

## Chapter 3

# Case Studies

### 3.1 Aragonite in NSW Caves: Introduction to Case Studies

All caves in this study are situated in the Lachlan Fold Belt. Three main areas were examined: Jenolan Caves, Wombeyan Caves and Walli Caves. Each area is introduced with its geological setting, caves containing aragonite and discusses possible reasons why aragonite occurs in those caves.

### 3.2 Jenolan Caves

#### Introduction

Jenolan Caves are located about 110 km west of Sydney in the Great Dividing Range, west of the Blue Mountains (Figures 1.3 and 3.2). They are accessible by road and are a world famous tourist destination. Tours have been conducted at Jenolan since about 1845 when the caves had little tourist infrastructure and Jeremiah Wilson ran a guest house in the Jenolan Valley (Dunlop 1977).

#### Geological Setting

##### Regional Geology

Jenolan Caves are situated in a north - south trending band of Silurian sediments, volcanics and limestone (Figure 3.1), adjacent to a regional unconformity between the Sydney Basin and the Lachlan Fold Belt (Figure 1.3).

The oldest rocks in the region are Ordovician Adaminaby group (**Oa**) (Glen, Stewart & Vandenberg 1990, Fairbridge 1953) comprising mudstones, interbedded sandstones, turbidites, siltstone and black carbonaceous mudstone. These crop out about 3 km to the west for about 15 km and about 8.5 km to the south of Jenolan Caves. About 3 km SW of Jenolan and east of the Jaunter Fault is a small outcrop of Triangle formation (Ordovician Kenilworth Group, **Okt**) comprising mafic volcanoclastic sandstone, metabasalt, shale, phyllite, schist, siliceous carbonaceous

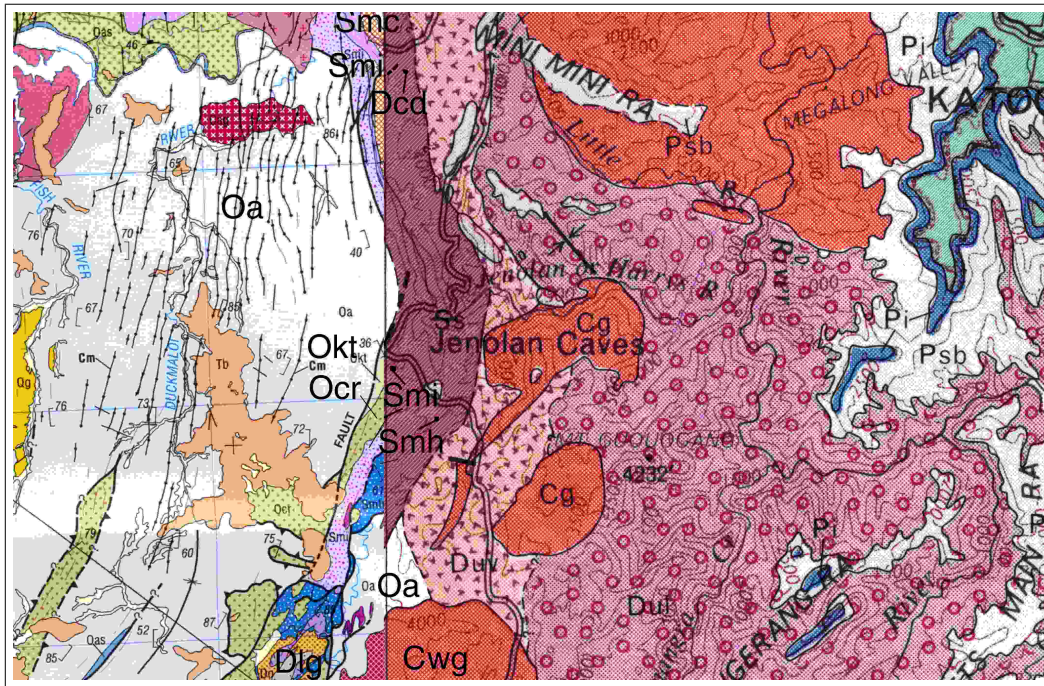


Figure 3.1: Geological Map of Jenolan Caves region showing geological outcrops mentioned in text. Area map RHS is from Brunker & Rose (1967); LHS is from Raymond, Pogson et al. (1998). Width of image: approximately 45 km. **Key:** **Tv** - Tertiary volcanics (basalt, dolerite, microsyenite, trachyte and tinguaita). **Pi** - Permian, Illawarra Coal Measures (Sydney Basin). **Psb** - Permian, Berry Formation (Sydney Basin). **Cg** - Carboniferous granite and granodiorite, **Cwg** - Carboniferous, Kanangra Granite (pale pink, medium grained hornblende granite), **Dlg** - Devonian, Gibbons Creek Sandstone of Lambie Group (thickly to thinly bedded quartz sandstone, siltstone, mudstone), **Dul** - Devonian, Lambie Group conglomerate, sandstone and shale. **Duv** - Devonian, undifferentiated volcanics (Bindook Porphyry), **Dcd** - Devonian, Dunchurch Formation of Crudine Group, **Skc** - Silurian, Kildrummie Group. **Ss** - Silurian, undifferentiated sediments, volcanics and limestone. **Smc** - Silurian, Campbells Formation of Mumbil Group (East), **Smh** - Silurian, Hollanders Formation of Mumbil Group (East), **Smi** - Silurian, Karawina Formation of Mumbil Group (East), **Ocr** - Ordovician, Rockley Volcanics of Cabonne Group, **Okt** - Ordovician, Triangle formation of Kenilworth Group, **Oa** - Ordovician, Adaminaby Group.

slate, chert, quartzite and sandstone. These are conformably overlain by volcanic sandstone, minor breccia and conglomerate of the Rockley Volcanics (Ordovician Cabonne Group, **Ocr**). This occurs both east and west of the Jaunter Fault, SW of Jenolan Caves.

Silurian outcrops include the Karawina Formation (Mumbil Group (East) **Smi**) comprising metamorphosed feldspathic quartz sandstone, conglomerate and siltstone. This is a small unit which crops out about 12 km SE of Oberon and about 11 km NNE of Jenolan Caves, immediately east of the Jaunter Fault. Minor lenses of limestone crop out along the boundary between this formation and the adjoining Campbells Formation. In an area extending from along the

Hollanders River near Tuglow, to about 6 km SW of Jenolan, is the Hollanders Formation (Mumbil Group (East) **Smh**) comprising limestone, mudstone, volcanilithic sandstone and siltstone. The Campbells Formation (Mumbil Group (East), **Smc**) comprises slate, phyllite, siltstone, feldspathic and quartz sandstone, and limestone, and crops out in an area about 11.5 km NNE of Jenolan Caves, adjoining the Smi formation. This study also noted rocks similar to Smc about 4 km NW of Jenolan Caves (Section 3.2). The Kildrummie Limestone Member, which is now included with the Campbells Formation, crops out about 16 km WSW of Jenolan Caves.

Devonian rocks in the area include the Dunchurch Formation (Crudine Group, **Dcd**) comprising feldspathic quartz sandstone, minor slate, ashstone and dacite. These crop out about 9 km NNW of Jenolan Caves as a NE-dipping unit, east of and conformably overlying the Silurian Cambells Formation. Immediately east of the Silurian rocks at Jenolan Caves lies a north-south band of volcanics (**Duv**). These include Devonian volcanics of the Bindook Porphyry Group (Brunker & Rose 1967). About 5 to 10 km east of Jenolan Caves, Lambie Group (**Dul**) conglomerate, sandstone and shale crop out. The Gibbons Creek Sandstone (Lambie Group **Dlg**) comprises thickly to thinly bedded quartz sandstone, siltstone and mudstone. It crops out about 16 km SW of Jenolan Caves in the Tuglow area.

Carboniferous granitic intrusions crop out in various places around Jenolan Caves. The closest bodies are about 5 km to the south east, about 15 km south and 10 km to the north east. The Kanangra Granite (**Cwg**) is a pale pink, medium grained hornblende granite, which crops out about 9 km S of Jenolan Caves in the Kanangra-Boyd National Park. The Kowmung River has deeply incised the granite, forming deep gorges. Where the granite adjoins Adaminaby Group sediments, the sediments have been contact metamorphosed. 7 km SE of Oberon is the Rossthdu Granite (**Cag**), a pale pink, coarse-grained equigranular biotite granite. 7 km E of Oberon is the Duckmaloi Granite (**Ckg**), a grey, coarse-grained biotite granite. Immediately south of Oberon is the Oberon Granite (**Cog**), a coarse-grained biotite-hornblende granite comprising two separate phases: Coga is a porphyritic core, Cogg is equigranular.

Permian rocks crop out around the area, including in the Jenolan valley. The Snapper Point Formation (**Psm**, Shoalhaven Group, Sydney Basin) occurs in the form of ridge cappings at Mini Mini Range, parts of Five Mile Hill, along the Kanangra Walls Road, at Kanangra Walls (about 20 km to the south) and also within the Jenolan Caves valley. The Snapper Point Formation is characterised by conglomerates with large quartz pebbles. Sandy grey mudstones of the Berry Formation (**Psb**, Shoalhaven Group, Sydney Basin) crop out along the Jenolan Caves Road near Mini Mini Range. About 17 km to the east of Jenolan are the closest outcrops of the Permian Illawarra Coal Measures (**Pi**, Sydney Basin). These comprise pebbly lithic sandstone, interbedded grey mudstone and carbonaceous claystone and coal seams, often found as an eroded layer below the cliff-forming sandstones of the Narabeen Group.

Tertiary volcanics (**Tv**) are represented in the area by Early Miocene (16-19 Ma) basalts filling earlier drainage patterns and often unconformably overlying Tertiary sediments. Basalt forms a

cap on the hills 7 km SW of Jenolan Caves.

To the west of Jenolan Caves is the north-northeast striking Jaunter Fault. The northern end of this fault is truncated by the Duckmaloi Granite near Oberon (Pogson & Watkins 1995, Raymond, O. L. & Pogson, D. J. (eds) 1998). The fault strikes north east at its southern end, curving to northwest at its northern end and dips to the west.

Powell, Cole & Cudahy (1985) described Carboniferous megakinks in the Lachlan Fold Belt. On their map, the position of a “Jenolan Megakink” was shown as a north-east oriented fold axis with its most north-eastern extremity at approximately the “Playing Fields” area. This megakink seems to correspond with the local change in limestone strike. From the most southerly limestone outcrop to about Playing Fields, the strike is roughly northwards. North of Playing Fields, the strike is about  $150^\circ$ .

### **Local Geology**

The Late Silurian Jenolan Caves Limestone (Chalker 1971) crops out as a narrow band trending roughly north-south and is about 6 km long (Figure 3.2). Silurian rocks crop out for about 20 km to the north of Jenolan Caves, and for about 15 km to the south south west. There is a small outcrop of limestone to the east of the main body which is marly and has few caves.

The Jenolan Caves Limestone continues for some distance northwards of its surface outcrop. North of the main outcrop, the limestone is partially buried under scree with occasional dolines and limestone outcrops visible. The northernmost outcrops of the Jenolan Caves Limestone include a limy shale. A few hundred metres north of Watersend Cave, the Jenolan River passes through a series of sharp bends (the northernmost part of Figure 3.2). This is caused by an outcrop of phyllite striking roughly northeast and dipping about  $45^\circ$  to the northwest. Dolines occur about 1 km to the north of this outcrop.

The southern end of the Jenolan Caves Limestone is generally considered to terminate a little north of the Kanangra Walls Road (Chalker 1971). However, Martin Scott and Tony Allan (pers. comm.) reported that a limy rock appears on the south side of the Kanangra Walls Road nearby, and continues for a short distance southwards for possibly a few hundred metres as a marly limestone devoid of caves.

Chalker (1971) commented that some of the limestone in the southern part of the deposit appeared to weather to a deep red colour. Her chemical analysis of the limestone 1 km south of Lucas Rocks contained approximately 96.5 %  $\text{CaCO}_3$  and 2.1 %  $\text{MgCO}_3$ . Chemical analyses of the limestone were reported by Carne & Jones (1919) at the Grand Arch as 97.62 %  $\text{CaCO}_3$  and 0.91 %  $\text{MgCO}_3$ . An inspection (this study) of the rocks in Camp Creek near Bottomless Pit showed a high proportion of dolomitic veins. The limestone appears to be less pure than that of the show caves or the northern limestone area. There are not as many caves in the southern limestone region compared to the rest of Jenolan.

