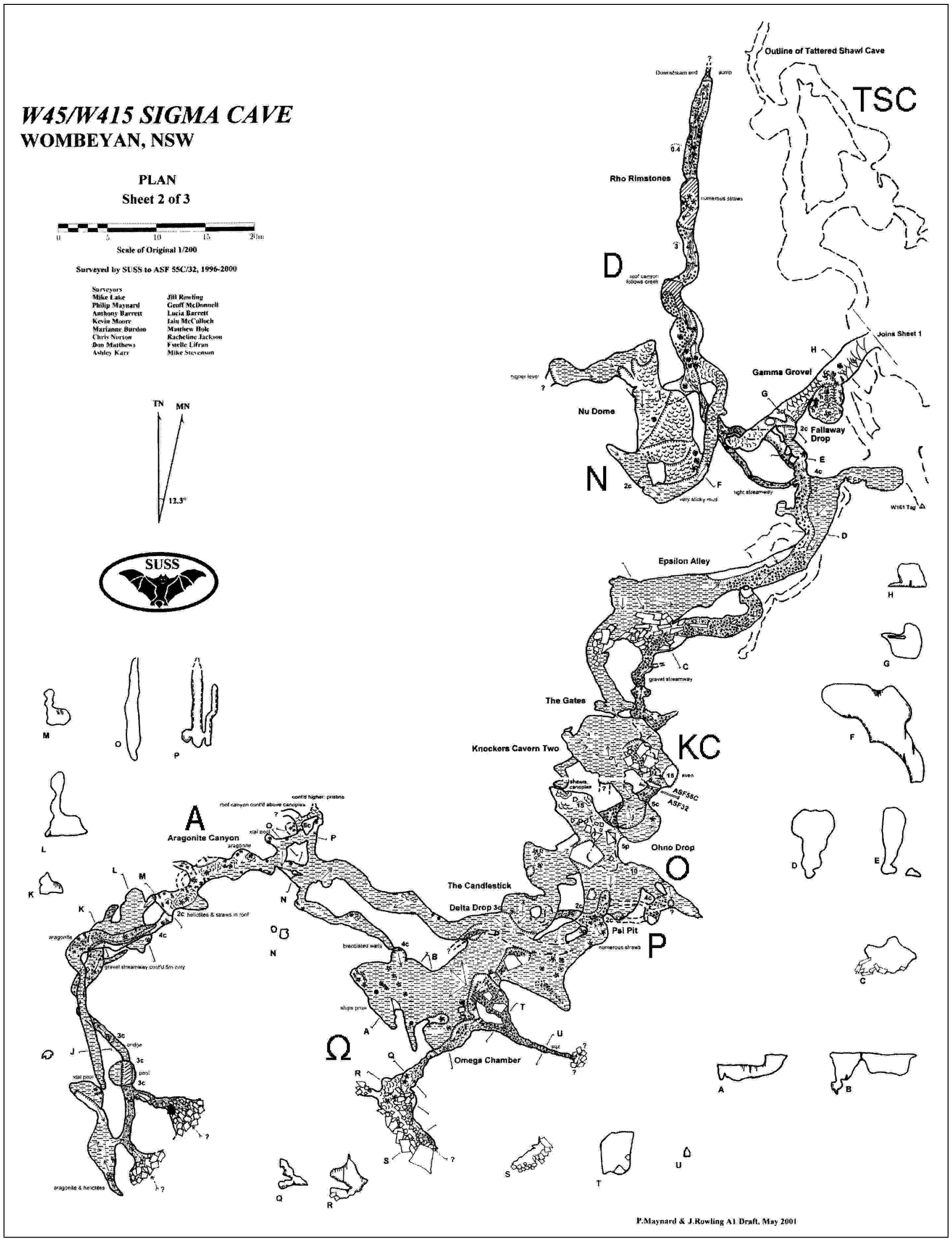


Figure 3.87: Map of Sigma Cave, southern region (plan view). Keys: A: Aragonite Canyon; D: Downstream; KC: Knockers Cavern Two; N: Nu Dome; Ω: Omega Chamber; O: Ohno Drop; P: Psi Pit; TSC: Tattered Shawl Cave. Based on Sydney University Speleological Society map 2W45.SUS1 by Phil Maynard and Jill Rowling, 2001.

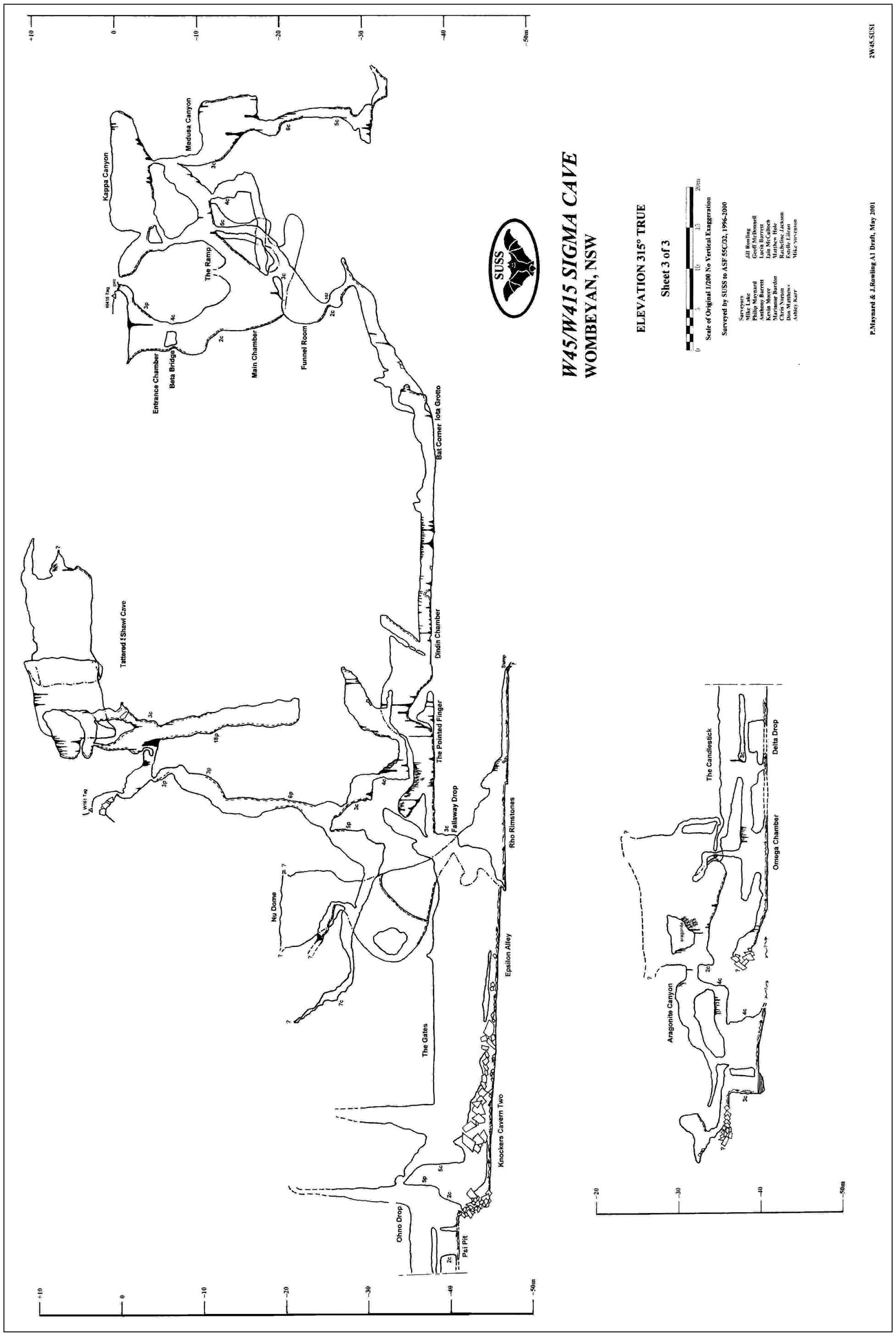


Figure 3.88: Elevation of Sigma Cave. Based on Sydney University Speleological Society map 2W45.SUS1 by Phil Maynard and Jill Rowling, 2001.

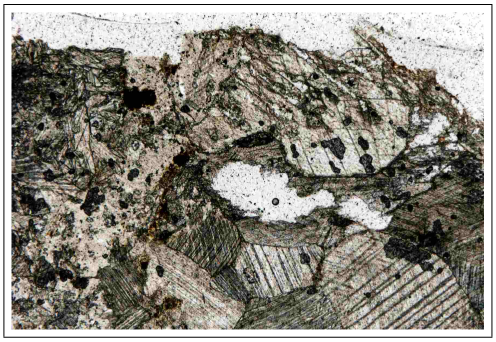
Cave Description

Sigma cave has about 3 km of surveyed passages forming an overall branching pattern (Maynard & Rowling 2001). It is developed along a NNE trending lineament corresponding to joints in the area and also possibly the strike of the original bedding. There are two main trunks to the cave: the main trunk is aligned along the NNE direction, and the downstream passages are aligned NNW. The two intersect at Fallaway Drop (Figures 3.86, 3.87). The cave is developed as a series of large chambers, interconnected by long, narrow tubes and canyons. Large chambers, often with flat or domed ceilings, include the Main Chamber, Nu Dome, Knockers Cavern, Psi Pit/Omega Chamber, Epsilon Alley. Refer to cave maps for the shapes of these chambers. Omega Chamber has a flat ceiling with irregular metre-length bedrock pendants. It has a tube in the ceiling which appears to have pre-dated the flat ceiling. Canyons include Kappa Canyon, the Medusa Series, part of the connection between Nu Dome and Fallaway Drop (although much of that is blocked with sediment) and Aragonite Canyon. The Medusa Series appears to be a captured vertical cave, as it is only connected to Sigma Cave at the top of Kappa Canyon. It is small at the base of the pitches, well cemented with calcite, and opens up towards the top to join the Kappa Canyon area which has a flat domed ceiling.

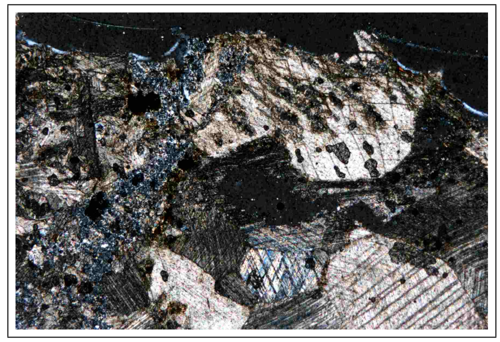
Flat ceilings are a feature of Omega Chamber and Knockers Cavern. They appear to post-date a period of tube development and may represent a period of ponded water. Usually, vertical shafts and caves in eastern Australia are shaped somewhat like an inverted paraboloid, with a small diameter at the top and a large diameter at the bottom. Some drops and shafts in Sigma Cave are the opposite, with a large flat roof and a small floor. Others are more conventional such as the aven at Psi Pit. The nearby aven in Knockers Cavern has a conventional cross section but the ceiling is bell-holed, like a series of hemispheres. Bell holes are also a feature of Medusa series, the Funnel Room and Main Chamber. Ceiling canyons are a feature of several areas of the cave including Downstream / Nu Dome, Epsilon Alley. Floor canyons are a feature of other areas, such as Kappa Canyon, Aragonite Canyon and parts of Omega Chamber where the present creeks flow. Areas of corroded bedrock include the lower levels of Epsilon Alley, (lower) Omega chamber, the Funnel Room, and an unnamed passage running parallel to the filled joint north of the Pointed Finger Chamber.

The northern half of the cave is relatively dry, with no active streamways. The southern half has a small, intermittent creek sourced in three places in Omega Chamber and one in south Aragonite Canyon which appear to have captured part of Sigma Creek and south Sigma creek respectively. There are several small streamsinks in the surface bed of Sigma Creek north of the junction of south Sigma creek as it passes onto the marble. These streamsinks appear to be captured by Sigma Cave and are a likely source of weathered igneous cobbles in the cave.

A large quantity of gravel has been deposited in the southern half of the cave and is being reworked by the present intermittent creek. The gravel predates the present speleothems. In Sigma Cave, there are three or four small stream sources in the southern section. Phil Maynard



Centre: possibly weathered feldspar. Σ2 PPL, x25.