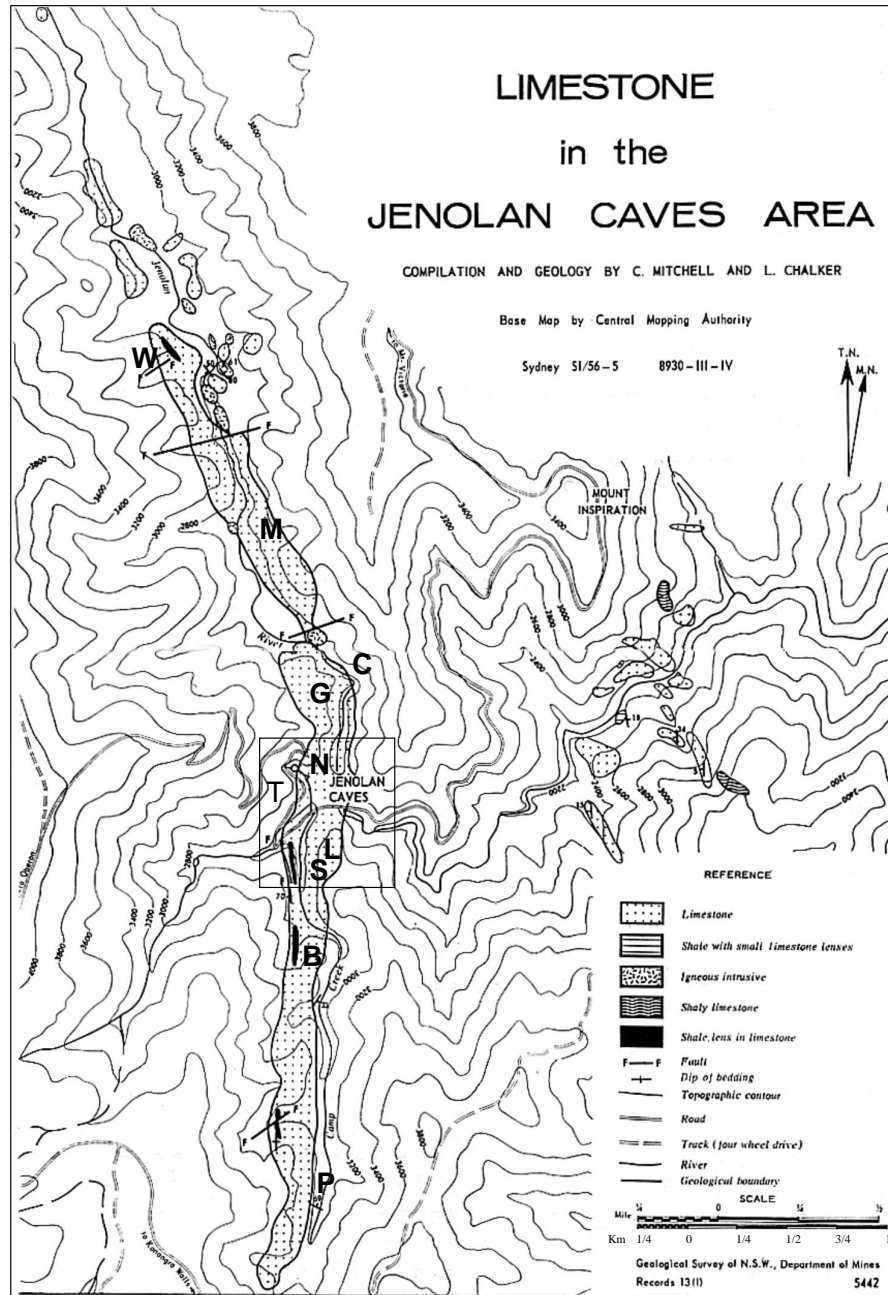


Figure 3.2: Map of Jenolan Caves Limestone outcrop by Chalker (1971), overlaid with cave positions mentioned in the text. Key to caves: B - Bottomless Pit, C - Contact Cave, G - Glass Cave, L - Lucas Rocks, M - Mammoth Cave, N - Northern show caves P - Paradox Cave, S - Southern show caves T - Show cave complex, W - Wiburds Lake Cave

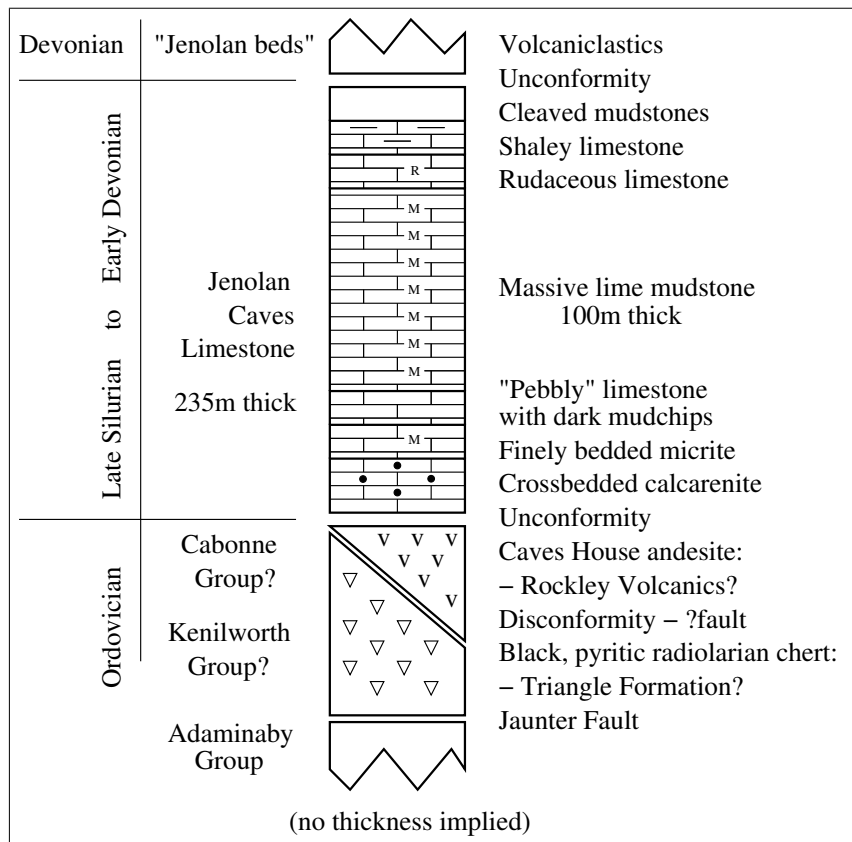


Figure 3.3: Stratigraphic sequence for the Jenolan Caves Limestone near Caves House based on Allan (1986).

To the west of Caves House the Jenolan Caves Limestone overlies an apparently effusive andesite called the Caves House andesite by Allan (1986). Allan described the Caves House andesite as stratigraphically below the Jenolan Caves Limestone, and disconformal with the Ordovician rocks. There was no contact metamorphism associated with the contact between this unit and the Jenolan Caves Limestone. Near Caves House but away from the andesite, the sediments immediately west of the Jenolan Caves Limestone are a black, radiolarian-rich siliceous mudstone with thin interbeds of basic tuffaceous sandstone and disseminated pyrite (David 1896, Allan 1986). This study noted that the western edge of the Jenolan Caves Limestone is irregular in places (faulted), with karst features and calciphile plants occurring in chert scree slopes up to 200 m west of the limestone outcrop.

Chalker (1971) identified a number of shale lenses in the Jenolan Caves Limestone near its western boundary. A thinly bedded region (sometimes argillaceous, sometimes schistose and slickensided) of the limestone was identified in Wiburds Lake Cave during this study - this is described later in the cave description.

The Jenolan Caves Limestone is 235 m thick (Allan 1986). The main limestone body varies

in colour and texture from a dark grey, relatively pure wackestone in the middle section of the deposit, to a creamy white stone (Chalker 1971), also noted during this study. Faunal lists for the limestone were prepared by Chalker (1971) and Pickett (1982). Chalker noted the presence of recrystallised parts of the main limestone body in McKeown's Valley, and described:

*... the small rhombs of calcite have been coated with iron oxide so that parts of the rock are pinkish red in colour. The amount of coating varies considerably and it occurs in small, thin, parallel bands less than 1 cm wide up to bands 10 cm wide with perpendicular bands of coated material connecting these to give a brick-like appearance. In those places where recrystallisation has occurred, it can be noted in thin section that the fossils have not generally been affected (J. Byrnes, pers. comm., 1970)*

(Chalker 1971)

The stratigraphically central portion of the limestone is a fairly pure lime mudstone. Allan considered that the Jenolan Caves Limestone was a detrital (as opposed to reefal) carbonate deposit. He concluded that the limestone had been deposited in shallow water, fed from a nearby carbonate source such as a fringing shelf of a volcanic archipelago with patch reefs.

Allan's figure 5.1 is a stratigraphic column through the Jenolan Caves Limestone, taken from near Caves House and included sections of the Binoomea Cut. Figure 3.3 is based on Allan's stratigraphic sequence. To the east, the upper beds of the limestone are thinly bedded with shales and mudstones (Allan 1986) before being terminated (apparently unconformably) by the Jenolan beds (Figure 3.3). Pickett (1982) noted a Ludlovian (Late Silurian) for the main body of the Jenolan Caves Limestone and a Pridolian (Latest Silurian) for the upper well-bedded part of the limestone. Figure 3.4 is a reproduction of part of Alan's measured stratigraphic column. Within the Jenolan beds, Allan noted a unit which he called the Jenolan rhyolite-porphyry, described as pyroclastic, massive, with numerous slickensided fault planes of random orientation and quartz veining. Allan considered that the Jenolan rhyolite-porphyry was from a rhyolitic submarine ignimbrite. Also within the Jenolan beds, Allan described a dacitic crystal tuff with a highly altered, pink-green groundmass. Allan identified quartz, feldspar (albitised plagioclase with little twinning), iron oxides, chlorite, calcite and epidote in an altered groundmass of the same minerals. Some micrographic intergrowths of quartz and k-feldspar were observed. He suggested this tuff originated in a submarine pyroclastic flow. These two units were used as markers in this study near Contact Cave.

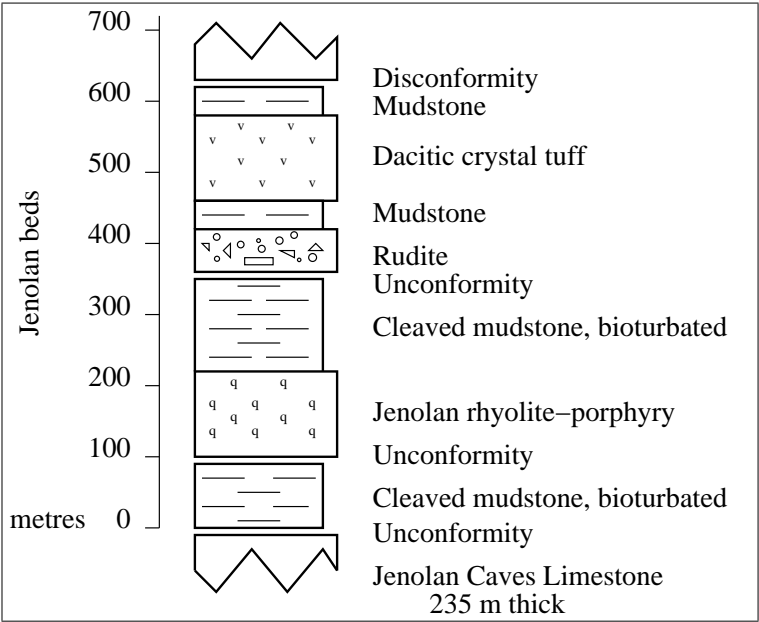


Figure 3.4: Stratigraphic sequence for part of the Jenolan beds overlying the Jenolan Caves Limestone. Based on Allan (1986).

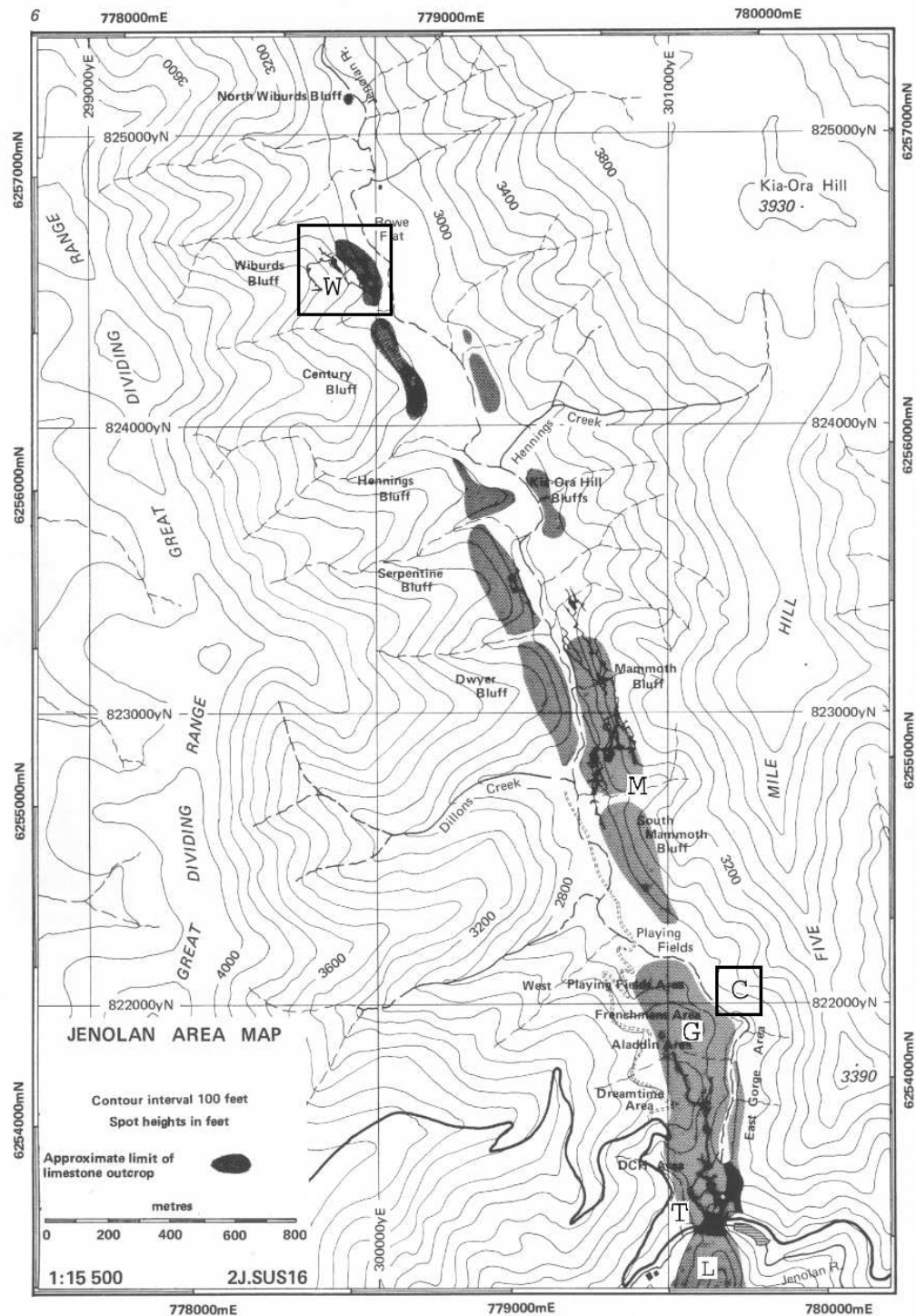
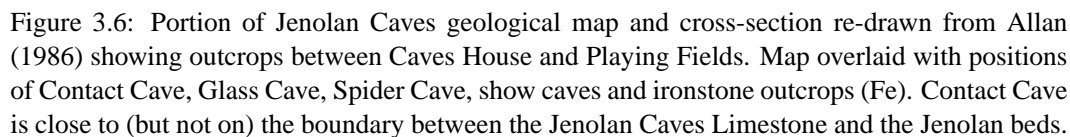


Figure 3.5: Map of northern part of Jenolan Caves Limestone outcrop by Dunkley (1976) overlaid with cave positions mentioned in the text. Study sites outlined. Key to caves: C - Contact Cave, G - Glass Cave, L - Lucas Rocks, M - Mammoth Cave, T - Show Cave complex, W - Wiburds Lake Cave



### **Dykes**

The Jenolan Caves Limestone is intruded by several dykes of varying chemistry (and presumably age). Occasionally a cave intersects an intrusion, for example, at a site called “Abusive Intrusive” in Mammoth Cave a weathered sill was identified by Cooper (1990). The fine-grained sill contains quartz, plagioclase and potassium feldspar. Cooper noted the contact zone had large calcite crystals and was preferentially weathered compared to the bedrock. He discussed other silicic intrusions which control speleogenesis, and noted the limestone was recrystallised near these sites. Cooper suggested the silicic intrusions were Carboniferous, the same as the granitic intrusions in the region, and undeformed by folding or faulting. I have observed zones of recrystallised limestone bedrock around a prominent joint a few metres south of Mammoth Cave entrance, and at “The Forty Foot” near the base of the entrance rockpile. They are not necessarily caused by intrusions.

Cooper (2001) mentioned that “dark brown basalt” dykes outcrop in several caves at Jenolan, and are developed parallel to east-west jointing. They act as aquicludes and in some cases guide the underground water along the jointing system. Cooper considered that the jointing system predated these intrusions. Allan (1986) suggested the mafic intrusions occurred during the Tertiary. In Spider Cave, at Sump 1, the Jenolan Underground River flows through a sump as the main passage is blocked by the east-striking dyke. The dyke outcrop (in the cave) is highly weathered and soft. Another example is a micromonzonite dyke which crops out between Serpentine and Hennings Cave and also to the east of Mammoth Bluff (Cooper 1993). Cooper considered it was Carboniferous.

Towards the northern end of the Jenolan Caves Limestone, a mafic dyke is exposed in Wiburds Lake Cave Cooper considered this dyke to be Devonian, the same as the dykes that occur in the Jaunter region to the south-west. Scheibner (1973) suggested similar altered dolerite dykes in the region were post Upper Devonian, pre-Kanimblan or early Kanimblan.

### **Other structures**

The main regional geological structures are a recumbent fold with a north-south axis, and two thrusts: the Jenolan Thrust which strikes north and separates the “Eastern limestone” from the Jenolan beds and “McKeowns thrust” which strikes north-northwest along the western edge of the Jenolan Caves Limestone. The fault zone of “McKeowns thrust” is characterised by a fault breccia containing black chert nodules (Cooper 1993). “McKeowns thrust” is parallel to and east of the Jaunter Fault.

The main body of limestone generally dips to the west, overturned in most areas, with near-vertical bedding near Caves House and more shallow bedding (albeit overturned) to the north. On the eastern side of the limestone outcrop, the bedding dips steeply to the east, whereas on the western side it generally dips to the west, overturned (Allan 1986). The “Eastern Limestone” (a local name for the outcrop) is a small impure limestone deposit to the east of the main body of the

Jenolan Caves Limestone. The area was described and mapped by Chalker (1971) and in more detail by Allan (1986).

Allan noted that the Jenolan Caves Limestone and the Jenolan beds are folded in a series of near-recumbent folds, with wavelengths of the order of 400 m. Parasitic folds with <40 m wavelengths were found superimposed on the larger scale folds. Allan also noticed that where the bedding had a westerly dip, the cleavage had a slightly shallower dip and noted that the cleavage always “follows” (lags?) the dip of the large scale fold structures.

Allan concluded that after the Jenolan Caves Limestone had been deposited in the Late Silurian, a long period of volcanism during Late Silurian to Middle Devonian times deposited the thick Jenolan beds. He suggested that from the Middle Devonian to Late Devonian or Early Carboniferous, the Jenolan region was subject to deformation involving two folding events and the Jenolan thrust (high angle thrust) (Allan 1986). The first event (Mid Devonian Tabberabberan orogeny) was an uplifting event; the Early Carboniferous Kanimblan orogenic event was a folding event which terminated the marine sedimentation of the Lachlan Fold Belt (Cas 1983).

### **Geomorphological Setting**

Jenolan Caves are situated on the eastern side of the watershed of the Great Dividing Range (Great Divide). The region is a dissected plateau with an average elevation of 1100 m ASL. Jenolan Caves forms an incised valley with the limestone outcrop standing proud of the valley floor at around 800 m ASL. The caves are in two long blind valleys, oriented north-south and surrounded by steep hills. The central part of Jenolan Caves features arches, bridges and a “valley in valley” structure. The northern valley, McKeowns Valley, is terminated by the Devils Coach House (cave). On the southern side, Lucas Rocks and the Grand Arch (cave) mark the end of the valleys formed by Camp Creek and Surveyors Creek.

The area is drained by the Jenolan River, a tributary of the Coxs River. There is a major change in drainage from north-south (parallel to strike) to eastwards following the Jenolan River. Its northern tributaries include the ephemeral Jenolan River (formerly known as McKeowns Creek), Dillons Creek, Stockyard Creek, the creek-sized Jenolan Underground River and an ephemeral underground creek in Mammoth Cave called Central River (Dunkley & Anderson 1978). The northern part of the Jenolan River sinks into gravel where it meets the limestone about 500 m north of Rowe Flat – the actual position of the sinking point depends on rainfall.

The underground conduits have limited capacity, so excess water flows in the surface creeks during floods. Tributaries from the south include Camp Creek, Surveyors Creek, and small underground streams called Styx and Lethe which appear in the southern show caves. Vaughan-Taylor and other divers are mapping water-filled parts of the caves and have identified several small underground streams (Vaughan-Taylor 2000, Vaughan-Taylor 2001a, Vaughan-Taylor 2001b, Vaughan-Taylor 2003). Some large water-filled cavities have been discovered under South Mammoth Bluff.

Small discharge fans are commonly found wherever small tributary creeks join the main surface creeks. Some of these are presently active (e.g. Dillons Creek) which deposited a large amount of material during the late 1980's. Other features such as the large scree slopes and rock streams are relics from an earlier, colder climate, possibly coincident with the most recent glacial maximum.

A series of flat-floored valleys joined by narrow limestone gorges are a feature of McKeowns Valley. Seismic work by Ian Cooper, James Reid (pers. comm.) and members of the Sydney University Speleological Society estimated the sediment depth on Playing Fields to be about 40 m. About 1 km north of Rowe Flat, there is little exposed limestone and much of the valley is buried by alluvial fans. Dolines are developed in some of these fans, indicating a sinking point for water and gravel into the Jenolan underground river system. The flat-floored valleys, ephemeral surface streams and limestone hills with underground drainage are typical karst landforms.

### **Geological and Karst History**

After the Kanimblan orogeny was complete, the strata in the region were close to their present orientation: that is, the beds of the Jenolan Caves Limestone were overturned. The region was generally subject to subaerial erosion. Small paleokarst deposits of graded-bedded crinoidal limestone are exposed in the show caves where the dip is sub-horizontal, contrasting with the general bedrock dip of about  $85^\circ$  in that part of the Jenolan Caves Limestone. One good exposure occurs in the Mud Tunnels, part of the show cave complex. The Silurian limestones must have presented an exposed karst surface when the Carboniferous limestones were deposited. Erosion during the Late Carboniferous led to the incision of the Jenolan valley. Most of the Carboniferous deposits have been eroded except for those which are preserved in the caves or in veins or fissures (Osborne 1990, Osborne 1993a, Osborne 1995).

During the Permian, gravel was deposited over some of the landscape as the region became buried under the Sydney Basin during a period of glaciation. Some of this horizontally-bedded gravel remains perched in areas near Lucas Rocks and the southern limestone valley area as a conglomerate.

According to Osborne, Zwingmann, Pogson & Colchester (in prep.), there were several periods of cave development at Jenolan: One of the earliest periods (phase 1) appears to be Mid Devonian (390 MA) fissure fills related to the volcanoclastic "Jenolan Beds". This was followed by a folding event. A post-tectonic deposition of laminated crinoidal caymanite (phase 2) followed during a marine transgression. This was followed by a thermal event (phase 3), estimated to be Carboniferous (ca. 340MA), forming calcite crystal-lined cavities, dolomite replacement of fabrics and alteration of palaeokarst. During the Permian, large caves were developed (phase 4) which then filled with gravels (phase 5). The Tertiary period appeared to be a period of meteoric speleogenesis (phase 6), paragenetic developments in the caves (phase 7), followed by Quaternary speleogenesis and exhumation of earlier deposits (phase 8). At present, Mg-rich minerals con-

tinue to be weathered from cave deposits and low-Mg calcite speleothems are depositing (phase 9) (Osborne 1999, Osborne et al. in prep.).

Some parts of the Jenolan Caves Limestone deposit are dolomitised. Not all parts of beds are dolomitised; in some areas there are islands of relatively pure micrite surrounded by dolomitised rock in which the bioclasts are preserved but the micrite is replaced by ferroan dolomite. This is similar to the descriptions of red weathered deposits mentioned by Chalker (1971). Sometimes dolomitisation has only affected specific bioclasts, e.g. in the show caves, Osborne has identified the sponges as having been dolomitised. This study has found dolomitisation of the bedrock parallel to the bedding near Contact Cave. There may have been two episodes of dolomitisation. The first episode appears to be primary (Late Silurian), resulting in partial dolomitisation of the bedrock parallel to strike near Contact Cave. The second episode resulted in local dolomitisation of caymanite and emplaced dykes. Allan (1986) suggested that basic dykes intruded the region during the Tertiary period. This study has found minor dolomitisation of the dyke in Wiburds Lake Cave, although it cuts across dolomitised bedrock. This infers that the dyke was emplaced after Osborne's Phase 3 which is not inconsistent with Allan's suggestions.

Caves have developed in the most pure limestones. Impure or dolomitised limestones, mudstones and dykes act as temporary barriers to cave development. Exposure of dolomitic beds to fresh water entering through cracks, joints or cave conduits has allowed dedolomitisation to occur, and this is presently happening in the show caves. This is discussed by Osborne (1999). Barriers to cave development near Contact Cave include the Jenolan beds to the east, together with dolomitised limestone parallel to bedding. Similarly, barriers to cave development at Wiburds Lake Cave includes argillaceous beds and a dyke.

### **Ironstones**

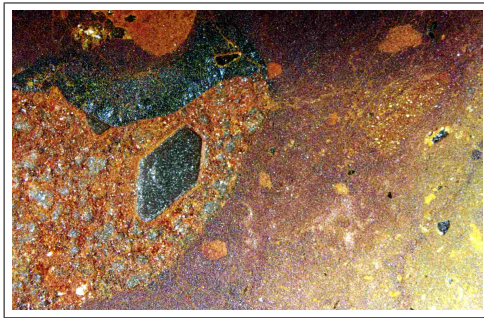
Within the Jenolan Caves Limestone and near both its eastern and western edges are deposits of ironstone: in some cases, limonite, goethite and manganese oxides appear to have replaced the micrite of limestone but not the larger bioclasts. Some of the more pure goethites appear to be cavity fills. It is suggested that this iron was concentrated after the in-cave weathering of ferroan dolomite. Other ironstones appear to be ferruginised quartz sediments (possibly palaeokarst fills).

Aragonite is associated with ironstones and ochres in several caves at Jenolan, such as Contact Cave, Wiburds Lake Cave, Glass Cave and the show caves, Orient Cave and Ribbon Cave (Figure 3.5). This is discussed further in sections pertaining to those caves.

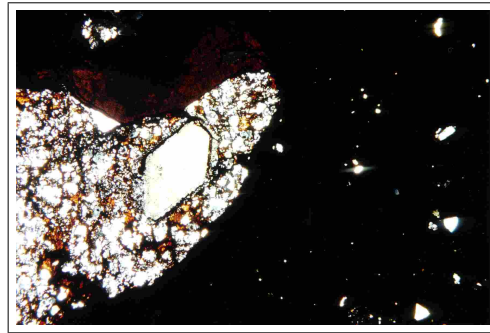
Ironstones occur in Imperial Cave (the Diamond Mines area). Small amounts of aragonite have been reported (Osborne, pers. comm.) from this site. Ironstones crop out in several locations on the surface, such as shown in Figures 3.6 and 3.30.

A small hemispherical doline on the eastern side of the Devils Coach House near the Six Foot Track is associated with goethite and highly ferruginised and dolomitised rock.