Σ2 XN, x25.

Figure 3.89: Carbonated volcanic arenite, sample Σ2, from "dyke" separating Knockers Cavern Two and Ohno Drop.

and Jason Moule reported (pers. comm.) that the creeks originated from an impenetrable but draughting rockpile of small, rounded, black-coated igneous rocks. The black coating is most likely manganese oxides.

Most of the floors in the cave are covered with mud or cemented fill, and floor bedrock is encountered only occasionally such as the small streamways and parts of Iota Grotto. Tattered Shawl Cave is directly above the Pointed Finger / Shawl Room area of Sigma Cave and may have originally been connected to it. It comprises two independent pits connected at the top with a small passage and a long canyon.

Dyke-like bodies exposed in the cave were identified by Osborne (1993*b*) as karstic grikes, filled with volcanic debris during the Early to Mid Devonian. In the cave, they occur as both light and dark volcanic arenite "dykes". Sample Σ2 is the lighter variety (Figures 3.80 and 3.89) from Ohno Drop. The darker ones contain more ferromagnesian minerals. Dyke-like bodies have altered the cave's development by allowing cavities each side of the dyke to develop independently of each other (Osborne 2003). Both Ohno Drop and Knockers Cavern Two have high avens, separated from each other by a thick "dyke" above which lies the scree slope and thickets on the surface.

There is not a lot of faulting evident in the marble near Sigma Cave. During the cave survey a small displacement was measured in Omega Chamber / Psi Pit area. The fault plane strikes north, dipping 64° to the west. Possible remnant bedding strikes north, dipping 67° to the east. A tilted shell bank of small thumbnail-sized brachiopod fossils (sp. indet.) was noted in the grey limestone walls of the downstream area and possibly NuDome, (Rowling 1999*a*) but the dip was not recorded. A westerly dip is tentatively suggested.

Sample Sites and Observations

Aragonite, or aragonite-like speleothems occur (in order of abundance) at Aragonite Canyon, Omega Chamber, Pointed Finger Chamber, downstream creek area, Iota Grotto, Kappa Canyon and Medusa series. Samples were taken from the following sites in the cave: Aragonite Canyon, Iota Grotto, Ohno Drop.

Aragonite Canyon

Aragonite Canyon is a curved, slot-shaped cave passage (Figure 3.90). At its eastern end, the marble bedrock is corroded into "boneyard" (a form resembling Swiss cheese) with hole diameters typically 0.3 – 0.5 m. The walls have a corroded appearance, with several small holes between aragonite canyon and the passage to Omega Chamber. High above the eastern end of Aragonite Canyon, there is an aven (not entered) which is a continuation of a ceiling channel. The central portion of Aragonite Canyon has a high semicircular ceiling channel and a flat sediment-covered floor. The walls are sinuous in places, and relatively parallel, about 1 – 2 m apart. Further to the west, the canyon has an elongated keyhole cross-section. The western part of Aragonite Canyon is developed on two levels. The upper level is a continuation of the ceiling channel and forms a circular tube with wall niches and a slot in the floor which is partially sediment filled. In several places, it forms a keyhole with the lower level. The lower level is a slot-shaped canyon with a sediment-cemented ceiling and floor, and one bedrock wall exposed on the south side which

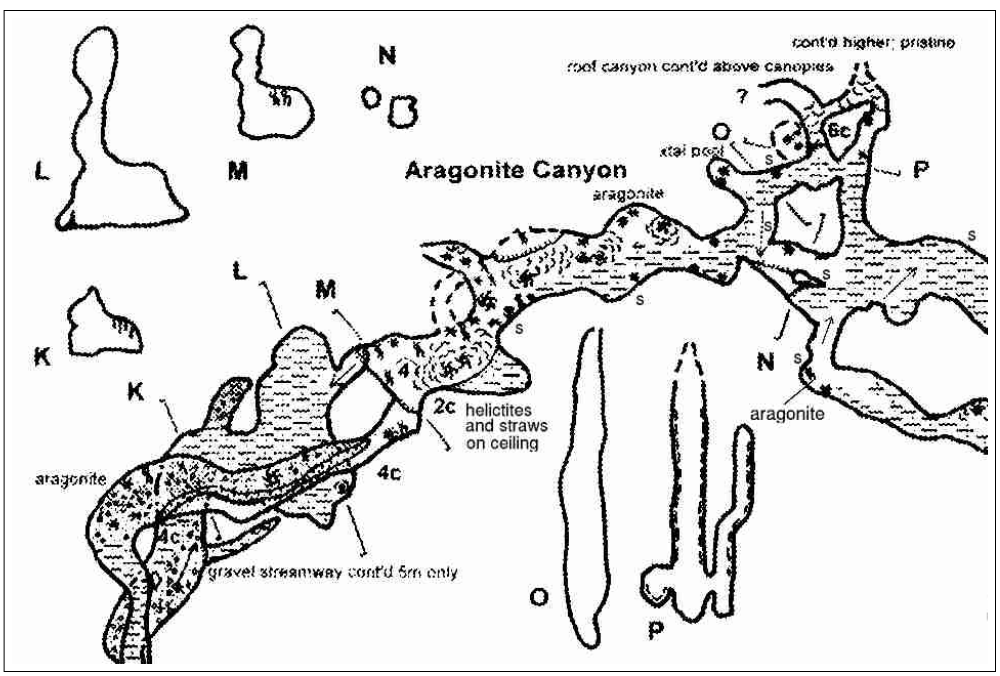


Figure 3.90: Map of Aragonite Canyon. Sample sites are marked "s".

Aragonite on bedrock, not on mud (east side).

Aragonite, sample Σ7 (east side).

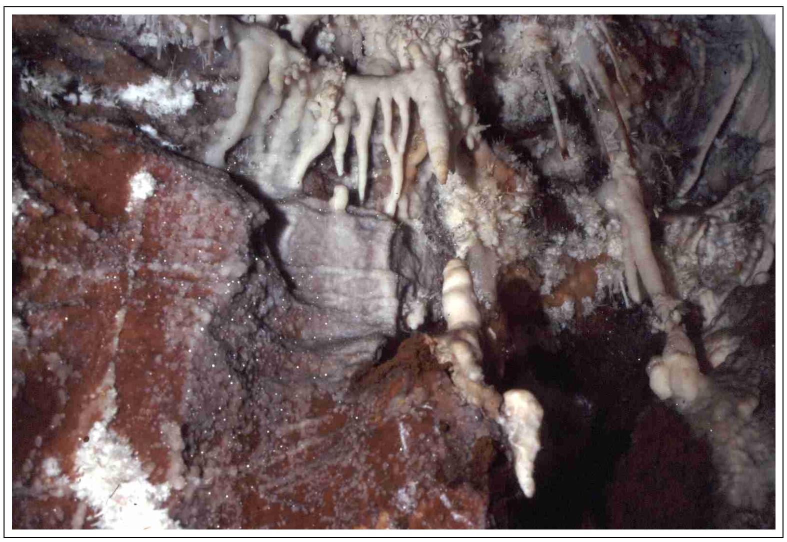


Figure 3.91: Aragonite Canyon view (west side).

appeared to be unmarmorised rudite (this was only inspected once on a cursory visit). The south-west part of aragonite canyon was not inspected. The mud in Aragonite Canyon is particularly moist and cloying, and may act as a humidity buffer.

Speleothems and samples in Aragonite Canyon

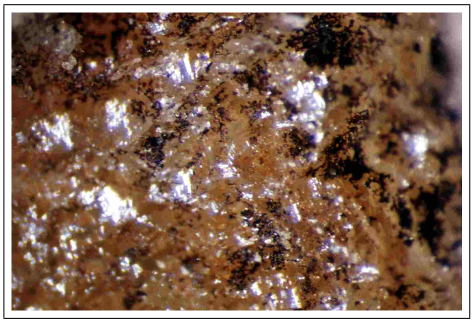
Aragonite occurs as prickly wall coating on marble bedrock and on mud. This form is mainly deposited on walls where breezes are felt. One of the holes on the eastern side is fringed with aragonite corresponding to where air movement is greatest (Figure 3.92). Above this line is a dark crystal vugh. Aragonite was sampled (Σ1 and Σ7) from this fringe (Figures 3.91 and 3.97).

To the south east of Aragonite Canyon, the corner of a higher level passage has anthodites associated with white “moonmilk”. Some of the anthodites had droplets of water on their ends. The marble bedrock at this site has crackle breccia and dark veins. One of the dark veins sampled (Σ8) contains major calcite and minor manganocalcite (XRD).

Figure 3.92: Aragonite in breezy area. Dark crystal vugh at top right.

The material is recrystallised, possibly from a dolomite precursor. The dark material appeared to be manganese and iron oxides (Figure 3.93). On the eastern side of aragonite canyon (west of the crawlway), aragonite occurs as a finer wall deposit. A sample (Σ9) of small skeletal aragonite coralloids showed a variety of microscopic crystal forms such as "church steeple" terminations (Figure 3.93). XRD indicated major aragonite, and trace scawtite ($Ca_7(Si_6O_{18})(CO_3).2H_2O$) (Appendix, Figure D.15). Tiny white blobs occurred at the ends of some of the aragonite needles. Aragonite fracture was characteristically across the blades. Some sugary crystal growth was most likely calcite. The substrate for the aragonite in this case was the muddy walls.

A "furze bush" is located high on a wall niche in the northeastern end of Aragonite Canyon, growing on a cemented gravel substrate. Some fallen "twigs" were sampled from near this furze bush, and were found by XRD to have major calcite, minor magnesian calcite, aragonite and hydromagnesite, traces of huntite and kaolinite (Appendix Figure D.16). The original aragonite structures are preserved in the shape (Figures 3.93 and 3.96). Most pieces are muddy. Some have a thin coating of hydromagnesite. The core of each piece is made of a bundle of rods (now calcite), with the optical axis aligned to allow light down the rods. These may have originally been hollow tubes. The surface of each "twig" has the characteristic flaring of the original aragonite crystals but with the points and edges blunted due to recrystallisation (to calcite). Broken "twig" ends have the aragonite-like 90° cleavage indicating the break occurred while the speleothem was aragonite. The present "twigs" exhibit cleavage more characteristic of calcite, or a mixture of both aragonite and calcite cleavage and parting between grain boundaries.



Vein sample, Σ8. Calcite rhombs resemble dolomite (x16).

Aragonite sample Σ9 (x13).

Sample Σ10. Broken “twigs” from near furze bush speleothem.

Figure 3.93: Aragonite Canyon samples.

Very old and dusty bat guano is present at the base of the aven at the eastern end of Aragonite Canyon. In the main part of Aragonite Canyon, numerous complex white and brown helictites and coatings form one wall.

The substrate is cemented gravel. Small stalagmites with a cross-patterned surface (possibly twinned) occur nearby. A small crystal pool is partially surrounded by velvet flowstone. A prickly stalactite / spathite was sampled (Osborne sample W114) from a broken specimen. This stalactite had a hollow tube in the centre, surrounded by flared aragonite crystals and with aragonite spikes on the outside. Some of the outer spikes

Figure 3.94: Prickly helictites from an aragonite stalactite (sample W114) have crystal “bundles” (suspected to be twins) and hydromagnesite on the tips.

(helictites) were examined (Figure 3.94), including material from the sidewall (a soft delicate aragonite). Some helictites had hydromagnesite coatings. The tips of the spikes have no obvious central canal, with hints of a fibrous structure. Tips are composed of three crystal "bundles" (possibly twinned) forming a Y-shaped groove. XRD indicates major calcite, minor magnesian calcite, aragonite, whewellite, skawtite and huntite (Appendix, Figure D.20). The helictites had partially recrystallised to calcite where they lay in the niche. This may have occurred when the speleothem was in situ, or may have reverted to calcite once the specimen was broken and left in the cave. The time it lay is estimated as 2 to 4 years based on known cave visitation dates. If the reversion occurred after breakage, it means the aragonite is kept in that form due to ions in the speleothem feed water and not intrinsically part of the clay or wall bedrock.