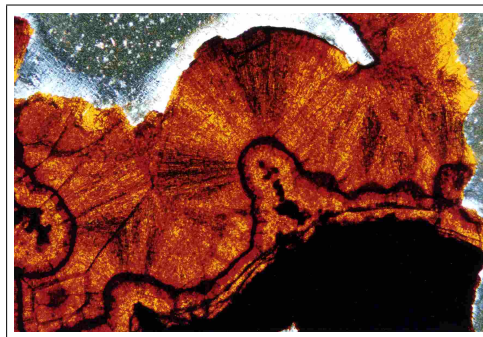
On the top of Lucas Rocks, small goethite concretions occur. Near the boundary between the Jenolan Caves Limestone and the “Eastern beds”, the limestone exhibits red veining, similar to the dolomitisation seen near Contact Cave. A small goethite concretion (sample JEN-1) from this area was thin sectioned. It is mostly opaque but with a small amount of quartz and feldspar resembling grains from the Jenolan quartz porphyry. In the concretion, goethite occurs as a massive earthy material and as a mammillary crust with fine monoclinic crystals (Figures 3.7).



TS JEN-1 N36370 Reflected light x13.  
Earthy and crystalline goethite reflects a variety of red and brown colours.



TS JEN-1 N36370 XN x13. ?Diopside and quartz grains in opaque goethite.



TS JEN-1 N36370 XN x50. Fine botryoidal crystalline goethite.

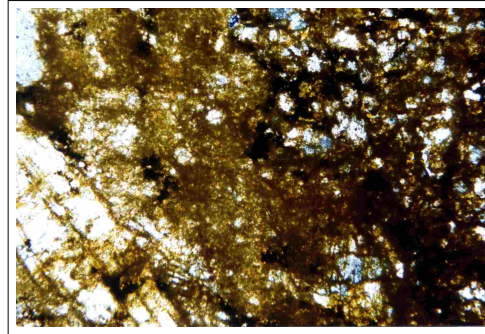
Figure 3.7: Thin Sections, Jen-1.

Along the zig-zag track between the village and Burma Road, following the western edge of the limestone, goethite occurs as nodules and earthy concretions with dark botryoidal aggregates (sample JEN-2). To the north of the cottages on Burma Road, on the western edge of the limestone, is a larger deposit of ironstones. Samples taken from this area include a small shard of botryoidal goethite (Jen-3) and a pebble of laminated goethite (Jen-4). In this same area, one small limestone boulder was partially ferruginised grading from limestone to gossan and goethite. The boulder was rounded, characteristic of regolith. Samples JEN-6, JEN-7 and JEN-8 were all chipped from this boulder. The most ferruginised portion comprises botryoidal aggregates and sparkly goethite crystals (sample JEN-8). An earthy area contains small paramorphs of calcite

after aragonite. There are some calcite veins and some bioclasts are preserved. A sample of gossan and ochre (Sample JEN-6) contains small calcite spar crystals which resemble pseudomorphs of calcite after dolomite and some mis-shapen spar resembling a paramorph of calcite after aragonite. The limestone (Sample JEN-7) is a light coloured stone with numerous crinoids and algae stems and a small quantity of iridescent goethite.

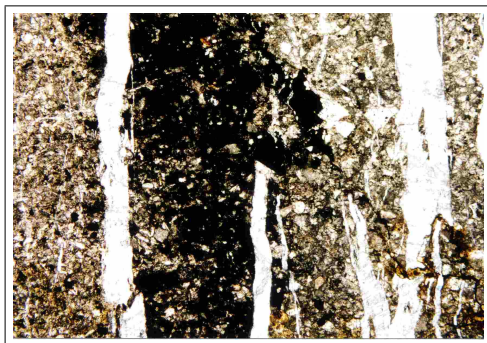


TS JEN-7 N36372 XN x13. Breccia of limestone, goethite and ferruginised, altered ?dolomite.

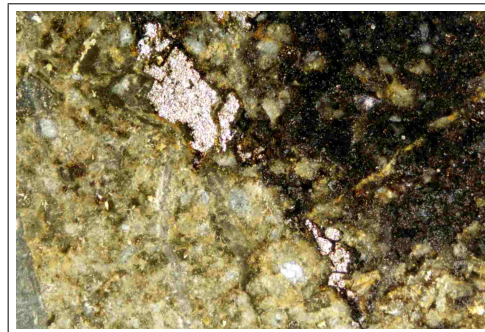


TS JEN-7 N36372 XN x50. Detail of altered region.

Figure 3.8: Thin Sections, Jen-7. Ferruginised limestone, near western boundary of Jenolan Caves Limestone.



TS JEN-5 N36371 PPL x13. Radiolarian chert with sheared calcite veins.



TS JEN-5 N36371 Reflected light x25. Note pyrite grains.

Figure 3.9: Thin sections, Jen-5. Radiolarian chert with sheared calcite veins.

Thin sectioning (Figure 3.8) shows the limestone texture is a wackestone, poorly washed biosparite. The limestone has a different fauna compared with Jenolan Caves Limestone and may be younger, related to the palaeokarst “Caymanites” as described by Osborne (1990), Osborne (1993a), Osborne (1995). The boundary between the limestone and the ferruginisation may be sheared. Some of the ferruginisation may be a replacement of ferroan dolomite which itself has replaced micrite, as the larger bioclasts are unaltered. Manganese occurs in ferruginised areas as small dendritic groups. There are both ferruginised veins and sparry veins.

Chert also occurs in the same area. Sample Jen-5 is a pebble of dark pyritic radiolarian chert with white crystalline calcite veins (Thin Section Jen-5 in Figure 3.9). Repetition twinning would infer that this rock is sheared, and most likely lies on the faulted contact between the Jenolan Caves Limestone and the western Ordovician units.

### **Caves Introduction**

There are over 330 cave entrances at Jenolan documented by speleological societies (Matthews 1985, Australian Speleological Federation 2002). About 15 of the caves are quite extensive. There are about a dozen caves of significance in the “Northern Limestone” area.

The “Southern Limestone” (a local term, not a geological name) is that part of the Jenolan Caves Limestone outcrop which lies south of Lucas Rocks. There are only about a couple of dozen caves in the “Southern Limestone”; mostly they are small. Two exceptions are Bottomless Pit (a deep cave) and Paradox Cave (an important bat maternity site). The “Southern Limestone” has rugged country and thick vegetation.

The Eastern Limestone is also little-visited, being in very rugged country with poor cave development. One cave, Harrys River Cave, is a medium-sized cave according to maps prepared by the Jenolan Cave guides and by Blue Mountains Speleological Society.

The “Northern Limestone” (a local name) is that part of the Jenolan Caves Limestone north of Lucas Rocks. The caves of the “Northern Limestone” are more easily accessible as there are walking tracks through the more rugged areas and sparser vegetation towards the north.

Compared with some other limestone cave areas in NSW, Jenolan Caves has a lot of cave passages per unit volume of rock. The show caves are the largest, best decorated and most extensive caves at Jenolan. They include three arches (bridges) (the Grand Arch, Carlotta Arch and the Devils Coach House), and the interconnected show caves leading from the northern and southern sides of the Grand Arch. The total passage length of the show cave system is in the order of 20 km.

The general nature of the southern show caves is a series of large chambers connected by small passages on various levels. The large chambers are cupolas and are well decorated with speleothems. Examples include the Temple of Baal and the Persian Chamber in Orient Cave. Some cupolas are blind; there is little evidence to suggest they ever connected to the surface naturally (R.A. Osborne pers. comm.). There is usually no evidence of a stream having ever been present. Rather, the large chambers form a roughly inverted teardrop shape with a cupola at the ceiling and a narrow passage, rockpile or calcite-cemented slot at the base. Exhibition Chamber is a large breakdown chamber.

Interconnecting passages have been extensively modified to allow the passage of tourists. In general, the large chambers are connected near their base. These passages are developed on multiple levels with paragenetic loops and complex junctions. Small creeks presently flow

through pools in the lowest levels, rising at the edge of the Blue Lake (an artificial reservoir) east of the Grand Arch.

Another type of cave near the show cave area takes the form of a deep vertical shaft with a small entrance and a calcite-cemented floor with no apparent extensions. Such caves are roughly cylindrical, and developed along the strike of the almost vertically bedded limestone. Examples include Fat Jacks Cavern (J-266, 21 m deep) at Lucas Rocks, Twin Shafts Cave (J-200, 45 m deep) near the Burma Road and Bottomless Pit (62 m deep) in a hill south of the show caves.

The northern show caves are quite different to the southern show caves. The passages are strongly influenced by north-south development along the strike of the limestone and are developed on multiple levels connected by rockpiles and shafts. The lowest passages are partially water-filled by the Jenolan Underground River (a small creek) and its tributaries.

South of Playing Fields (Figure 3.5), the caves tend to have prominent north-south oriented passages, corresponding to the strike of the limestone. North of Playing Fields, this pattern tends more towards the northwest following the strike of the Jenolan megakink.

Wiburds Lake Cave combines features of large chambers, northwest strike-developed passages, multiple levels and tectonic features (Figure 3.34).

Active streamways are present in several caves: the Imperial, Cerberus and River show caves, Mammoth Cave, Spider Cave and intermittently in other caves such as Serpentine, Hennings and Wiburds Lake Cave. A lake is sometimes present in Wiburds Lake Cave.

Osborne noted that pyrite was emplaced in the Permian cave gravels but not the Cainozoic ones, and that oxidation of this pyrite led to deposits of sulfate speleothems and aragonite (Osborne 1995). Jenolan Caves are often well decorated, mostly with calcite speleothems; however, aragonite and other minerals occur. A long term mineralogical study in the show caves is being conducted by Colchester, Pogson and Osborne (Osborne et al. 2002).

Some of the caves at Jenolan which contain aragonite speleothems include Orient Cave, Ribbon Cave, River Cave, Mud Tunnels, Cerberus Cave, Glass Cave, Contact Cave, Spider Cave, Mammoth Cave and Wiburds Lake Cave. Other caves at Jenolan which may contain aragonite are Temple of Baal, Dwyers Cave and Hennings Cave.

### **Caves Chosen**

Two caves (Contact Cave and Wiburds Lake Cave) were selected as major study sites. Other caves examined at Jenolan were the show caves, Glass Cave and Mammoth Cave. Spider Cave had been examined some years earlier (around 1989 – 1990). Study sites are shown in Figure 3.5.

The reason why Contact Cave and Wiburds Lake Cave were chosen as major sites was because aragonite had been reported in them. Aragonite had been reported in Contact Cave by Ernst Holland (pers. comm.) and by David Colchester and Ross Pogson from the Australian Museum (pers. comm. to R.A. Osborne). The aragonite in Wiburds Lake cave has been reported by cavers in the Sydney University Speleological Society. These caves are relatively easy to access and

there have been little modifications made to them compared to the show caves. Glass Cave was also considered as it had been visited twice prior to this study commencing, and contains aragonite. However, repeat visits are inconvenient because of the number of people and equipment needed to safely access the delicate site, and access restrictions to the area limit trips to one trip per team of 6 people per year. Mammoth cave was also considered, as the aragonite site “World of Mud” is extensive. It was visited once but repeat visits would be inconvenient due to the effort, number of people and amount of equipment needed to safely access the site. Spider Cave was not considered due to the small amount of aragonite apparently present, and the inconvenience of physical access for repeat visits. The show caves are easily accessible; however, care would need to be taken when sampling because of the possibility of chemical contamination from years of show cave infrastructure (e.g. zinc from fencing, copper from wiring etc) and the social / ethical problems resulting from removal of material from well-known speleothems. Some aragonite material from the show caves has already been sampled by others, and their results are noted in the case studies.

### **Cave Observations at Jenolan: Contact Cave**

#### **Location**

Contact Cave is a small cave located high on a steep hillside above cliffs, on the eastern edge of the limestone to the south east of Playing Fields (Figures 3.5 and 3.6) about 150 m above the normally dry bed of the Jenolan River and due north of the Devils Coach House. It was called “Contact” Cave because it was thought to lie on the contact between the limestone and the Jenolan beds. It lies within a few metres of the contact (Figure 3.10).

Vegetation near the cave is open woodland. Blue Gum (*Eucalyptus bicostata*) and some herbs favour the limestone contact area. Ribbon Gum (*E. viminalis*), *Acacia falcata*, *A. melanoxylon*, blackthorn (*Bursaria spinosa*) and herbs including nettles (*Urticaria sp.*) and grasses favour the limestone. Red Stringybark (*E. macrorhyncha*) and Blaxlands Stringybark (*E. blaxlandii*) prefer the volcanics.

To the north and parallel to the valley, the hillside is steep and mostly scree-covered along the contact region between the Jenolan Caves Limestone and the Jenolan beds. Some of these scree slopes may be small mass-movement deposits.

The cave is developed in partially dolomitised limestone below a loose covering of scree comprised mainly of rocks from the Jenolan beds. The bedrock (where exposed) appears to be partially dolomitised limestone and suspected palaeokarst. The hillside west of the cave is Jenolan Caves Limestone and again partially dolomitised. Further to the north, the hillside is broken by scree-filled gullies.

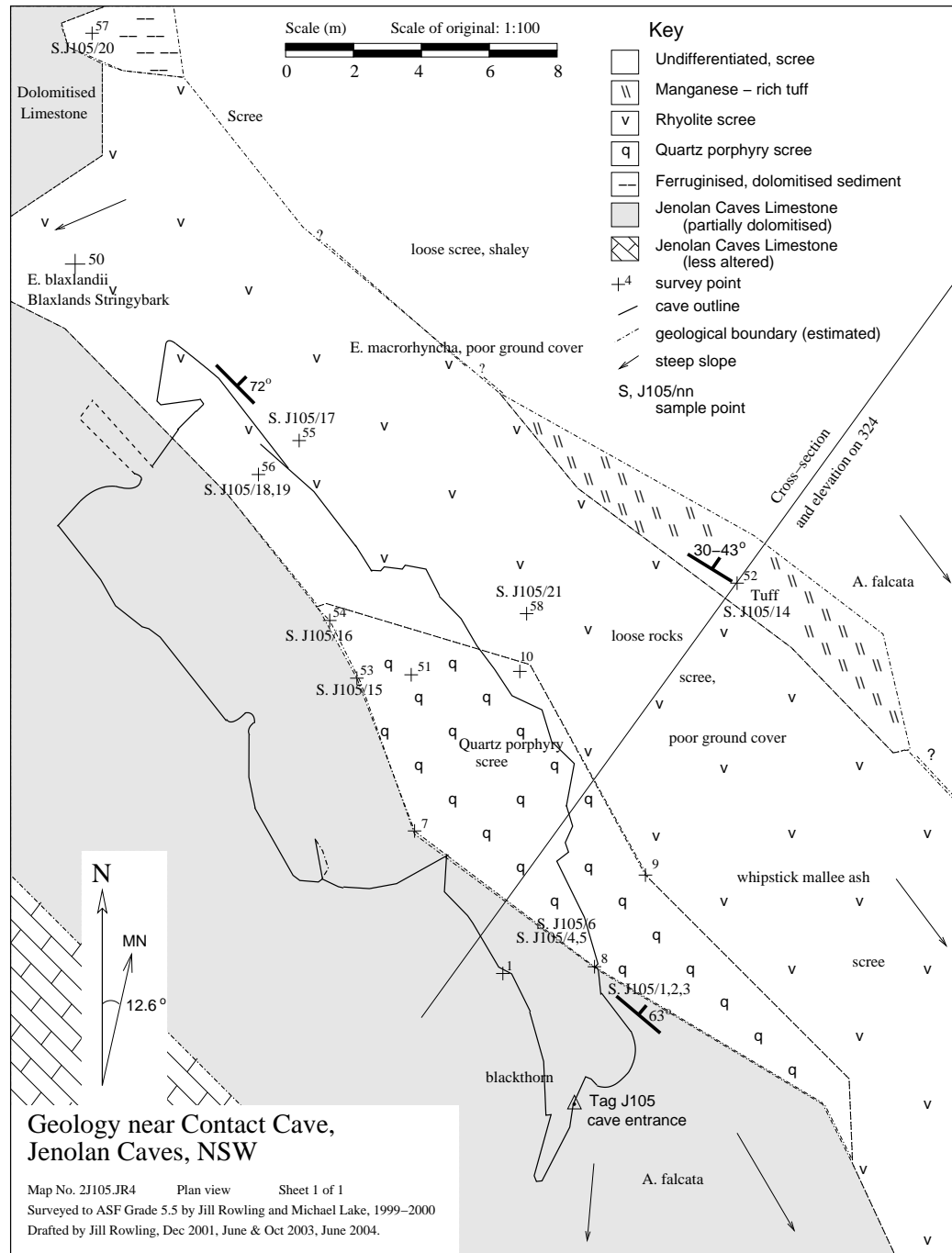


Figure 3.10: Map of area near Contact Cave showing the local geology, general outline of the cave, vegetation notes, position of nearby sample and survey points.

### Geological Setting

The Jenolan Caves Limestone does not crop out in all of the area above the cave. Some of it is covered by volcanoclastic scree. In the Contact Cave area, the limestone dips and faces to the east. It is not overturned as occurs in the western part of the outcrop. The strike and dip changes over a short distance as shown in Figure 3.10.


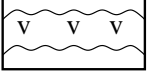
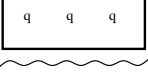
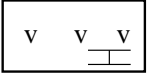
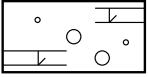
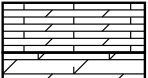



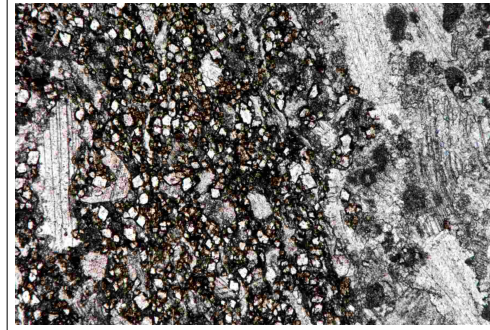
| Correlation with Allan (1986) |                          | Unit description  | Sample Numbers              | Sample point<br>(u/g = underground) |
|-------------------------------|--------------------------|---|-----------------------------|-------------------------------------|
| "Jenolan beds"                | ?Dacitic Crystal Tuff    |    | J105/13                     | About 70 m east of Contact Cave     |
|                               |                          | Disconformity   |                             |                                     |
|                               | Jenolan Rhyolite-Porphry |    | J105/17,18,19<br>J105/14,21 | 55,56<br>52,58                      |
|                               |                          | Disconformity   |                             |                                     |
|                               |                          |    | J105/22,23,24,25            | 7,8,9,10                            |
|                               |                          | Disconformity   |                             |                                     |
| Jenolan Caves Limestone       |                          |  | J105/15,16                  | 52,53                               |
|                               |                          | Disconformity   |                             |                                     |
|                               |                          |  | J105/20                     | 57                                  |
|                               |                          | Disconformity   |                             |                                     |
|                               | Shaley limestone         |  | J105/6                      | 8                                   |
|                               | Rudaceous limestone      |  | J105/4,5<br>J105/5ug        | 8<br>S5 u/g                         |
|                               |                          |  | J105/1,2,3<br>J105/11       | S1surf near 8<br>S5 u/g             |
|                               | Massive lime mudstone    |  |                             |                                     |
|                               |                          | No thickness implied  |                             |                                     |

Figure 3.11: Stratigraphic sequence for part of the Jenolan Caves Limestone and the Jenolan beds near Contact Cave.

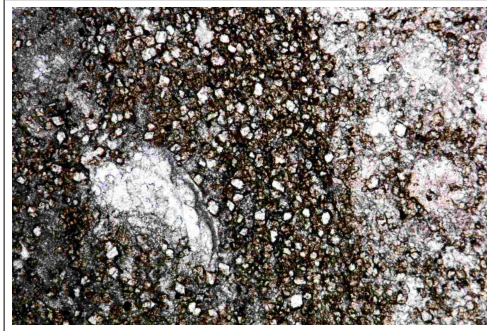
Near Contact Cave, the uppermost strata of the Jenolan Caves Limestone closest to its eastern boundary with the eastern volcanics contains fragments of brachiopod and crinoid set in a matrix of lime mud. This mud is dolomitised in places, with dolomitisation taking place after lithification. The stratigraphic sequence near Contact Cave is shown in Figure 3.11. See also the section in Figure 3.15. The following notes refer to the different units shown in Figure 3.11.



TS J105/1 N35858 PPL 12.5x. Dolomite and micrite.



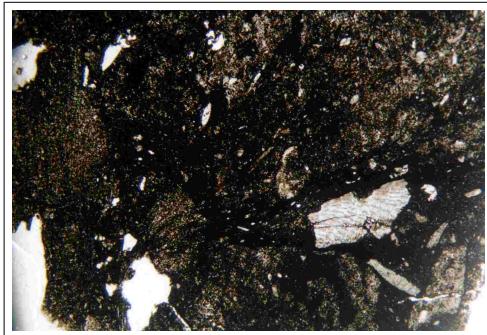
TS J105/2 N35859 PPL 25x. Dolomite and unaltered bioclasts.



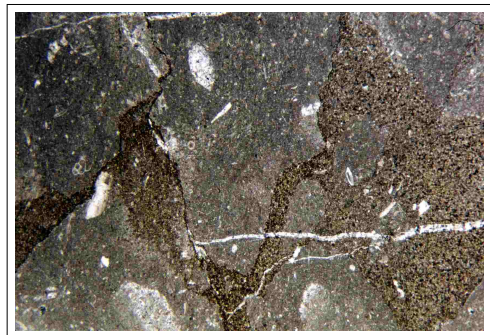
TS J105/3 N35860 PPL 25x. Dolomite and unaltered bioclasts.



TS J105/4 XN 3.2x. Large bioclasts suspended in a matrix of dedolomite and opaques.



TS J105/5ug PPL 3.2x. Large bioclasts, partially altered, in a matrix of dedolomite and opaques.



TS J105/11 XN 3.2x. Dolomitic seam in biomicrite.

Figure 3.12: Thin Sections J105/1 to J105/11: Contact Cave

**Dolomitised limestone**

This unit has a conformable boundary with the massive lime mudstone and is considered to be part of the Jenolan Caves Limestone. In the field, it is coloured grey, brown, yellow and pink, with bryophytes often found growing on the coloured surfaces. The limestone texture ranges from almost pure micrite to biomicrite and some sparite. Texture ranges from lime mudstone (J105/1) to rudstone (J105/2). (Thin Sections TS J105/2 N35859, TS J105/1 N35858, TS J105/3 N35860 in Figure 3.12). Sample J105/2 was the oldest, followed by samples J105/1 and J105/3 is the youngest. Bioclasts include crinoid, brachiopod and possible trilobite fragments. In-cave sample J105/11 was also from this area, extrapolated from the dip (Figures 3.10 and 3.18) and will be discussed later.

**Zoned, dolomitised limestone and ferroan dolomite**

This rock is a brown to reddish colour in outcrop and occurs close to the eastern boundary of the limestone. Bryophytes usually grow on surface outcrops. Polished slabs of surface rocks show a variety of white and grey bioclasts floating in a sea of reds and browns. There is some thinly bedded limestone in this unit. The rock texture is a sparse to medium biomicrite with some quartz and clay. Bioclast fragments range in size up to about 10 mm long, comprising brachiopod and bryozoan fragments. Inside Contact Cave, this rock unit is a darker brown, soft and highly porous, having numerous holes due to chemical leaching (Figure 3.12 TS J105/4, TS J105/5ug). Samples J105/4, J105/5 and J105/5ug were from this zone. Sample J105/5ug was from inside Contact Cave and will be discussed later.

**Dolomitised, thinly-bedded limestone**

Sample J105/6 was from this zone. J105/6 appears to be conformable with the underlying limestones, but contains more quartz and is thought to be a thinly-bedded region deposited in a more muddy environment. It is a hard brown, yellow and grey limestone with a variety of bioclasts including crinoid and brachiopod fragments and a higher proportion of quartz than the earlier units. Dolomitisation of the specimen was in veins, with some undolomitised grey limestone present.

**Ferruginised, dolomitised sediment**

This is a tough brown, yellow and grey lime sediment with a variety of bioclasts including fenestellid bryozoan, algae, possible sponge spicules and brachiopod fragments and a higher proportion of quartz than the Jenolan Caves Limestone. Sample J105/20 is from this zone. Thin section of J105/20 (Figure 3.13) shows relatively unaltered bioclasts, in an altered ferruginised background containing ferroan dolomite and silica (chalcedony). There is little silica in the bioclasts, although some of the algal stems have dolomitic interiors. Most of the limestone is altered (dolomitised and ferruginised) but the bioclasts are unaltered. The relationship between this rock

and the older units appeared to be disconformal near sample J105/20, giving the appearance of a cavity fill (or a caymanite). Although it has been positioned stratigraphically as per Figure 3.11, it could be positioned anywhere between there and before the crystal tuff deposition due to the erosional contact. The bioclasts and appearance in thin section suggest the unit is related to the one cropping out behind the guides' cottages on the Burma Road (JEN-7, Figure 3.8). J105/20 crops out at a similar altitude to JEN-7. (Compare bioclasts in Figure 3.57).

#### **Carbonated basic lava flow with liesegang rings and occasional quartz phenocrysts.**

This appears in the field as a red or grey rock; the red colouration is a surface oxidation or alteration. Internally, the rock is tan to grey and has fine red particles. Samples J105/15 and J105/16 are from this area (Figure 3.13 TS J105/15, TS J105/16). Thin section shows an even textured rock containing biotite, plagioclase, orthoclase and some quartz. Rare phenocrysts include quartz, and K-feldspar, with embayments filled with quartz with opaque centres. Calcite and dolomite has replaced some minerals and filled some voids. XRD of J105/15 indicates major quartz, muscovite, biotite, minor illite 2M1, and several other minor minerals. XRD of J105/16 is similar with more lepidolite (mica) and less other micas. The exact relationship between this rock and the limestone was unclear. It was adjacent to the limestone and initially thought to be intrusive, but there were no signs of alteration to the limestone or slickensides on the sample. It appears to be in sequence with the Jenolan rhyolite-porphyry.

#### **Quartz porphyry with small, rusty orange goethite-lined cavities.**

This unit appears to be part of the Jenolan rhyolite-porphyry; its exact boundary is unclear. Cooper (1993) referred to a similar rock outcrop to the west of KiaOra Bluffs as "Jenolan quartz porphyry". See also the stratigraphy near Wiburds Lake Cave, Figure 3.31. The outcrop near Contact Cave comprises a small area of quartz porphyry, appearing as a grey rock with white, pink and brown quartz phenocrysts. Samples J105/22, J105/23, J105/24 and J105/25 are from this area (Figure 3.14 TS J105/24). It comprises numerous quartz phenocrysts with a fine quartz matrix. Rare plagioclase laths are highly altered (partially redissolved in the melt?). Goethite veins are common. Some quartz phenocrysts are embayed; there are subhedral, euhedral and fragmented forms. Muscovite and orthoclase also occur. This was interpreted as a pyroclastic deposit. Goethite-lined cavities on weathered surfaces of this rock are from dislodged phenocrysts. Freshly cut surfaces show the cavities are filled with quartz and occasionally plagioclase; many phenocrysts are surrounded with a thin layer of goethite.