A white corroded-looking chalky speleothem was sampled (Osborne sample W111). Its substrate was mud and gravel, and appeared to be a corroded dripstone or stalactite. The speleothem was very powdery and porous. It was comprised of very fine layers of calcite, aragonite and phosphates with detrital calcium silicates. XRD of the hard crystalline portion indicated major calcite, minor aragonite, calcium silicates (actinolite, zoisite, riversideite), phosphates (vauxite, koninckite, leucophosphite, arrojadite) epsomite, and magnesian calcite (Appendix, Figure D.18). XRD of the soft powdery part indicates major aragonite, braunite, wollastonite, gageite and calcite with minor osbornite, perovskite, and phosphates (diadochite, variscite, collinsite) (Figures 3.98, Appendix, Figure D.19). Actinolite and other silicates are probably detrital and incorporated into the speleothem by dripping water. They normally weather readily in fresh water to goethite and clays but may be more stable in a high pH environment such as in a cave (Loughnan 1969). Most likely the carbonates are deposited as aragonite due to both magnesium (in epsomite) and phosphate from bat guano, and reverting to calcite as the phosphates crystallised. Possibly the minerals were initially deposited as a gel or fine suspension, resulting in the very fine crystal structures seen. The most likely source of silica is gabbro in the gravel, altered by bat guano.

The western (middle) chamber also contains numerous complex helictites and small anthodites, again with a gravel substrate. Helictites (suspected aragonite) are associated with fine gravel in the upper western keyhole-shaped area of Aragonite Canyon. Cavers have reported a small amount of aragonite from the southernmost area near the stream sources (Figure 3.90).

Near the eastern side of Aragonite Canyon, a sample (Σ11) was taken of a small speleothem associated with a dark bedrock vein and clay (Figure 3.95). The speleothem was a thickened helictite. XRD analysis indicated major calcite, minor manganocalcite and huntite. Its tips were hollow and porous. The surface of the speleothem was microscopically crenulated, characteristic of hydromagnesite. The dark vein was calcite only (from XRD) with no aragonite present. The clay was examined with XRD indicating major clays (kaolinite, kaolinite 1Md, kaolinite 1T, gibbsite), quartz, calcite, minor birnessite, manganite, pyrolusite, clinochlore, vermiculite (Appendix, Figure D.17). As clinochlore was also present in the gabbro at the junction of Sigma creek and south Sigma creek, this is the most likely source of the gravel in this part of the cave.

In one of the passages between Omega Chamber and Aragonite Canyon, a small shawl hangs above a crystal pool. The pool crystal has an unusual feathery appearance and may be a calcite paramorph after aragonite. Each pool "crystal" is a serrated triangle reminiscent of a Koch fractal.

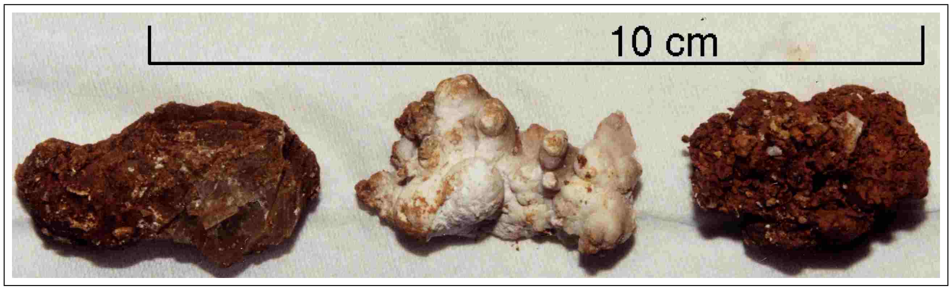
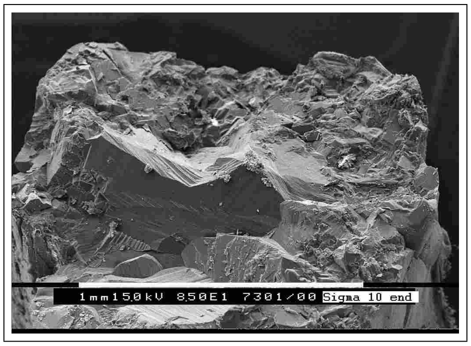
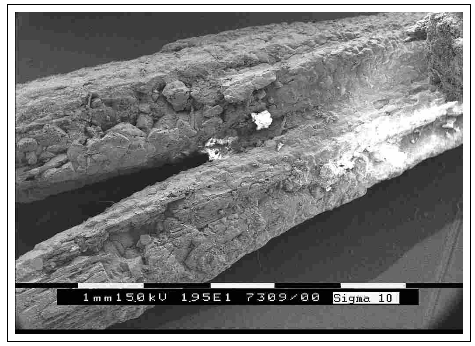


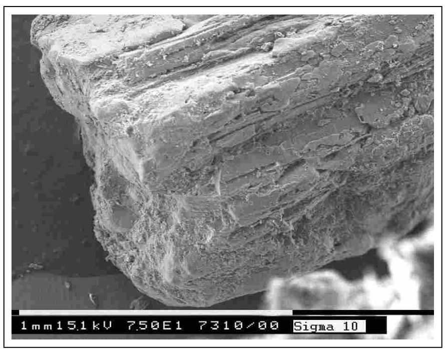
Figure 3.95: Sample Σ11 near aragonite canyon. Top: dark vein (left), speleothem and clay (right). Bottom: crenulated surface of speleothem is characteristic of hydromagnesite.



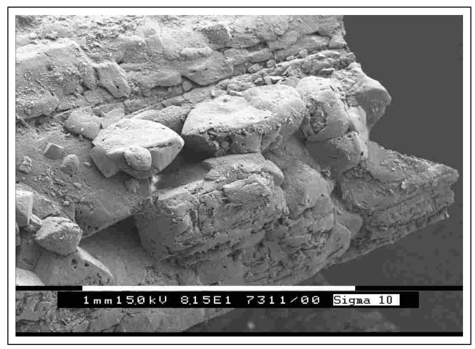
Broken section of anthodite needle. Lines on (calcite) inner section may be polysynthetic twinning. Background bundles may be aragonite.



"Twig" anthodite piece. Aragonite laths and needles with coating of hydromagnesite. Note porous structure. Diamond-shaped crystals are likely to be magnesian calcite.



(Original) cut end of anthodite. Orthorhombic cleavage on $\{010\}$ infers this was aragonite when broken. Coating may be clay and hydromagnesite.



Rhombs, most likely calcite, on surface of anthodite. Coating may be hydromagnesite. Note triangular pits in lower LHS xtals. RHS specimen fracture is aragonite-like.

Figure 3.96: Sample Σ10, "twigs" from near furze bush, Sigma Cave.

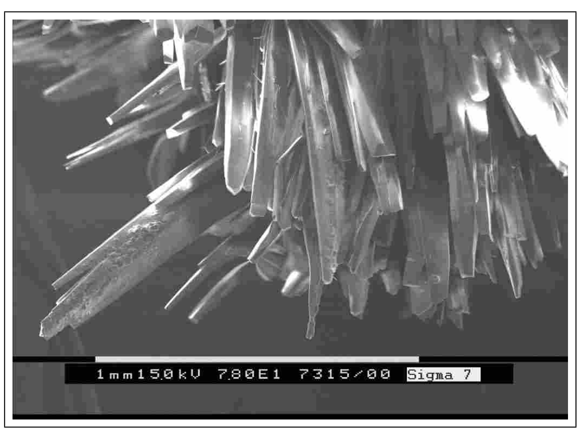
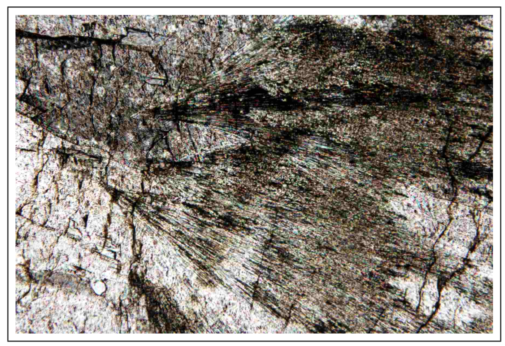


Figure 3.97: Aragonite Canyon, eastern side. Detail, aragonite sample Σ7.

Sawn speleothem. From left to right: fluffy region, crystalline region, fine layered region.

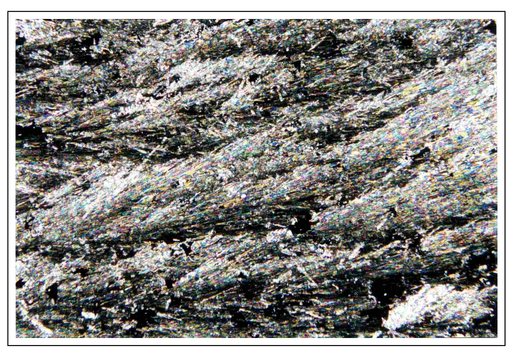
TS W111a XN x13. Darker area is aragonite, detrital calcium silicates and phosphate. Lighter area is calcite and aragonite.

TS W111a PPL x13. Fine aragonite bands; darker bands may contain detrital calcium silicates and epsomite.



TS W111a XN x50. Powdery needle crystals form islands within the consolidated aragonite and calcite. Calcite paramorphs speckled with inclusions. Some cleavage is aragonite-like, others are calcite-like.

TS W111b XN x13. Delicate aragonite undulose extinction with some phosphate.



TS W111b XN x50. Powdery part of speleothem comprises thin feathery columns of aragonite with undulose extinction.

Figure 3.98: Sample W111, speleothem, Aragonite Canyon. Thin sections on loan from Osborne.

Helictite, Pointed Finger Chamber

In the wall of Pointed Finger Chamber are a number of "saw" shaped helictites. A broken one was examined and found to have aragonite-like coatings on its underside and a dirty white coating on the upper side, possibly hydromagnesite with manganese oxides (Figure 3.99).

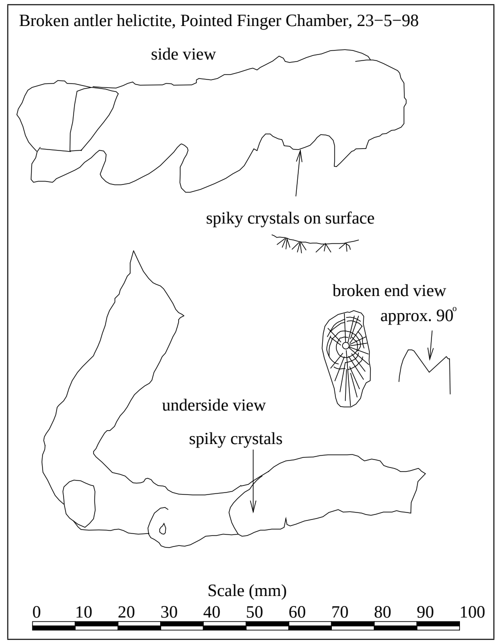


Figure 3.99: Broken antler helictite, Pointed Finger Chamber.

Speleothems: downstream creek area

In the downstream creek area, a bend in the creek is caused by a dyke-like structure (filled joint). Small "aragonite splinters" were noticed on the exposed red wall of this structure during the cave survey in 1998.

Speleothems and samples: Iota Grotto

In Iota Grotto, there are several helictites which appear to be partly calcite and partly aragonite. The helictites are all of the same variety and occur in three areas of Iota Grotto. One of these was sampled (Σ6, Figure 3.100). It is formed from three twinned blades of calcite with surface needles presenting characteristic aragonite forms. Due to the rough surface and three twin planes, they tend to absorb light internally and appear slightly darker than normal calcite helictites, however they are clear. They have poor UV response.