#### **Rhyolite and rhyolite-porphyry**

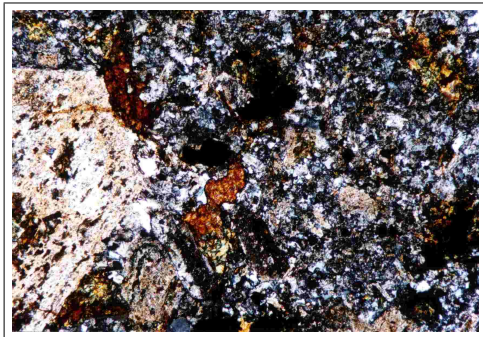
This material occurs as both an outcrop and as a scree slope in situ, west of the dacitic crystal tuff. The scree slope contains rhyolitic rocks similar to those described by Allan (1986) for the



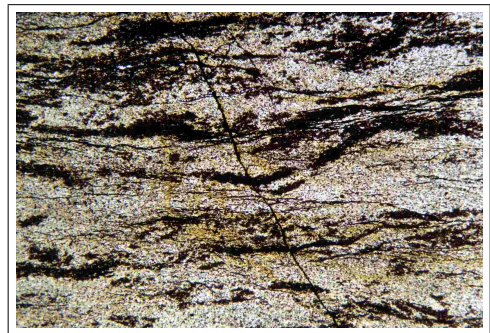
TS J105/20 N36885 PPL 13x. Bioclast (algae) little affected by ferruginisation.



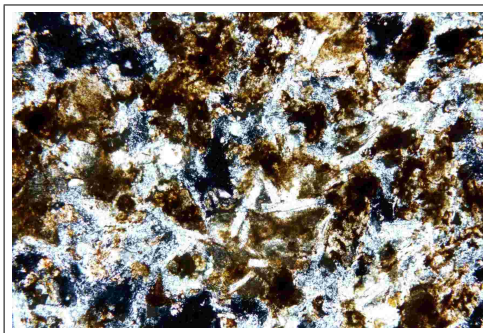
TS J105/20 N36885 XN 13x. Ferruginised, dolomitised sediment with silica.



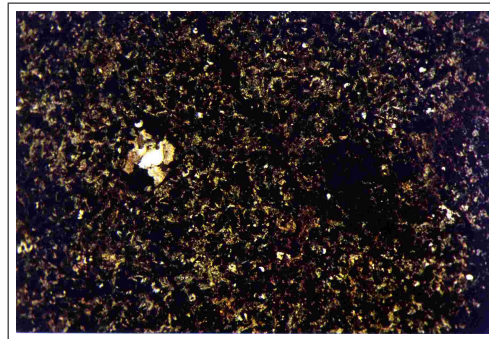
TS J105/13 N35849 XN 25x. Dacitic crystal tuff.



TS J105/14 XN 3.2x. Welded tuff.



TS J105/15 XN 50x. Lava.



TS J105/16 XN 8x. Lava, with quartz phenocryst and dark vein.

Figure 3.13: Thin Sections J105/13 to J105/20: near Contact Cave

Jenolan rhyolite-porphyry. This material was also found at lower levels, as a scree slope. The scree in the steeper areas about 20 m to the north of Contact Cave resembled a mass movement deposit. Allan noticed that the eastern boundary of this unit was sheared.

Some of the textures seen in this unit include:

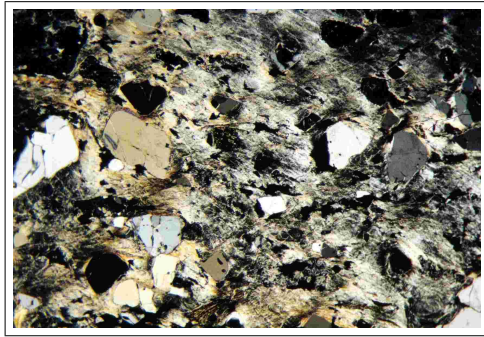
- A porphyritic rhyolite with visible flow structure comprising subhedral to euhedral quartz phenocrysts with fluid or gaseous inclusions, partially dissolved feldspars, some opaques and red veins. The matrix is altered, possibly from a fine quartz and feldspar groundmass (Figure 3.14 Thin section TS J05/19).
- Deformed and delaminated rhyolites with small euhedral quartz crystals lining voids, and quartz veins (sample J105/17).
- Slickensided, fine-grained aphanitic rhyolite (sample J105/18).
- A dark, iron and manganese-rich fine-grained rhyolite with white quartz veins and red boxwork (Figure 3.14, Thin section TS J105/21).
- A very fine grained tuff which is mainly quartz, muscovite and clays, and minor manganese oxides (todorokite and manganite), high quartz and biotite from XRD. This unit is the most easterly, and the most extensive. It crops out as a laminated rock with varying orientation. It strikes  $135^{\circ}$  and dips  $30^{\circ}$  to  $47^{\circ}$  to the east (Sample J105/14). The rock is highly jointed. Manganese oxide dendrites are common (Figure 3.13 TS J105/14). It occurs to the east of Contact Cave in place of Allan's yellow and purple shale sequences.

### **Crystal tuff**

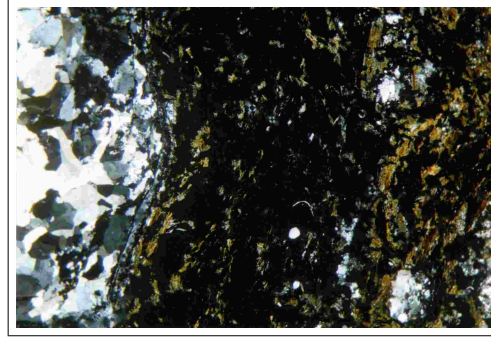
This rock crops out from about 50 m E of Contact Cave all the way to the Six Foot Track on top of the hill east of Contact Cave and is a pink and green rock with porphyritic texture. Sample J105/13 is from this area (Figure 3.13 TS J105/13). The hand specimen had an interesting weathered shape, resembling a feldspar crystal. This rock has a distinctive texture and colour, comprising fragments of feldspars and various pink and green minerals in a fine matrix. It is highly altered, with irregular crystal shapes and a porphyritic texture, partially dissolved feldspars and irregular opaques. The groundmass is a finer version of the same material. XRD indicated major albite, quartz, orthoclase and microcline. This unit was interpreted as corresponding to Allan's dacitic crystal tuff (Allan 1986).

### **Dolomitisation**

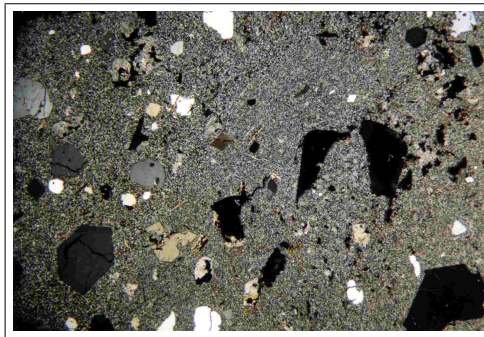
The dolomitised limestone unit near Contact Cave appears to exhibit primary (episode 1) dolomitisation. Rocks from the dolomitised limestone unit are composed of alternating layers of dolomitised lime mudstone and partly dolomitised wackestone. Only the micrite is dolomitised. Dolomitisation occurs in a zone parallel to the bedding and as invading veins replacing micrite. In



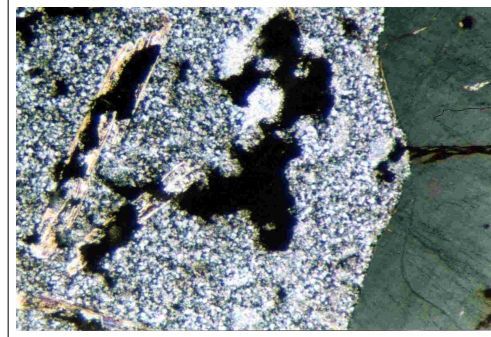
TS J105/19 XN 5x. Rhyolite.



TS J105/21 XN 5x. Rhyolite with quartz vein.



TS J105/24 XN 6.4x. Jenolan quartz porphyry.



TS J105/24 XN 20x. Jenolan quartz porphyry.

Figure 3.14: Thin Sections J105/19 to J105/24: Above Contact Cave

general, dolomitisation is invasive, replacing micrite with zoned crystals of ferroan dolomite. Dedolomitisation has occurred on the outer surfaces of these rocks, resulting in a highly weathered surface with mainly iron oxides present. Inside these rocks, this grades to a somewhat opaque area (reflects white - possibly a zone of Mg accumulation) whereas the innermost part is least subject to dedolomitisation. No bioclasts appeared to have been altered (Figure 3.12 TS J105/1, TS J105/2, TS J105/3). Different stages of dolomite appear: for example, a dolomitised vein appeared to have been truncated by a larger-grained invasive dolomite perpendicular to bedding.

The following rock units near Contact Cave are also dolomitised, but appear to be secondary localised dolomitisation (episode 2): Zoned, dolomitised limestone and ferroan dolomite (ZDLFD); Dolomitised, thinly-bedded limestone; Ferruginised, dolomitised sediment (FDS); Carbonated lava flow. Bryophytes favour these rocks more than the undolomitised limestone or the other volcanics.

Rock from the ZDLFD unit has no intact micrite; All of the micrite has been dolomitised, and in some cases, parts of the bioclasts have been altered as well, leaving a ghost outline in dark opaque minerals where the unaltered bioclast used to be (Figure 3.21 TS J105/5ug). There is an

apparent concentration of dark opaque material (reflects red) close to the edges of the bioclasts, assumed to be goethite (TS J105/4). The FDS and thinly-bedded units had mainly intact bioclasts and dolomitised micrite. Dolomite is rare in the carbonated lava flow unit, and seems to be a void replacement mineral.

### Ferruginisation

All dolomitised rock units are ferruginised to some extent. The most highly ferruginised units are the ZDLFD, thinly-bedded and FDS units. In the FDS unit, grey areas of unaltered wackestone are interspersed with a rusty material containing pseudomorphs of goethite after pyrite. This rusty material appeared to follow veins. XRD of sample J105/6 showed major calcite, quartz, haematite and goethite with minor montmorillonite-14A and pyrite. It was unclear as to whether the pyrite was primary or secondary - it was not visible on polished sections and may be finely disseminated in the many rusty veins. The FDS unit had reddish coatings, proud of the limestone, which are most likely residual material from weathering.

Ferruginisation was pronounced in the carbonated lava flow unit. This occurred as both lie-segang rings and as a zoned surface oxidation. This may be due to the porous nature of the rock coupled with oxidising pyrite, allowing iron minerals to accumulate in the oxidising zone.

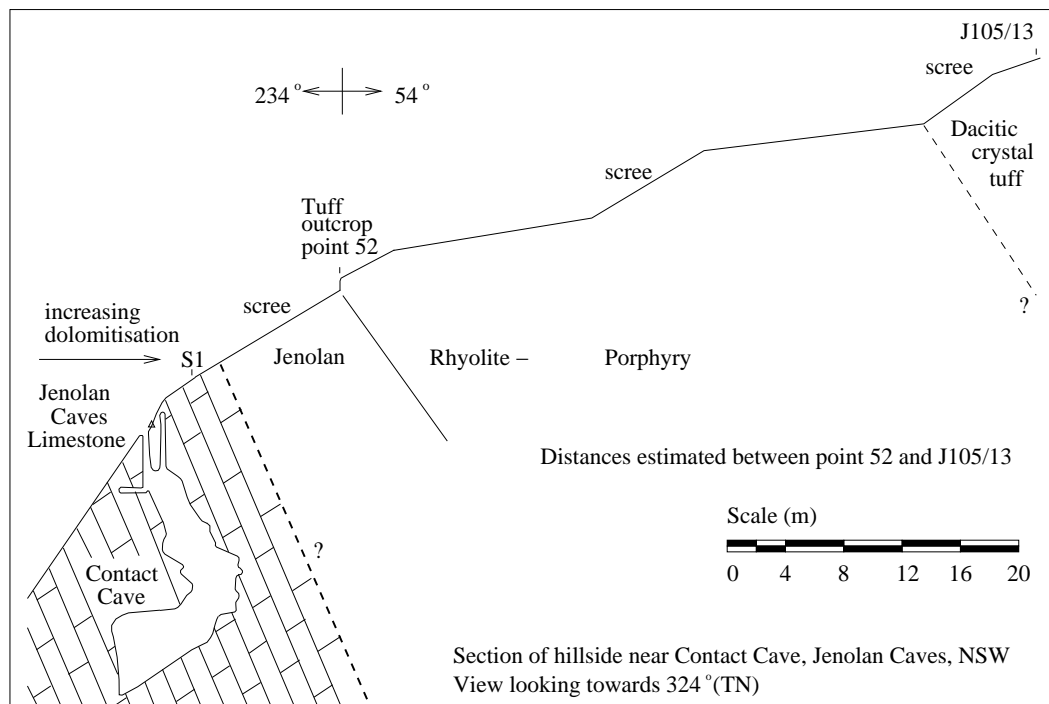


Figure 3.15: Section of area near Contact Cave. View towards the north showing the local geology and general outline of the cave. Numbers are sample and survey points.

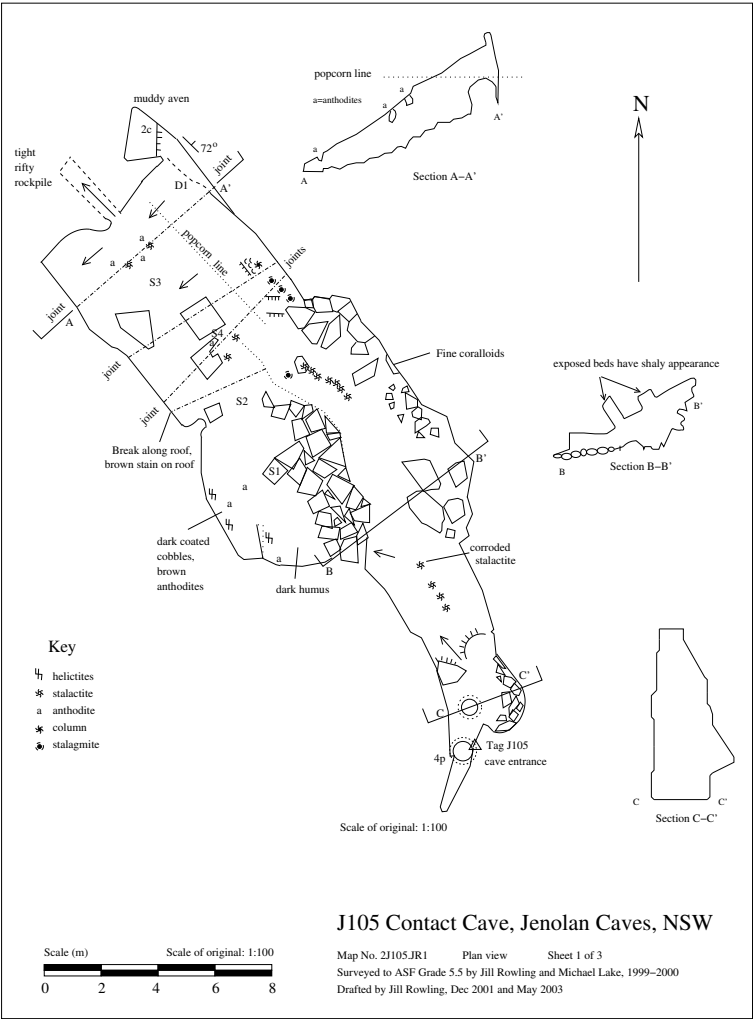


Figure 3.16: Detailed map (plan) of Contact Cave with passage cross sections, showing features, speleothems and sample points (this page to be replaced by A3 sized insert)

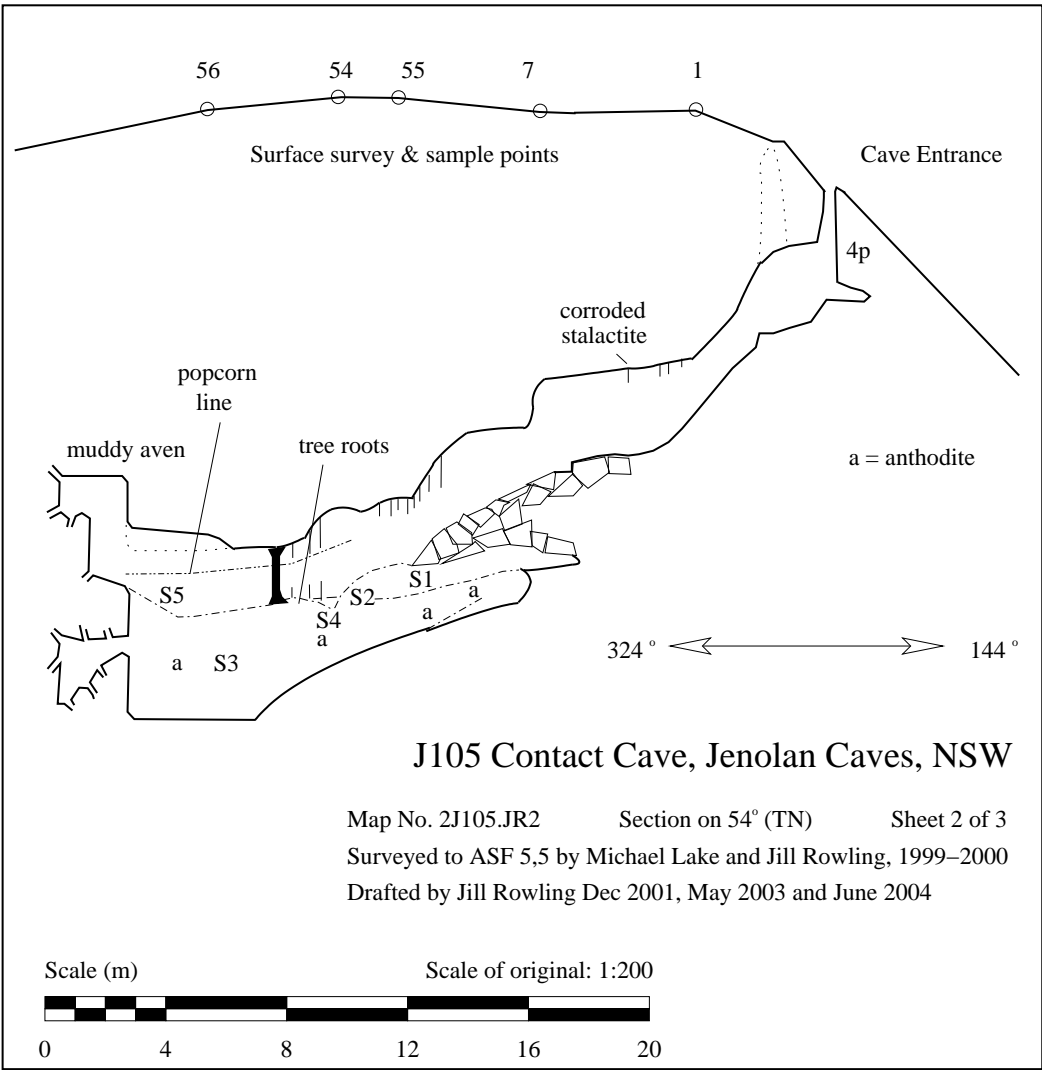


Figure 3.17: Section map of Contact Cave. View towards the east showing the general outline of the cave with the position of the popcorn line and aragonite. Numbers are sample and survey points. No vertical exaggeration.

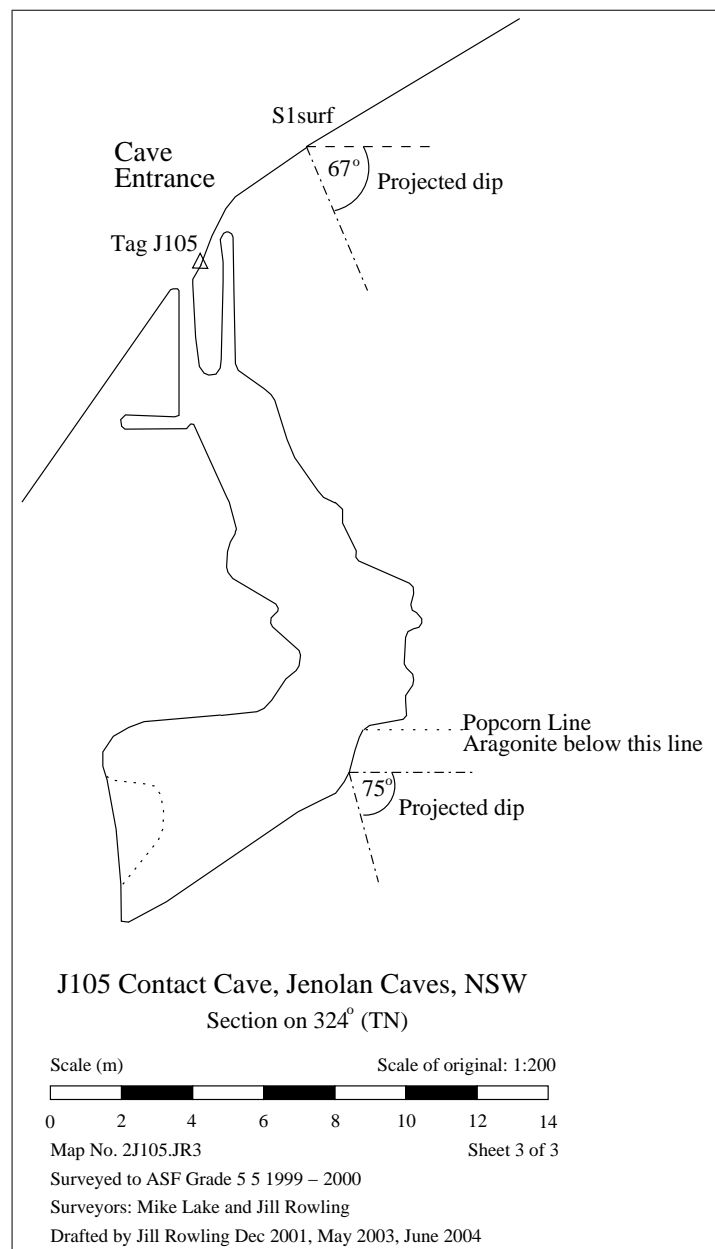


Figure 3.18: Section map of Contact Cave. View towards the north showing the general outline of the cave with the position of the popcorn line and aragonite. The dip changes slightly from top to bottom. No vertical exaggeration.



Figure 3.19: “Popcorn Line”, gabled ceiling and joint in Contact Cave.

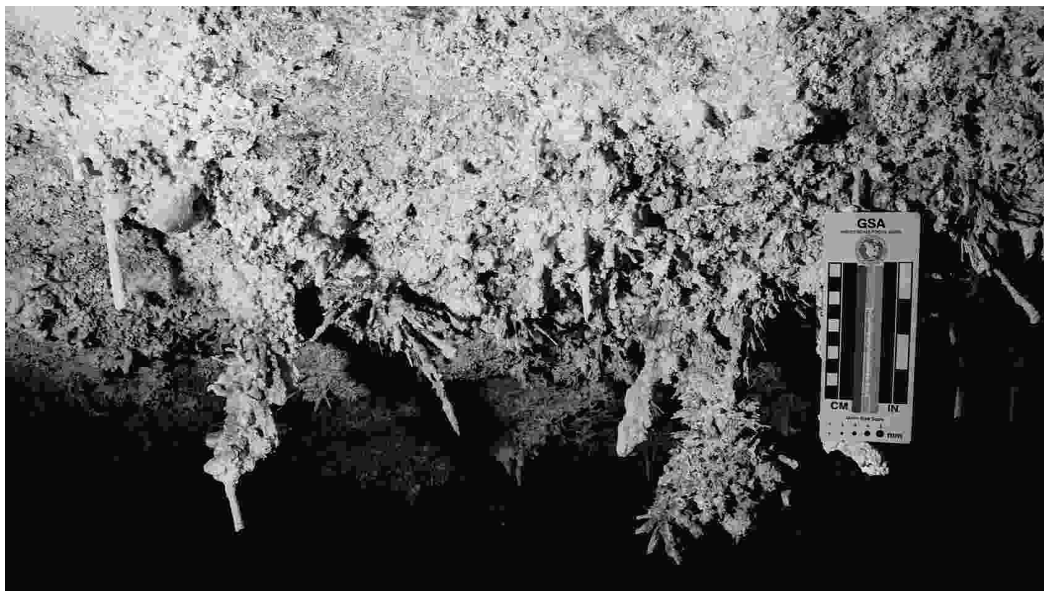


Figure 3.20: Anthodites in Contact Cave

### Cave Description

Contact Cave is a small cave comprising two chambers. The easternmost chamber, developed along a northerly joint, has a gabled ceiling and a rockpile floor (Figure 3.19). The other chamber is developed at  $90^\circ$  to both the strike and dip. It has a low, sloping ceiling and floor. The cave entrance is a 3 m vertical shaft. In the cave's twilight zone, the floor is organic-rich earth as the vertical entrance, coupled with a steep floor slope, acts as a pit trap for surface water and organisms. Refer to Figure 3.17. To the north of the twilight zone, the cave ceiling becomes lower and there are few speleothems. The floor is steep and covered with boulders. The ceiling appears to be unstable at this point and some thinly bedded limestone is exposed (Figure 3.16, cross-section B-B'). Although Welch (1976) suggested that shale can be seen in the cave, none was seen during this study. Thinly bedded limestone may look like shale to cavers. Contact Cave was resurveyed during this study as the existing cave survey (Dunkley 1976) was considered inadequate. Large blocks have been wedged from the eastern wall, giving it an unstable block-like appearance. At the northern (lower) extremity of the cave, there is virtually no secondary mineralisation and the cave degenerates to a rockpile. This rockpile lies under deep surface scree and the surface bedrock is not exposed. On the surface about 10 m north of this point, dolomitised ?palaeokarst crops out, associated with gossan. A north-striking joint in the east of the cave does not follow the strike; it is a few degrees off. Passage cross-sections show that the eastern part of the cave is mainly influenced by jointing. Joint planes in the eastern part of the cave are vertical, striking  $336^\circ$ ,  $250^\circ$ ,  $237^\circ$  and at right angles to the bedding resulting in trapezoidal cross-sections, whereas the western ceiling appears to be more influenced by fracture and flaking along the strike of the limestone. The south-west area of the cave is almost filled to the ceiling with earth and boulders.

### Sample sites & observations - Bedrock

Sample J105/5ug was a dolomitic pebble from the floor of the eastern side of the cave near the prominent joint in the ceiling and had apparently fallen from it. One end had a rusty appearance with a black (manganese?) surface coating. This "limonite" was soft and clayey in the cave but became firm once dried. It is highly porous (Figures 3.21 and 3.12). This "limonite" did not react to dilute HCl but the harder material did. The harder material was a highly altered porous limestone, with brachiopod and crinoid fragments in a dark brown matrix. Porosity was



Figure 3.21: Sample J105/5ug: Dolomitised limestone

about 10%. Some veins appeared to be filled with manganese dendrites. This was interpreted as a limestone which had been dolomitised, then dedolomitised, then the porous material replaced with manganese oxides and iron oxides. (Thin Section J105/5ug in Figure 3.12). This material is from the “zoned, dolomitised limestone and ferroan dolomite” (ZDLFD) unit shown in Figure 3.11.

### Site S5

The eastern wall of the cave is composed of limestone in which dedolomitised zones have been replaced by porous clays, iron and manganese oxides. Sample J105/11 is from this wall.

It is a piece of limestone with low porosity, sampled from point S5 (Figure 3.16). It was loose on the floor but had apparently fallen from the nearby shattered wall which is split along the bedding. One side of the sample had a microgour coating of fine orange sediment. This was crystalline, not mud. A thin section showed that the original rock was wackestone (Figure 3.12 TS J105/11) with partial dolomite replacement of micrite. A thin dark line often separated the dolomitised regions from the unaltered micrite. This was thought to be iron oxides coming out of smaller



Figure 3.22: Sample J105/11: brown areas of slabs are dolomitised.

zoned dedolomite crystal pseudomorphs. Bioclasts included fragments of brachiopod spines and possibly gastropods. A small fracture was noted to have a slight displacement. There appeared to have been a couple of different generations of sparry veins, both before and after dolomitisation.