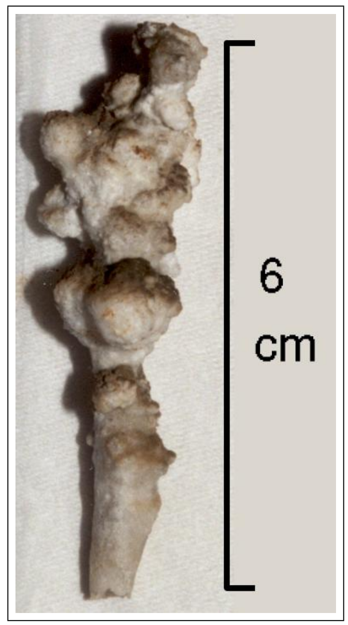
The angles between their branches are similar to those found on aragonite anthodites (roughly 30°). The substrate of some of these helictites is the veined bedrock and for others it resembles the filled dyke-like structures. Dark and light minerals (suspected to be manganese oxides and huntite) have been deposited near the bases of the speleothems. Under the microscope, the base of Σ6 is developed as a set of three similar "horns" of calcite with different optical alignments. One main "horn" is twinned axially. Each "horn" has similar horn-shaped projections which are twinned like the main stem in a recursive fashion. The main tip has a 90° chamfer as each twin half terminates with a 45° chamfer. The lower edges are smooth and the upper edges appear as though etched and have fields of small spikes, some resembling overlapping scales. The base has thin crystal sheets which fracture like aragonite. The fields of spikes resemble those seen in a sample from cave W43 (Figure 3.112). Nearby is a "Cave Turnip" (about 4 cm dia.) with an outer coating of clear, recrystallised calcite. "Cave turnips" occur elsewhere – discussed later with reference to Cow Pit – and are superficially described in Hill & Forti (1997).

The northern end of Iota Grotto has bare walls with a corroded appearance (Figure 3.100). XRD of the wall coating (sample Σ4) shows major gypsum, anhydrite, bassanite, minor calcite and trace brushite and sepiolite (Appendix Figure D.14).

The walls at Iota Grotto have a corroded appearance

Detail (x13) of gypsum coating, sample Sigma 4.

Helictite sample x2 Σ6, Iota Grotto



Stalactite, sample Σ12, Iota grotto

Figure 3.100: Iota Grotto and Samples Σ4, Σ6 and Σ12.

A small stalactite (sample Σ12, Figure 3.100) was found lying on the ground in Iota Grotto. It has hemispherical protuberances. Its base comprises (by XRD) major calcite, minor mangano-calcite and trace aragonite. The inside wall of the slot-shaped central canal is lined with small spikes, presumably a corrosion feature exposing tiny needles, suspected to be aragonite.

Speleothems and Observations: Kappa Canyon

This dry area is developed on multiple levels and is well-decorated with large calcite speleothems. At the junction of Kappa Canyon and Medusa Series, and other areas there is cave coral. Some of the coralloids have depressions in their centres either filled with needle crystals or with white pasty "moonmilk", or both. They are thought to be calcite speleothems with aragonite centres. A similar type of coralloid was examined from cave W-43 (Figure 3.112).

A partially cemented deposit of aligned, angular clasts (possibly porphyry) occurs in Kappa Canyon (Rowling 1998*b*). This deposit is reminiscent of a similar deposit located in Basin Cave a little to the north-west of Sigma Cave, which was dated to 27,850 BP (Gillieson, Spate & Head 1985). The origin of the clasts is unclear, as they are some distance from the present cave entrance, however not all of the present ceiling is marble. Some of this material may be a clastic fill that blocked an earlier cave entrance which is now covered by speleothems.

Speleothems in Medusa Series

Aragonite is not recorded from the Medusa Series but it has some aragonite-like speleothems. In wall niches at the top of this series of drops, small (1 cm to 4 cm diameter) "cave turnips" were noticed. Some of these had broken open naturally, possibly by gas build-up. The substrate was unknown as it was completely covered with calcite. They are most commonly found associated with small stalactites, occurring as a sphere partway down the length of the stalactite. Diameters vary from about 1 cm to about 4 cm. The outside of the speleothem appeared to be creamy yellow calcite, often with a recrystallised appearance. Inside the speleothem is a radially arranged hollow sphere of needle crystals, resembling aragonite, with a centre of mud with white "moonmilk". and in Iota Grotto; they also occur in other caves at Wombeyan such as Wollondilly and Kooringa. A similar speleothem was examined in Cow Pit (discussed later).

Medusa area was named for a perched and cemented gravel fill above one of the drops, covered with long recrystallised helictites ("Medusas Head").

Cave Weather Measurements

The air in Sigma Cave is relatively fresh, with mildly elevated CO_2 recorded from Aragonite Canyon (Table 3.4). The CO_2 was ascribed to organic decomposition of both bat guano and soil washed in from Sigma creek and South Sigma creek. Humidity was high (Table 3.5).

Date	**Location**	**Pump range**	**CO_2 %**
6th April 2002	East of Aragonite Canyon, site Σ11	1	0.5
6th April 2002	East of Aragonite Canyon, site Σ11	5	0.3
6th April 2002	Aragonite Canyon, site Σ7	5	0.3

Table 3.4: CO_2 measurements, Sigma Cave, using the MSA pump with Dräger tubes on the 1 and 5 pumps ranges as indicated in the table.

Location	**Av. wet bulb °C**	**Av. dry bulb °C**	**Depression °C**	**RH %**
6th April 2002				
Knockers Cavern Two	16.0 $\delta-$	16.0 $\delta+$	0.0 $\delta+$	>98

Table 3.5: Temperature measurements at Sigma Cave and calculated humidity , with three measurements taken at the site.

Synthesis - Sigma Cave

One of the calcite-inhibitors in Sigma Cave is magnesium. Minerals in the filled joints, and other minerals, possibly hydrothermally deposited, are presently leaching out of the bedrock and causing the present aragonite and aragonite-like speleothems to be deposited. Bedrock veins appear to be calcite replacing ferroan dolomite. Aragonite may deposit at times in the small crystal pool between Omega Chamber and Aragonite Canyon and in other speleothems at Iota Grotto, Kappa Canyon and the filled joint in the downstream area.

Another set of calcite-inhibitors, specific to Aragonite Canyon, are phosphates and sulfates (presumed bat origin), and ferromagnesian minerals (presumed gabbro origin). It is suggested that bat guano deposited on the gravel has hastened its chemical breakdown, releasing magnesium, manganese and other calcite-inhibitors from minerals in the gabbro. Aragonite is depositing as fine helictites directly on perched gravels. Aragonite is deposited in areas with higher air flow in aragonite canyon, indicating some concentration of minerals by evaporation and CO_2 outgasing. Where aragonite speleothems have laid on the ground, they gradually revert to calcite.

Wollondilly Cave

Wollondilly Cave is a show cave with two entrances. The two entrances are separated by about 150 m horizontally and about 15 m vertically, which encourages air movement through the cave. Historically, it was shown as two separate caves and later dug out to allow it to be shown as one tour. Aragonite was reported from the lower roof of The Cathedral and at the base of Jacobs Ladder by cave guides and has been found in Star Chamber and The Loft during this study.

Location and Geological Setting

Wollondilly Cave is towards the eastern side of the marble, near the saddle west of Wombeyan Creek, to the northwest of Victoria Arch (Figure 3.76). The cave is developed in saccharoidal Wombeyan Caves marble, which is mainly a cream to yellow colour with grain sizes ranging from about 1 mm to about 5 mm. Thin section (Figure 3.101) shows a mainly recrystallised texture, with some dolomite and dark areas suggestive of impurities. Major joints strike northwest and northeast, and dip to the east and west at about 45° forming gabled ceilings in areas such as in Mulwaree Cave. There is little evidence of original bedding. One joint outside the lower entrance strikes about 82° and dips about 67° to the south.

Cave Description

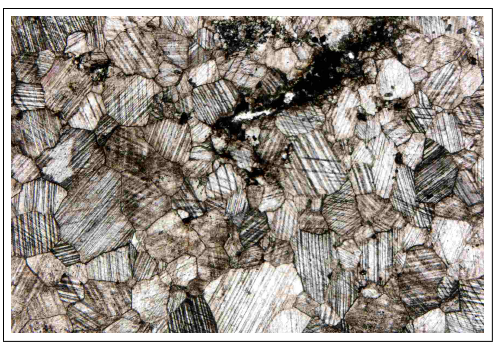
Wollondilly Cave may be considered as two caves which are joined at the lowest point ("The Fortifications"), which was dug out to aid tourist movement (Figure 3.102). There is no section (elevation) map of the cave available, so vertical relationships between chambers can only be estimated. The plan is incomplete. Wollondilly Cave is well-decorated with speleothems (mostly calcite). Where bedrock is seen, it is relatively smooth with large scalloping (around 300 mm scallop lengths). Many interconnecting passages are formed by the joining up of circular cavities and solution-enlarged joints. Passage directions are joint controlled.

The southern part of Wollondilly Cave includes the upper entrance, the passages called Mulwaree Cave, Queen Victoria Cavern, Mirandas Cave, Star Chamber and the large chamber called the Cathedral.

Mulwaree Cave, developed along the NNW-striking joint set, is a mainly level passage with a gabled ceiling formed by blocks which have fallen from the joint. Crystal vughs and dark filled joints are exposed in the cave bedrock, best seen in Mulwaree Cave. Queen Victoria Cavern is possibly developed along the strike of the original bedding, as both the ceiling and floor dip to the west. Mirandas Cave is aligned along the NE-striking joint set at a lower level to Queen Victoria Cavern and Star Chamber. Star Chamber and The Loft form a rounded rectangular shape with a flat ceiling and floor, with the longest dimension aligned towards the east. The chamber is partly filled with gravel (described in more detail with the samples). It intersects The Cathedral at a high level but the ceiling is lower than that of The Cathedral. The Cathedral is a very large teardrop-shaped chamber with a high domed ceiling 60 m above its rockpile floor and some 20 m below the surface (Dyson et al. 1982).

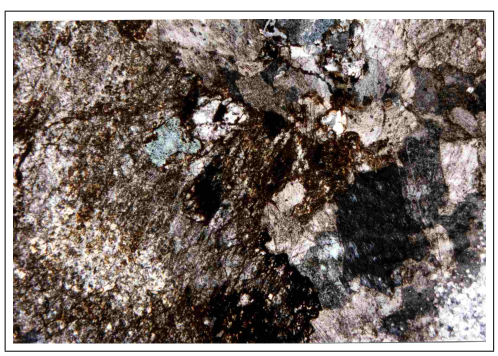
The northern part of Wollondilly Cave includes the lower entrance, the Pantheon, Jacobs Ladder, The Fortifications and the unlit Coronation Cave. The Pantheon is a low, flat chamber with a blocky floor following the contours of the ceiling. Jacobs Ladder is a canyon-like region of the cave oriented E-W and is much lower than The Pantheon. Upper chambers and passages in this region are not mapped.

The lowest (western) part of the cave (Fortifications and Coronation Cave) is often wet from seepage. The Fortifications are developed along the NE-striking joint set. Passage cross sections in this low section are typically long wide ovals with a flat ceiling. Coronation Cave is mainly developed along the NW-striking joint set. The floor is flat, and the ceiling height varies from about 2 m to about 4 m.. The cross-section varies from a low, flat oval to canyon-like or with ceiling slots and small domes.



TS W144-13a N35929 PPL x13. Wombeyan marble. Dark material may be surface contaminants (plants).

TS W144-13b N35930 PPL x13. Marble; recrystallised sparite with possibly biosparite and possibly remnant crinoid fragments.



TS W144-13b N35930 XN x13. Some ferroan dolomite is present (lower left).

Figure 3.101: Thin Sections, rocks in the Wollondilly Cave area.

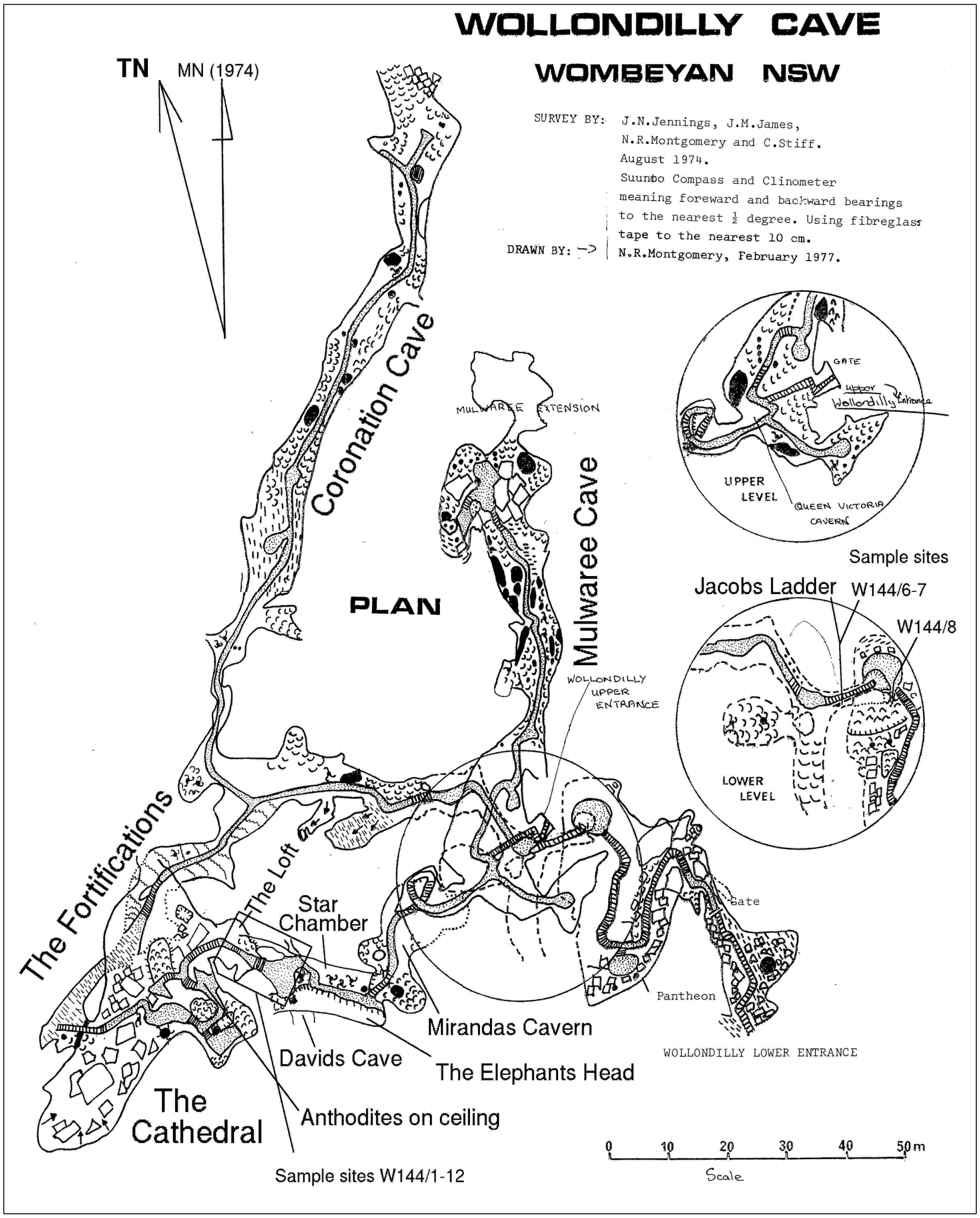


Figure 3.102: Map of Wollondilly Cave (based on unpublished map by Sydney Speleological Society; Mulwaree extension based on map by Sydney University Speleological Society). Boxed area (sample site) is expanded overleaf.

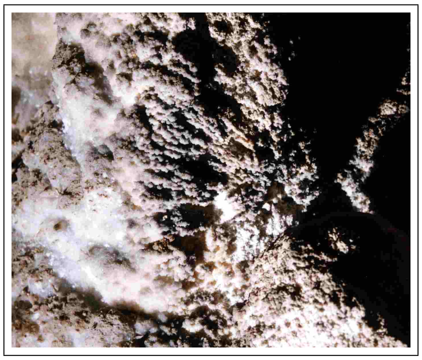
Observations: Star Chamber

Star Chamber is located to the east of the Cathedral. It has a rounded rectangular shape in plan and section, and fairly smooth walls. The south wall features several long pendants (e.g. "The Elephants Head"). A lower set of passages (Davids Cave - unmapped) connect to Star Chamber on the south side via a 2 m drop below the pendants. A small canyon-shaped passage joins Star Chamber on its NW end (Figure 3.104). A mass of rounded cobbles and fill at the western end of Star Chamber has been partially excavated and forms the substrate for a number of canopies with aragonite-like speleothems and upturned helictites. Star Chamber has a fairly flat ceiling with a large number of chalky-looking stalactites. Small samples of spiky material and a small helictite was collected from the walls.

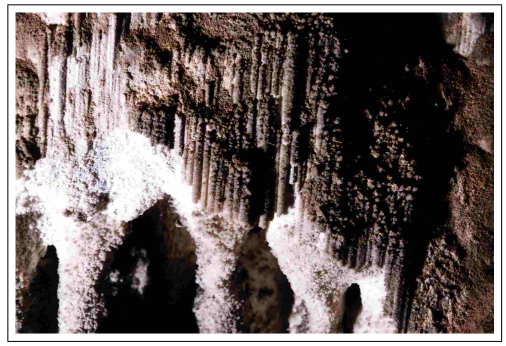
At the western end of Star Chamber there are grey deposits on the walls, caused by dust settling on carbonates which have precipitated from cave fill. On either side, stalactites and flowstone have a rough coating of fine coralloids. Under the hand lens, some of the more spiky coralloids have an aragonite-like appearance, with a white powder on the surface of the speleothem (possibly huntite). The material fluoresces blue-green with long wave UV. Sample W144/1 (Figure 3.103) is a small piece of horizontally aligned coralloid. XRD indicates major calcite, minor magnesian calcite, aragonite, huntite, pyrolusite and trace vaterite. It is in an area of high air movement. Sample W144/2 (Figure 3.103) is a small piece of vertically aligned coating over moonmilk in the same area as W144/1. It is very brittle and appears to be recrystallised. Crystal terminations are bladed and resemble those of aragonite. The material fluoresces blue-green with long wave UV. XRD indicates major calcite with minor huntite.

Ribbon helictites are found in the ceiling of this section, and a small group of long, upturned vermiform helictites on the north wall are associated with a white powdery deposit (possibly huntite and hydromagnesite) – Figure 3.103. I have observed that upturned helictites are often associated with magnesium ions (e.g. in Tantanoola Cave, South Australia). Nearby, a canopy has small recrystallised anthodites (Figures 3.103). One small piece was sampled (W144/3) from the rear of the canopy and found to be very brittle, with microscopic twinning. Raman spectroscopy of some squareish crystals indicated mainly calcite and minor aragonite. XRD of another small piece indicates major bassanite, manganocalcite, minor calcite and gypsum (XRD). Most likely the material is being deposited as aragonite, then reverting to calcite as availability of calcite poisoners decreases (depends on moisture levels) resulting in multiple twinning.

Sample W144/4 is of a small piece of filigree helictite / coralloid from a canopy on the south western wall of Star Chamber. Crystal terminations included those of aragonite and of calcite. Raman spectroscopy indicated calcite, possibly aragonite but very high fluorescence. XRD indicates major calcite, with minor aragonite, trace huntite and hydromagnesite.



Sample W144/1: aligned coralloids. Width of view about 10 cm.



Sample W144/2: Vertically aligned fluting. Width of view about 15 cm.

Canopy, sample W144/3. Width of view is about 2 m.

Upturned vermiform helictites behind canopy. Width of view is about 40 cm.

Sample W144/3: Recrystallised anthodites. Width of view is about 20 cm

Sample W144/3: Recrystallised anthodites. Width of view is about 10 cm

Figure 3.103: Star Chamber: western end.

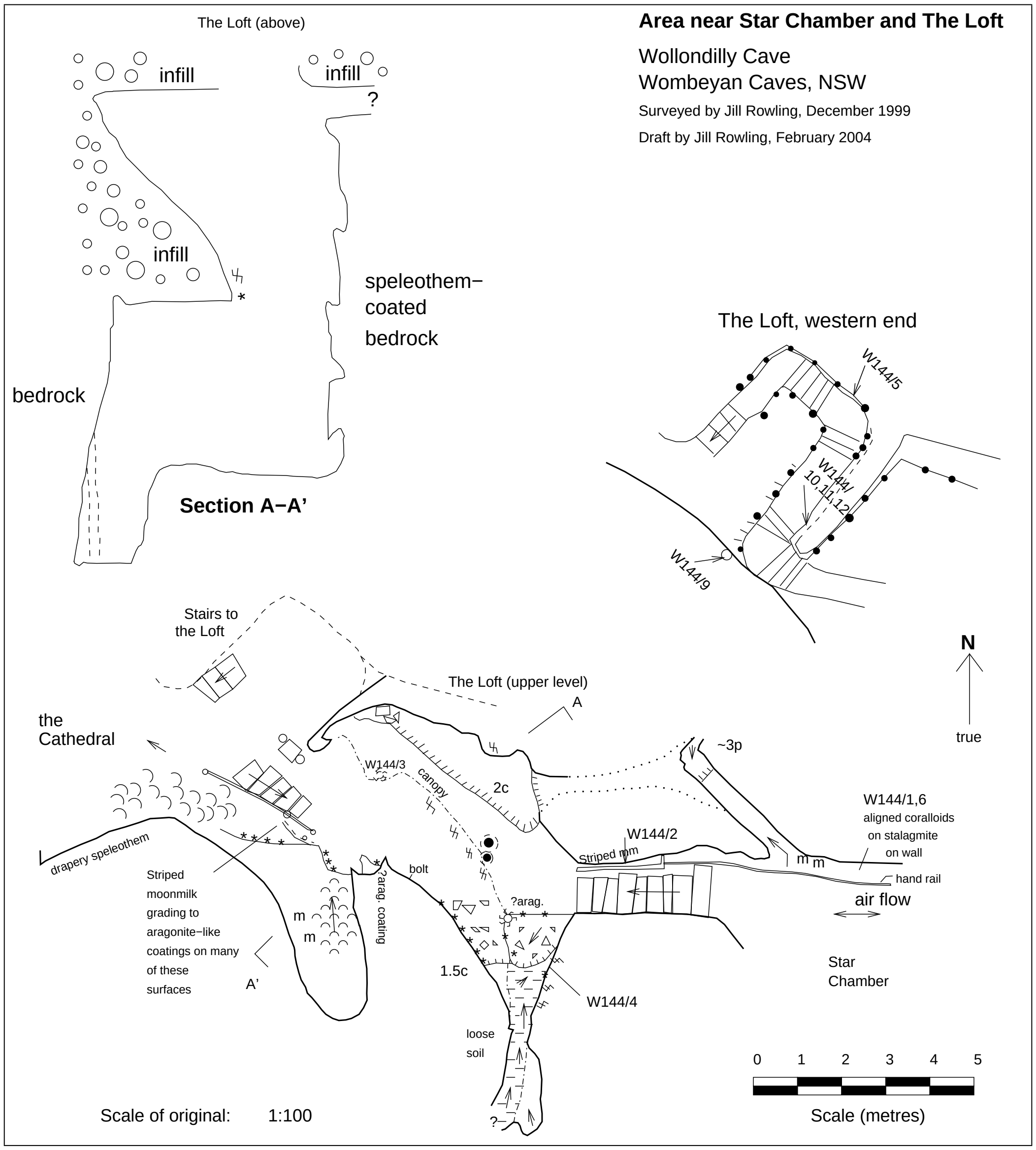


Figure 3.104: Map of area between The Cathedral and Star Chamber, including western end of The Loft, Wollondilly Cave. W144/1 etc.: sample points.

Observations: The Loft

The Loft is an area joining the ceilings of The Cathedral and Star Chamber (Figure 3.105). It has a flat ceiling with numerous irregularly-shaped chalky stalactites, and a mass of cobbles and gravel on the floor. The gravel has been partly excavated and appears to have been deposited by a creek. The cobbles are mainly porphyries, similar to the ones in Wombeyan Creek. The fine parts of the gravel comprise quartz, clays, fragments of porphyry and breakdown products. Air flow in the chamber is moderate, and the humidity is low. On the 7th April 2002 in the Loft, the average wet bulb was 13.5°C, the average dry bulb was 16.0°C, the wet bulb depression was 2.5°C and the calculated relative humidity was 76.0 %. The average was taken over three measurements.

Corrosion pits in wall niches and speleothems (Figure 3.105) may be due to deposits of bat guano, although bats are not present in large numbers in the cave. The powdery, granular material from a corrosion pit (W144/9) was examined with XRD. This indicated: Major calcite; Minor magnesian calcite, variscite, epsomite, aragonite, vaterite and hydroxyapatite (Appendix, Figure D.25). The grains comprise sparkly, sugary grains and crinkly flattened grains. Some fibrous material resembled needle form calcite. Some long crystals resembled aragonite but with feathered terminations.

Both the gravel fill and the walls of The Loft are coated with a white and yellow / orange fluffy mineral resembling a fungus, about 5 mm deep. This occurs on the undersides of alcoves and along the more sheltered walls where water seepage may occur from gravel banks (Figure 3.105).

The deposit varies in colour and texture from a white, low density and somewhat fluffy coating about 2 to 3 mm thick, to a pale orange or yellow low density coating about 2 to 4 mm thick. The substrate for this fluffy material is a fine, bedded quartz gravel and sand with cobbles of porphyry. Its response to UV light varies from blue to green. Samples W144/5 and W144/10 are of the white fluffy material. XRD of the fluffy material W144/5 shows it contains major calcite, with minor aragonite, vaterite, manganocalcite, phosphates (ardealite, cacoxenite, diadochite), and minerals from the gravel (quartz, anorthite and biotite) (Appendix, Figure D.23). XRD of sample W144/11 (yellow-brownish fluffy material) indicates: Major calcite and quartz; Minor cacoxenite and ardealite; Trace aragonite. XRD of the substrate (W144/12) indicates higher quantities of minerals from the gravel and some magnesium-rich minerals: Major calcite and quartz; Minor hydromagnesite, aragonite, heneuite (a phosphate), manganoan calcite and magnesium carbonates nesquehonite, hydromagnesite, lansfordite (Figure 3.107).

Sample W144/11 is of the yellow to orange fluffy material and sample W144/12 is of the substrate (Figures 3.106 and 3.105). It is mainly composed of needle fibre rods, about 1 x 2μ m thickness, and from 10μ m up to 1 or 2 mm in length. The rods are rectangular with chamfered or 90° terminations. The material also contains occasional irregular blobs about 2 to 5μ m diameter. Generally this material mostly resembles needle fibre calcite similar to that reported by Moore & Sullivan (1997), Fischer (1988) and Phillips & Self (1987). The yellow and pale orange material is composed of a mixture of shorter, wider needle fibre rods, some longer needle fibres, quartz and other crystal grains and irregular blobs. The yellow material has a higher quantity of needle-fibre calcite, and the pale orange material has a higher quantity of quartz and clays. Some of the needle fibres have rectangular terminations but many have pointed terminations. Some of the quartz crystal grains are coated with these short fibres.

Area of Sample W144/5: Fluffy north wall deposits. Width of image: about 4 m.

Overview of The Loft area with steel bridge on top left. Width of image: about 4 m.

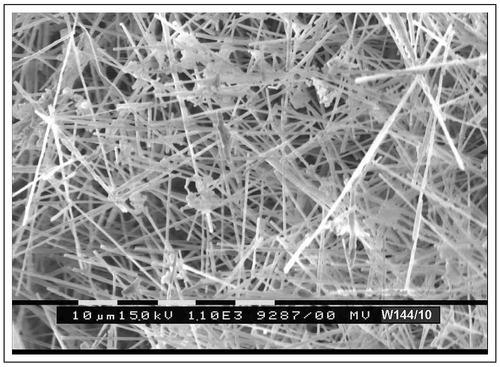
Hollow from which sample W144/9 was taken.

Sample W144/9, x13.

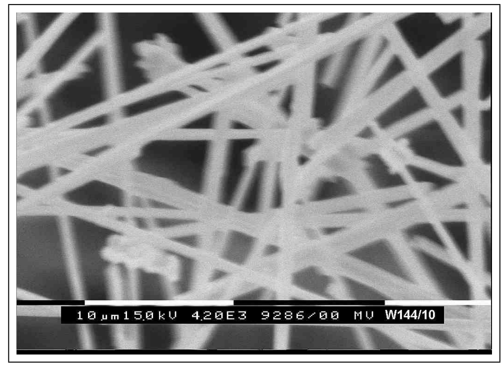
White and yellow-orange fluffy material coats gravel in The Loft.

Sample W144/11 (x13) is a low density white and orange material.

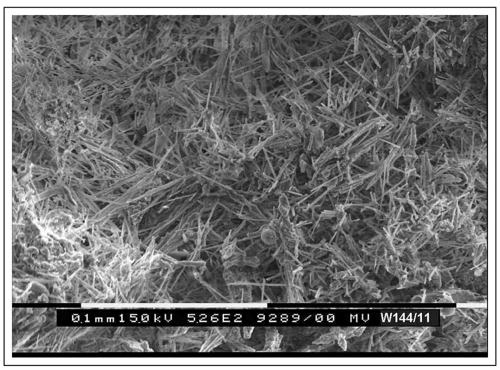
Figure 3.105: The Loft



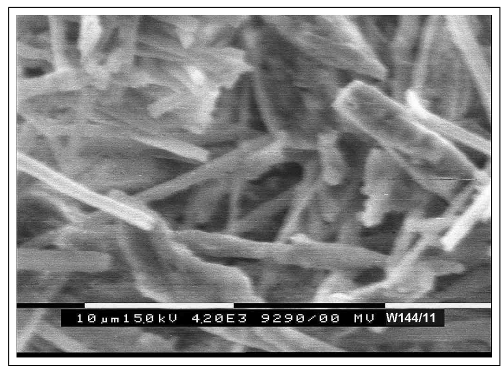
White fluffy material (sample W144/10) is an open thatch.



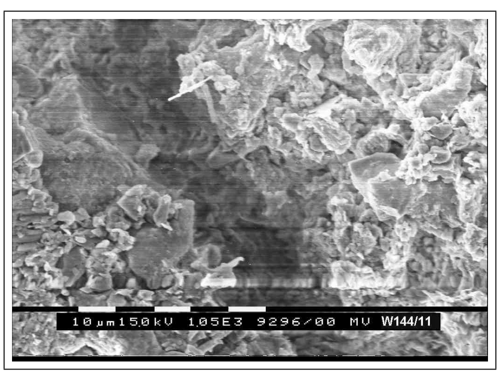
White fluffy material (sample W144/10) is made of fine rods.



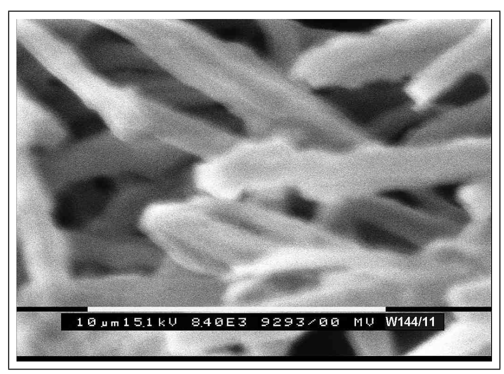
Yellow fluffy material (sample W144/11) is more dense.



Yellow fluffy material (sample W144/11) has a range of rod shapes.



Substrate (sample W144/12) is quartz and clays.



Yellow fluffy material (variant, sample W144/11) .

Figure 3.106: Fluffy material from The Loft: mainly needle fibre calcite with minor aragonite and vaterite.

Observations: The Cathedral

An anthodite-like helictite has developed on the lower flat ceiling of this chamber. It is completely inaccessible, about 10 m from the floor and about 15 m below the Star Chamber / Loft area. It may have been caused by magnesium-rich solutions seeping through cracks. In the area of the cave known as “The Cathedral”, at the base of the stairs the track goes under a flat ceiling. This point is roughly 15 m below “The Loft” site. High on the ceiling there is a deposit of aragonite which takes the form of an anthodite. It is out of reach. Possibly phosphates have been transported below “The Loft” deposit, allowing aragonite to precipitate in the lower chamber at the expense of calcite.

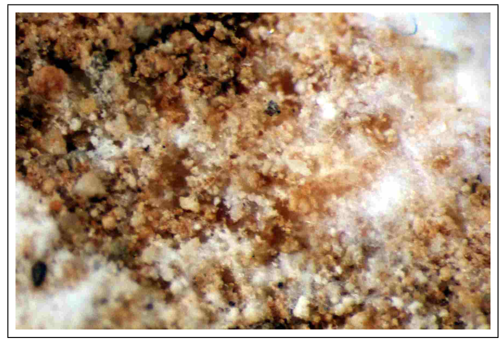
Observations: Jacobs Ladder

The tourist track ascends a steep ladder approx 8m high in an area called “Jacobs Ladder” At the base of this ladder is a small crystal pool with an unusual coating of fine needle shaped pool crystal (Figure 3.107). This area of the cave is cold and wet, with a wind blowing as air moves between entrances. XRD of sample W144/6 from the prickly pool crystal indicates major calcite and trace magnesian calcite. It superficially resembles a somewhat recrystallised aragonite. XRD of the substrate W144/7 indicates mainly detrital material, including major micas (muscovite and biotite) and tamarugite ($NaAl(SO_4)_2.6H_2O$); minor halloysite-7A, tridymite, sanderite (magnesium sulfate) and bernalite (hydrated iron oxide) (Appendix, Figure D.24). The origin of the substrate minerals is likely to be breakdown of porphyry and granite washed into the cave during an earlier period of the cave’s development. There is a possibility that the hydrated iron oxide may come from the tourist infrastructure.

Observations: The Pantheon

This chamber is above Jacobs Ladder in an area which has a lot of air movement. One of the stalagmites in The Pantheon has a lacy deposit of hopper calcite forming “anemolites” (Figure 3.107). Each crystallite is made of a fibrous triangular prism with only the prism corners well-formed; the remainder of the crystallites are hollow. It looks like a hopper crystal, as only the outer shape of the crystallite appears to be growing. Crystallite terminations include church-steeple forms, similar to aragonite. The white material includes moonmilk, needle fibres, small coralloids and engulfed frostwork. W144/8 is a small sample of the material. XRD analysis indicates calcite. It is thought that the material may occasionally deposit as aragonite and revert to calcite according to moisture levels (low moisture levels would be more conducive to aragonite formation). At other times, the material deposits as needle-form calcite (“lublinite”) and engulfs earlier deposits. The roof above the sampled area has considerable moonmilk coatings.

The Loft. Sample W144/10 (x13) is very low density white fluffy material.



The Loft. Sample W144/12 (x16) contains loose sediment grains with thin needles of calcite.

In "The Pantheon". Stalagmite with anemolite surface.

Detail of anemolite surface. Sample W144/8 is of the (calcite) anemolite.

Crystal pool near base of Jacobs Ladder. Sample W144/6 was from this prickly pool crystal.

Figure 3.107: Samples from The Loft, The Pantheon and Jacobs Ladder.

Synthesis - Wollondilly Cave

Aragonite is not a common mineral in Wollondilly Cave. In Star Chamber, aragonite occurs in speleothems as small crystals and granules, in an area with air movement. Mineral associations with aragonite include: Mg: huntite and hydromagnesite. Mg, Mn: huntite, magnesian calcite, pyrolusite and vaterite. SO_4, Mn: bassanite, manganocalcite and gypsum. The origin of the minerals appears to be cave fill containing weathered detrital igneous rocks, and an old bat guano deposit in The Loft above the site.

In The Loft, aragonite occurs as microscopic crystals in a fluffy coating, in an area with air movement. Mineral associations with aragonite in The Loft include: Mg, PO_4, SO_4: magnesian calcite, variscite, epsomite, vaterite and hydroxyapatite. Mn, PO_4: vaterite, manganocalcite, phosphates (ardealite, cacoxenite, diadochite) Mg, PO_4: hydromagnesite, heneuite (a phosphate), manganoan calcite and magnesium carbonates nesquehonite, hydromagnesite, lansfordite. PO_4: cacoxenite and ardealite. The origin of the PO_4 and SO_4 appears to be a weathered bat guano deposit. The origin of the Mg and Mn may be from chemical breakdown of detrital igneous rocks and gravels, and also may be from breakdown of dolomitised bedrock.

Aragonite-like speleothems (anthodites) occur in The Cathedral but were unable to be sampled so the mineral association cannot be determined. As the area is below The Loft, Mg is a possible association.

No aragonite was found at Jacobs Ladder, although the crystal coatings appeared to be paramorphs of calcite after aragonite. The area was wet and had a high air movement. The substrate contained the following mineral associations: Mg, SO_4: tamarugite ($NaAl(SO_4)_2.6H_2O$); sanderite (magnesium sulfate). Weathered detrital igneous rocks are suggested sources of the minerals.

No aragonite was found at The Pantheon, and no calcite-inhibitors were detected. Hopper crystals were suggestive of calcite paramorphs after aragonite.

Cow Pit

Location

Cow Pit is a steep-sided doline about 200 m west of Wollondilly Cave. It lies on the western side of a low hill and has a prominent Kurrajong tree at its northwestern edge.

Geological Setting

Cow Pit is developed in marble, similar to Wollondilly Cave. Two other rocks crop out: a bone breccia, possibly part of the Broom deposit (Broom 1896, Hope 1982), and the eroded remains of speleothems occur on the surface. These two sediments are typical of cave fill and indicate that the present land surface has been eroded from a previous karst surface One joint set near the cave strikes about 102° and dips about 50° to the south. Another set strikes about 172° and dips about 55° to the east. A third set strikes about 202° and dips about 64° to the west.

Cave Description

Cow Pit is a pit, roughly boot-shaped in long section, with a small dark zone in the northwest corner (Figure 3.108). On the northern side, the steep doline walls are partially covered with stalactites and algae. There is a steep rubble slope in the southern side – all other sides are precipitous. Bone breccia crops out in the walls, filling cavernous solution hollows in the marble. The floor is steep and covered with large boulders and rubble. High on the northeastern side of the pit, there are small phreatic tubes and anastomoses, occupied at times by Boobook Owls. In the dark zone, there are few speleothems and a considerable amount of bone breccia and fill.

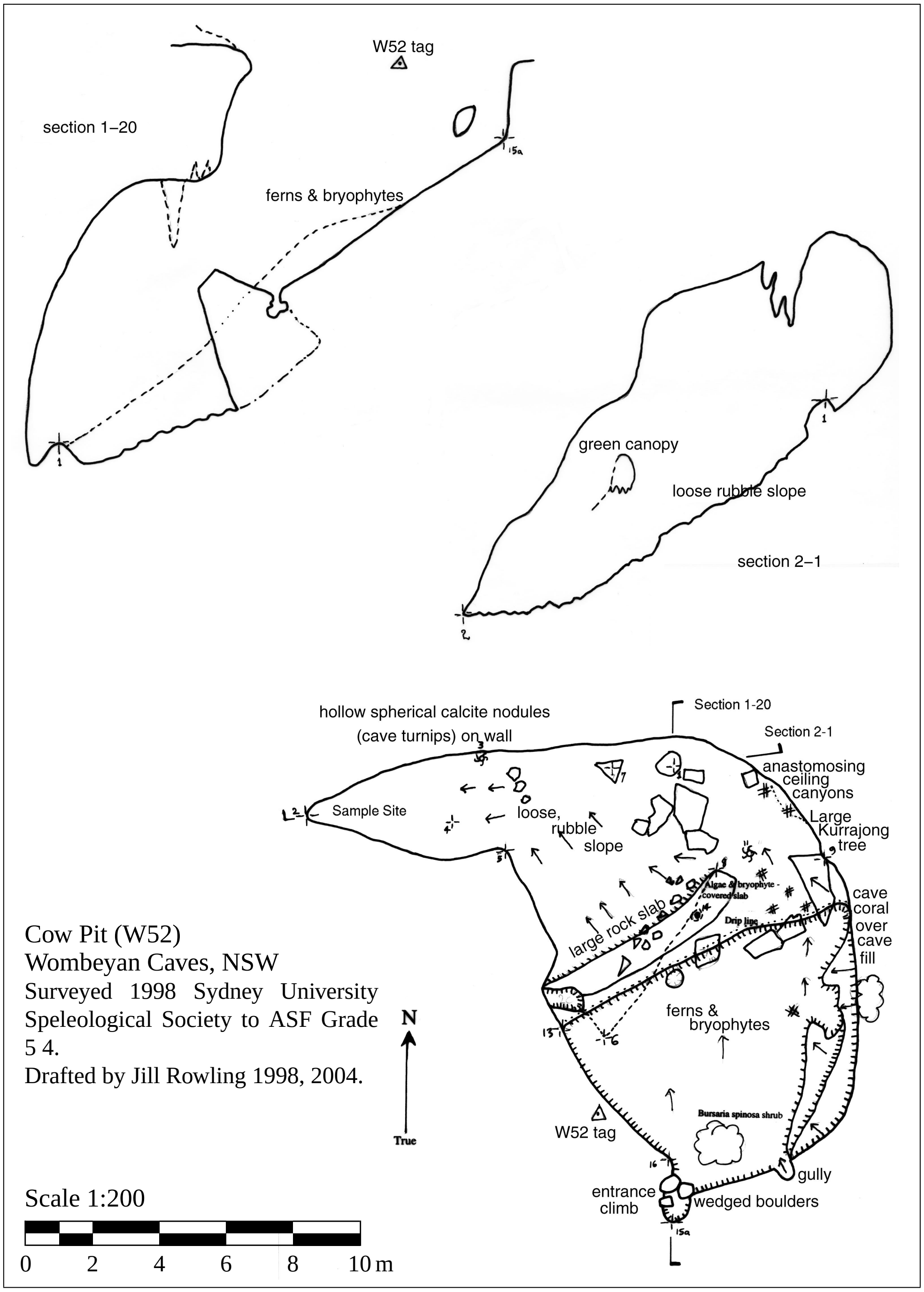
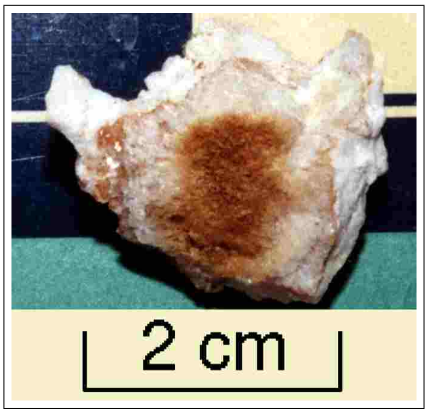


Figure 3.108: Map (plan and elevation) of Cow Pit, based on unpublished Sydney University Speleological Society map 2W52.SUS1 sheets 1 and 2.

Sample Sites and Observations

In the dark zone, speleothems include a stalactite, coatings and “cave turnip” speleothems. Humidity was not measured: the cave humidity follows that of the surface closely due to its open nature. XRD of a sample of hard white coating (W52/4, similar to that in Figure 3.109) indicated major calcite, minor aragonite, huntite and hydromagnesite. Its surface texture is very small crystals, with apparent random orientation. Cut surfaces fluoresce blue-green with long wave UV. The “cave turnips” are small hemispheres about 1 to 2 cm diameter (Figure 3.109).



“Cave turnip” sample W52/1, Cow Pit.

Detail of “Cave Turnip” inner surface.

Cow Pit. Area with “cave turnips” and concrete-like hard white coatings.

Cow Pit. Red sediment exposed behind speleothems. Sample W52/5.

Figure 3.109: “Cave turnips” and other speleothems, dark zone of Cow Pit.

Many are broken open, apparently by internal pressure, and reveal a hollow interior partially filled with cave mud and a white “moonmilk”. Samples of broken “cave turnips” indicate the interior may once have been aragonite. XRD and Raman spectroscopy indicates calcite. The interior is layered as follows: The outer coating is yellowish conventional calcite flowstone with the calcite C axis perpendicular to the substrate. An inner sparry layer of pinkish calcite exhibits curved cleavage and curved C axis orientation, resembling sparry aragonite which has reverted to calcite. A thin red layer separates portions of this sparry layer. The next inner layer resembles coconut meat fibre. It is clear calcite, and recrystallised from an acicular precursor. Fine feathery patterns are an optical effect caused by repeated twinning in the columns. Occasional fine branches can be seen on the fibres. The innermost crystalline layer is a light brown acicular calcite. It is highly corroded and easily broken. The fine needles are flattened, and have irregular edges. The material resembles corroded aragonite.

XRD of a sample (W52/5) of the red bone breccia wall (Figure 3.109) indicated: Major calcite and quartz; Minor aragonite, pyrolusite, birnessite and hydroxyapatite; Trace hydromagnesite, goethite and huntite (Appendix, Figure D.21). This material forms the substrate for most of the speleothems in the dark zone of Cow Pit. The quartz is detrital. The calcite included clear coatings over tan sediment, and multiply-twinned columnar crystals, either recrystallised moonmilk or paramorphs after aragonite. Hydroxyapatite (detected in the bone breccia) is unlikely to prevent calcite from depositing as it is not very soluble. The aragonite is most likely present due to the more soluble magnesium and manganese-rich minerals acting as calcite crystal poisoners, especially hydromagnesite and pyrolusite, coupled with low humidity to concentrate the minerals.

XRD of a sample of crumbly red cave fill (W52/6) indicated: Major calcite and quartz; Minor pyrolusite, kaolinite (1Md and 1T), alunogen, biotite, metaschoepite ($UO_3.2H_2O$), beusite (a phosphate); Trace hydromagnesite and goethite. (Appendix, Figure D.22). This appears to be detrital material sourced from the volcanics as well as the bone breccia.

Synthesis - Cow Pit

Mineral associations with aragonite at Cow Pit include: Mg, Mn, PO_4: pyrolusite, birnessite, hydroxyapatite, hydromagnesite and huntite. Mg: huntite and hydromagnesite in hard white speleothem coating.

Cow Pit appears to be an unroofed cave, developed in a karstic landscape with pit-trap caves in which small animals were either trapped to form the bone breccia, or were inhabited by owls which deposited the bone material which was later included with cave sediments. The gravel component of the reddish cave fill is fine, including detrital material from both the Wombeyan marble and from the volcanics. The origin of the magnesium and manganese-rich minerals in this case is difficult to determine precisely as they could come from both the volcanics and from veins in the marble although no dolomitic veins were noted in the surface bedrock samples at Cow Pit.

Several caves at Wombeyan have “cave turnips”. Caves which have these spheroids have been visited as part of this study include Sigma Cave, Wollondilly, Kooringa (Korringa) Cave and Cow Pit at Wombeyan Caves (Rowling 1998*c*). Hill Cave (Timor, NSW) also has these speleothems (G.K. Smith, pers. comm.). The origin of the “cave turnips” may be magnesium-rich moonmilk and swelling clays, which have been coated with calcite speleothem (flowstone). The interior was most likely alternating aragonite and calcite. When the “turnips” break open, the interior may revert to calcite as the more soluble Mn ions are released.

Other Caves at Wombeyan

Other caves at Wombeyan were briefly examined for aragonite and aragonite-like speleothems.

Guineacor Cave

Guineacor Cave is a former show cave. It is situated to the north of the hill containing the Broom deposit, about 100 m to the north-west of Wollondilly Cave entrances (Figure 3.76. About 15 m of rock separates the southernmost part of Guineacor Cave from the northernmost part of Mulwaree Cave (Wollondilly Cave). Guineacor Cave has a single entrance, and a single chamber about 40 m long aligned north-northeast along the strike of a prominent joint. One joint set near the cave strikes about 122° and dips about 57° to the south. Another set strikes about 220° and dips about 60° to the west. The cave appears to be aligned with this second joint. The western wall is covered with flowstone and helictites. XRD of some of this material (W121-4) indicates major calcite with trace huntite. Large helictites in the ceiling resemble the rod and wing shapes which occur in Orient Cave, Jenolan. Near its entrance is flowstone, with small acicular crystals associated with bat guano (possibly gypsum). Most of the speleothems in Guineacor were inactive during the study. Small samples (W121/1 and W121/2) of acicular speleothems have typical calcite fracture and a sooty coating. Thin sections of typical rocks above the cave (W121/5) (Figure 3.77)show a relatively pure marble with no dolomitic veins. Samples of Broom breccia (W121/6) show a high phosphate content in thin section. Samples of speleothem (W121/7) lying on the surface above the cave indicate the speleothem was deposited on bone breccia, most likely as very fine layers resembling biogenic calcite with (possibly diurnal) cyclic variations in deposition.

The lack of aragonite but presence of aragonite-like speleothems in Guineacor Cave may be due to the higher purity of the marble, coupled with the chemical stability of the bone breccia. The presence of huntite in small quantities indicates there is some magnesium leached into the cave, but insufficient to prevent calcite from being deposited.

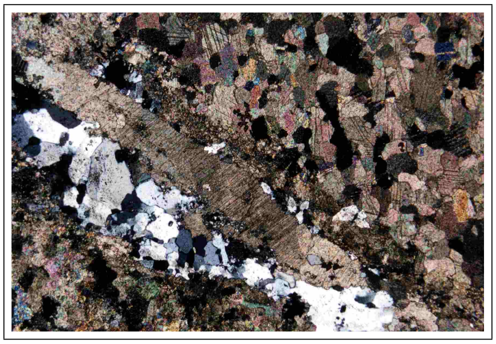
Cave W43

Location

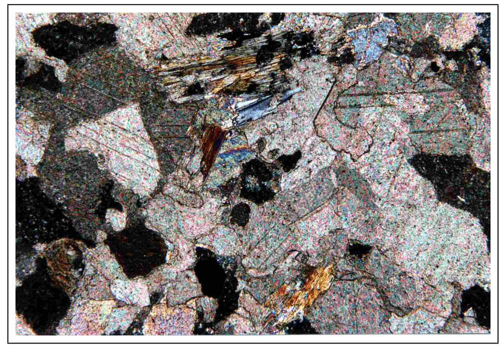
Cave W43 (variously known as “CO_2 Pit”, “Joe Jennings Cave” and “Big Crystal Squeeze Cave”) is located near “White Bend” (Figure 3.76), close to the most northerly edge of the marble outcrop.

Geological Setting

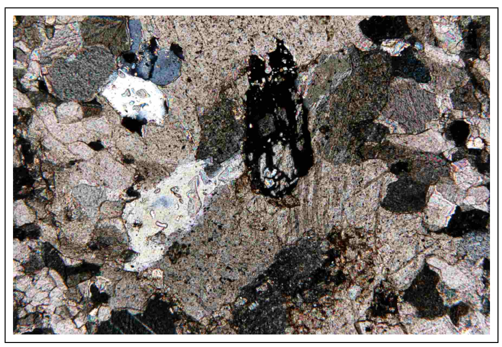
Cave W43 is developed in saccharoidal, marmorised Wombeyan Caves marble. Although the cave is located near the northern limit of the outcrop, there may be carbonate underneath the volcanics to the north of the cave (not necessarily cavernous). Veins in the marble have melilite and wollastonite with a small amount of dolomitisation (Figure 3.110). One joint set near the cave strikes about 137° and dips about 73° to the southwest. Another set strikes about 252° and dips about 65° to the northwest.



TS W43-2 N36084 XN x13. Wombeyan marble near cave W43. Upper edge of vein is dolomitised. Vein contains melilite.



TS W43-3 N35937 XN x50. Wombeyan marble with fibrous possible wollastonite inclusions.



TS W43-4 N35938 XN x50. Veins contain melilite and some dolomite (lower middle).

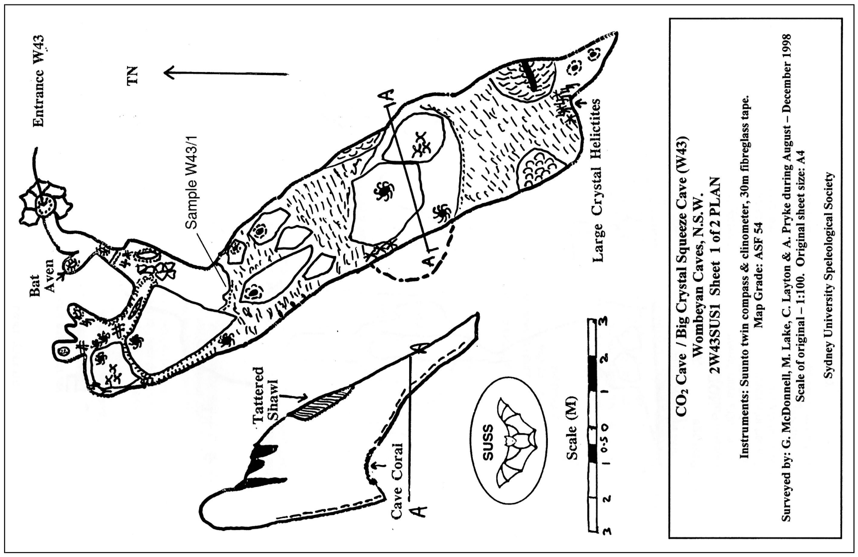
Figure 3.110: Thin Sections, rocks in the W43 area.

Cave Description

Cave W43 is a small cave with a dug-out entrance and one chamber. It is particularly noted for its foul air (high levels of CO_2 and possibly low O_2) and coated speleothems. Observations are based on one short visit to the upper part of the cave in 1998. Much of the chamber is filled with large boulders. Figure 3.111 is a map of the cave. The cave is a slot shape, striking north west and dipping to the south west (McDonnell 1999).

Sample Sites and Observations

Speleothems include calcite stalactites and flowstone, with a large quantity of cave coral. Some flowstone has an unusual surface, comprised of cubes with vertical striations, as though re-



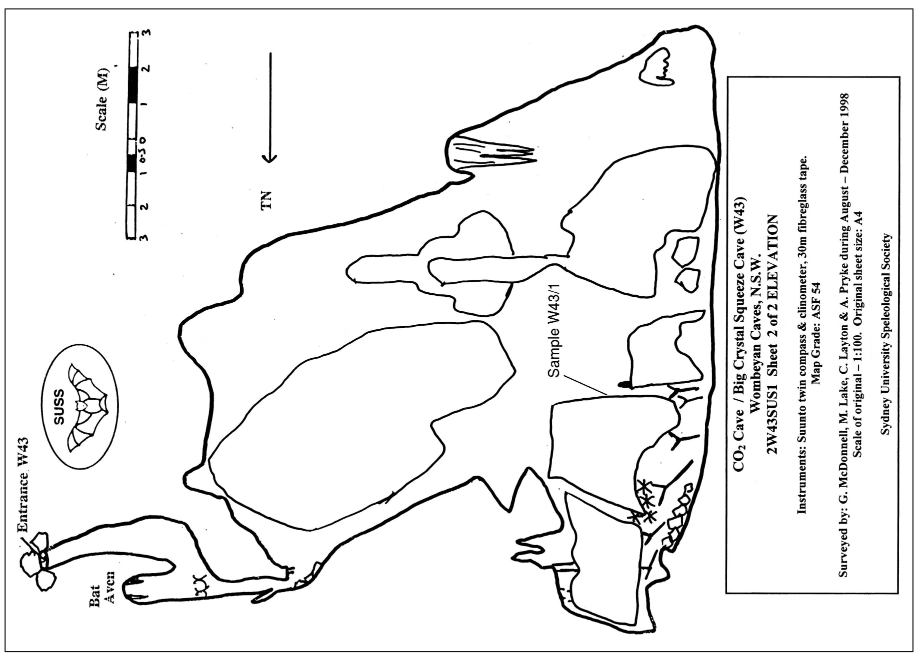


Figure 3.111: Map, Cave W43 (“CO_2 Cave”, “Joe Jennings Cave” or “Big Crystal Squeeze Cave”. Map by Geoffrey McDonnell, Sydney University Speleological Society, SUSS Bull 38(3) 1999 p23-24. Position of sample W43/1 indicated.

crystallised or etched. Helictites in the lowest part of the cave are recrystallised to a series of boxy rhombs, possibly from being submerged in water supersaturated with respect to carbonate. Calcite overgrowths are epitaxial: they are oriented according to the original speleothem’s surface. Coralloids in the upper parts of the cave have a pitted surface, similar to the ones seen in Kappa Canyon (Sigma Cave).

The most prominent coralloids occur near the entrance passage, on the floor and walls. One of these was collected (sample W43/1) in 1998 by Mike Stevenson from the large coralloid-covered boulder immediately below the first landing. The speleothem has an orange surface colouring, grey sooty upper surface, corroded lower surface and has some aragonite-like features (Figure 3.112). The mud contains dark minerals similar to manganese oxide dendrites, white powder similar to “moonmilk” and some bat guano. The upper surface is crenulated. Small pockets on crenulations are filled with an acicular mineral which resembles aragonite. XRD analysis of one of these nodules of the outer surface indicates it is all calcite. On the corroded lower surface, there are small areas of fine needles resembling the underside of aragonite flowstone. Raman spectroscopy of this lower spiky surface indicates a small peak corresponding to aragonite as well as a large calcite peak. Fluorescence was high.

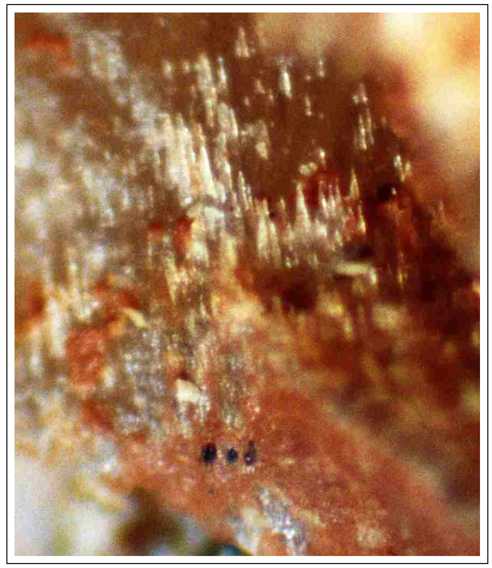
Synthesis - Cave W43

Cave W43 may have once contained aragonite, which has mostly reverted to calcite. The presence of acicular needles in the coralloid pits infers a similar origin to those seen in Kappa Canyon, Sigma Cave. Aragonite may be related to dolomitic veins in the bedrock. If the cave was partially water-filled, this would have led to the removal of soluble hydromagnesite, reversion of aragonite to calcite, and epitaxial growth of calcite over the lower speleothems.

Synthesis - Aragonite at Wombeyan Caves

Aragonite at Wombeyan Caves is associated with minerals containing magnesium, manganese, sulfate and phosphate ions. In Sigma Cave, aragonite in Aragonite Canyon is associated with magnesium-rich minerals released from breakdown of ferromagnesian minerals (eg clinochlore, sapphirine) in detrital gabbro, as well as from dolomitic and manganese-rich veins in the bedrock. Acids associated with bat guano appear to be mostly responsible for the breakdown of the gabbro. Aragonite is precipitated in an area of mild air movement. Forms taken include a variety of helictites, coatings and stalactites. Aragonite appears to be depositing in speleothems along with calcite, phosphates and sulfates. Manganese and magnesium carbonates are common precipitates. Aragonite elsewhere in Sigma Cave is associated with magnesium and manganese ions leached from dyke-like filled grikes composed of igneous clastics. Aragonite at Wollondilly Cave is associated with the leaching of magnesium ions from minor dolomite in the bedrock and from breakdown of ferromagnesian minerals (e.g. vesuvianite and diopside) in igneous rocks. The igneous material is detrital, comprising hypersthene porphyry, dacite and Columba granite, washed into the cave at an earlier period similar to the present Creek Cave. Breakdown of igneous rocks has been aided by bat guano. A white fluffy deposit of needle-form calcite, including small quantities of aragonite, is associated with an old bat guano deposit. Minerals associated with aragonite in Wollondilly Cave include huntite, hydromagnesite, vaterite, gypsum and phosphates. Aragonite in Cow Pit may be associated with “Cave Turnip” speleothems and a concrete-like

Coralloid x2.4. Mainly calcite.



Undersurface corroded needle detail (aragonite).

Upper crenulated surface.

Needle shaped paramorphs of calcite after aragonite. (x16)

Figure 3.112: Cave W43: Coralloid sample W43-1 contains aragonite.

white coating. Small amounts of aragonite were present in wall coatings. Minerals associated with the aragonite contain magnesium, manganese and phosphate ions. The lack of aragonite but presence of aragonite-like speleothems in Guineacor Cave may be due to the higher purity of the marble. The small quantities of magnesium ions present are insufficient to prevent calcite from being deposited. Aragonite in cave W43 may be associated with dolomite in the bedrock. The main speleothem types and sub types associated with aragonite at Wombeyan Caves are anthodites, "furze bushes", beaded helictites, stalactites, spathites, "cave turnips", coatings, crenulated coralloids, moonmilk and fluffy coatings. Except for Aragonite Canyon, anthodites and "furze bushes" are rare at Wombeyan. "Cave turnips", crenulated coralloids and concrete-like coatings are common.