Osborne’s sample J173 is also from near point S5. The sample is of limestone with small aragonite crystals wedging the rock apart. XRD indicated calcite with some quartz (Ross Pogson, pers comm). The crystals are possibly paramorphs of calcite after aragonite.

### Sample sites and observations - Speleothems

There are not many speleothems in the entrance area. The first unusual speleothem in Contact Cave is a stalactite with a prickly outer surface, reminiscent of aragonite stalactites seen in other caves. This stalactite is brown and is most likely a calcite paramorph after aragonite. It is just in the cave’s dark zone (Figure 3.16). It is assumed that the stalactite was once aragonite; however, it appears to have lost its hydromagnesite coating and has inverted to calcite.

In the eastern part of the cave, a line of (apparently calcite) stalactites follows the north-striking joint along which are tree roots (apparently eucalypt). Generally the stalactites in this area are a tan colour, assumed to be from humic acid. At the northern end of this line of stalactites is a calcite column (Figure 3.16).

Secondary deposits in the south-west area of the cave include dark manganese oxides coating pebbles and speleothems. Speleothems in this area are mainly dark coated anthodites and stalactites. Some cave coral occurs on the edges of boulders exposed to air movement. Between the entrance rockpile and the central floor of the cave, there is a small deposit of hemispherical speleothems known as “potatoes”. These are apparently associated with old bat guano deposits and may be phosphatic. The ones in Contact Cave have a dark coating, assumed to be manganese oxides.

The eastern part of the cave has calcite speleothems associated with a north-south striking joint in the ceiling, and tree roots. Calcite covers the floor at this point. This is the only part of the cave that has calcite flowstone. Small crenulations occur on some areas of flowstone; other areas are smooth. Its colour ranges from creamy to a rusty brown. Calcite stalagmites occur below many of the stalactites. Generally the stalagmites are a light brown colour. No stalagmites were found below anthodites.

There is a prominent “popcorn line” in the north-east part of the cave (Figures 3.16, 3.17, 3.18 and 3.19). This appears to correspond to a humidity level. Below this line, both calcite and aragonite is deposited. Above this line, there are few secondary deposits apart from the calcite along the main joint. The actual form taken by the “popcorn line” is a white pasty “moonmilk” with small hemispheres and cave coral which appear to be associated with air movement.

The western wall and ceiling of the main part of Contact Cave are covered with secondary mineralisation below dolomitised limestone, dark in places. This is the main occurrence of aragonite in the cave. This part of the cave is floored with clays and shards of secondary minerals fallen from the ceiling.



Figure 3.23: Anthodites in Contact Cave

Aragonite in this part of the cave is deposited either as a surface coating on the ceiling such as the shard J105/9 (associated with substrate crystal wedging) or as stalactitic forms such as anthodites along west-striking joints (Figures 3.20 and 3.23). Four samples, including a fallen anthodite and some scrapings collected by D. Colchester and R.A. Osborne, are in the Australian Museum collection. One sample contains dolomite (R.A. Osborne, pers. comm.). Coatings on the surfaces of anthodites and other speleothems in the main (western) part of the cave resembles a dark pink pasty material. Other coatings are white, grey or black.

Anthodite forms are stalactitic, irregular, globular or acicular. Helictites were found on the ceiling, near joints and near anthodites. Many were coated with pasty material. Forms taken were vermiform (using Hill & Forti (1997) classification). Colours ranged from white, browns, and dark grey to black. Aragonite speleothems occur along the east-west trending joints.

#### Site S1

Sample J105/7 was loose on the floor at site S1 (Figure 3.16). This is an elongated, dense coralloid (Figure 3.24), assumed to have fallen from the coated ceiling. An inner core of clear aragonite is surrounded by an outer layer of light brown aragonite. The lower outer surface has a slight depression fringed with fine crystals, thought to be aragonite. Raman spectroscopy was attempted on these fine crystals, but background fluorescence swamped the diagnostic signals. A possible peak at 698.2 could be diagnostic for aragonite. XRD of a powdered portion of the base of the speleothem indicated major aragonite with minor rhodochrosite and wollastonite (Appendix, Figure D.11). There is no evidence for a stalactitic drip-point, but there is a slight lens-shaped depression where water may have collected near the tip. It is assumed that this speleothem developed by water seeping across its surface. The very fine nature of the surface crystals indicate a relatively fast precipitation rate compared with the more coarse aragonite of the specimen's core.



Figure 3.24: Sample J105/7 – length 45 mm

#### Site S2

Sample J105/8 was collected from site S2 (Figures 3.16, 3.25). It is a bulbous, dense coralloid with a corroded appearance. Like J105/7, it was found on the floor but is most likely to have fallen from the coated ceiling.



Figure 3.25: Sample J105/8. Length: 72 mm

It was coated with white and tan material. The bulbous ends are characteristic of speleothems which are influenced by air movement.

An area near the base of the speleothem was excavated to obtain material for XRD. The crystals fractured with a splintery fracture, mainly exhibiting aragonite cleavage on most crystal laths. Inside appeared to be an aragonite core with some clays. XRD indicated major aragonite and calcite, minor magnesian calcite, braunite, goethite, lepidocrocite, blödite, bassanite, anhydrite, aluminite and alunite. Some of these minerals may be associated with bat guano (Appendix, Figure D.12).

### Site S3

Sample J105/9 is an aragonite shard from site S3 (Figure 3.16). It was lying on the floor of the main part of the cave and had apparently been wedged from the ceiling. The ceiling at this point is completely coated with white powdery minerals, the same as on the shard. The floor where it was resting appears to be clay with a high proportion of hydromagnesite. When snapped in two, the specimen was seen to consist of hemispherical aggregates of aragonite cemented with finer aragonite. Its creamy white coralloid surface appeared to be mainly aragonite coralloid with some fine white powder. The small surface hemispheres were made of fine radiating aragonite needles. The structure of the speleothem is a flat shard of aragonite, composed of several hemispherical aggregates. The cut section shows its ray-fan pattern with interlocking crystals. Figure 3.26 shows part of the shard, with a piece cut from the shard. The nucleation point of the aggregates is the upper surface of the shard. The lower surface was mainly covered with white and yellow powdery minerals. Some pink, brown and yellow ray-fan crystals were present but the majority were white or clear aragonite. XRD indicated major aragonite, with minor calcite, dolomite, hydromagnesite, huntite and goethite.



Figure 3.26: Pieces cut from sample J105/9, 3.25x

### Site S4

Sample J105/10 was a pink powder from site S4 on the ceiling (Figures 3.16 and 3.27). It was pasty when wet. This was sampled from between some of the smaller anthodites. Under the microscope, the powder is a mixture of clear needles, white and pink grains and small salmon-pink rosettes of crystals and a ginger-coloured clay. XRD of the sample indicated major hydroxylapatite, aragonite, dolomite, huntite and hydromagnesite. Minor minerals included rhodochrosite, calcite, vaterite, gypsum, clays, beryllonite, epsomite, ardeallite (Appendix, Figure D.12). This

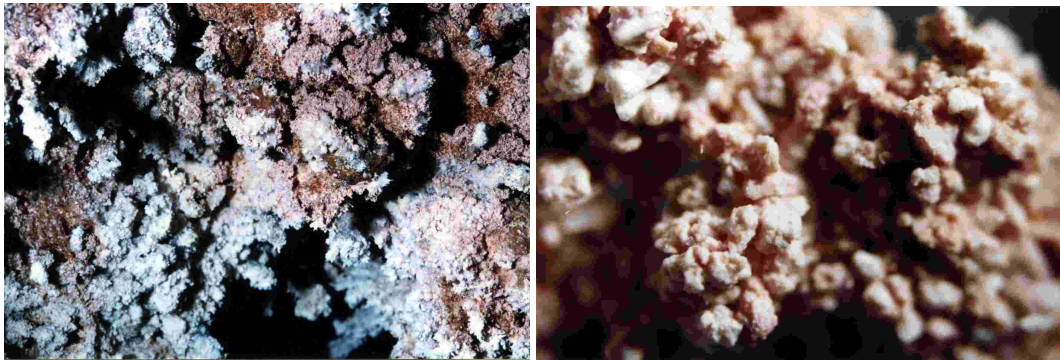


Figure 3.27: Sample J105/10. Left: Area view (width of view about 15 cm). Right: close up of pink powder (width of view about 3 mm).

was interpreted as partly due to dedolomitisation of bedrock (giving rise to magnesium-rich minerals) and partly due to the effect of bat guano on clays and limestone.

**Cave Weather Measurements**

Some cave weather measurements were taken on 12th July 2002. As it was winter, a humidity inversion was expected. The inversion detected was only slight, possibly because the cave is small and has a small entrance, so little air movement occurs. The psychrometer is not calibrated for very high humidity measurements. The cave has very low levels of CO<sub>2</sub>.

| Location   | Av. temp. °C | RH % | CO <sub>2</sub> % |
|--|--------------|------|-------------------|
| Outside cave entrance, 11:30 am                      | 10.1         | 34.0 | -                 |
| Entrance chamber, about 4 m from ladder              | 12.2         | 94.0 | -                 |
| Near survey point “10m” at base of entrance rockpile | 12.4         | 92.3 | 0.1               |
| Near boulder in lower part of cave                   | 12.3         | 92.7 | 0.1               |

Table 3.1: Temperature, calculated relative humidity, and CO<sub>2</sub> at Contact Cave, 12th July 2002.

**Synthesis - Contact Cave**

The original limestone has been dolomitised and ferruginised, preferentially replacing the original micrite with ferroan dolomite. In most cases, the larger bioclasts are unaltered by dolomitisation. The slow oxidation of pyrite in the thinly-bedded limestone and the “zoned, dolomitised limestone and ferroan dolomite” (ZDLFD) unit above the cave, releases strong acids such as sulphuric acid. Strong acid can also release both manganese and magnesium from the ferroan dolomite in the bedrock. Another source of manganese is the volcanics, e.g. the tuffs to the east of the cave. The acid can neutralise with carbonates in the bedrock to form soluble calcium sulfate. Gypsum was detected as a minor mineral in Contact Cave.

Upon encountering the cave environment, the released manganese and magnesium minerals from the bedrock can combine with calcium and carbonate ions, precipitate on the ceiling and coat the carbonate speleothems, inhibiting calcite from depositing and instead enhancing the deposition of aragonite, rhodochrosite, huntite, hydromagnesite and dolomite. The substrate for most of the aragonite in Contact Cave is the dolomitised limestone ceiling. Crystal wedging can expose fresh pyritic bedrock to oxygenated water, repeating the process of pyrite oxidation and release of sulfate, magnesium and manganese to the cave environment. This process appears to be happening along the eastern wall of the cave and in the loose, thinly-bedded areas of the ceiling.

Bats are not common in Contact Cave, but there is fresh guano and some of the floor deposits are characteristic of old bat guano piles (“potato” speleothems). Guano is a source of sulfate and phosphate, and this may act as a minor calcite-inhibitor, possibly preventing fallen aragonite speleothems from reverting to calcite.

During winter, a slight drying effect due to cold dry air pooling in the lower part of the cave, may concentrate minerals on the stalactites and walls by evaporation. This leads to the development of a “popcorn line” in the cave.

Aragonite deposition in Contact Cave may be enhanced by the presence and concentration of calcite-inhibiting materials. The main calcite-inhibiting substances associated with the speleothems in Contact Cave are magnesium and manganese-rich minerals and to a lesser extent, phosphatic minerals. Aragonite, dolomite and rhodochrosite are being actively deposited where these minerals are present. Calcite is being deposited where magnesium-rich minerals are not present.

## Wiburds Lake Cave

### Location

Wiburds Lake Cave is located in Wiburds Bluff, a steep limestone hill with a precipitous eastern face located towards the northern end of the Jenolan Caves Limestone outcrop, on the western side of Rowe Flat (Figure 3.28). The upper part of the hill, above the cliff top, is chert. The lower flanks of the bluff are partially covered with scree. On the eastern side of the bluff are several cave entrances, some of which give access to Wiburds Lake Cave. The ephemeral Jenolan River passes close to the base of Wiburds Bluff, and may be the source of a lake which is intermittently present in the cave (Figures 3.5, 3.30 and 3.34).

To the east of Wiburds Bluff is Rowe Flat, a flat floored valley covered with alluvium. Remnant alluvial terraces can be seen near the north-western side of Rowe Flat beginning near the J58 entrance to Wiburds Lake Cave and in the valley north of Rowe Flat. Some of the depressions on Rowe Flat are formed by burrowing animals; other larger features appear to be karstic. Three small dolines near its south end occasionally fill with water. Calciphile plants and small dolines occur up to 5 metres up the hillside east of Rowe Flat. The eastern hillside is mainly covered with a loose scree of crystal tuff which form terraces towards the south-east end of Rowe Flat, and appear to pre-date the more northerly terraces. A side stream has reworked the eastern side terrace and sinks near Rowe Flat.



Figure 3.28: Wiburds Bluff from north Rowe Flat.



Figure 3.29: The Big Rift with Rowe Flat in background. Photo by Peter Winglee in Dunkley (1976).

High near the north western side of Wiburds Bluff is the “Big Rift”, a prominent feature above Wiburds Lake Cave which may be the remnants of a collapsed cave comprised of a set of strongly outcropping joint and bedding bound blocks (Figures 3.29 and 3.30). The dominant structure of the rift is oriented mainly east-west, with the eastern side curving towards the south and both ends terminated by a steep scree slope. Beyond the western end of the “Big Rift” is a doline, developed in a steep scree slope of fault breccia and thought to be a western continuation of the “Big Rift”. North (downslope) of the “Big Rift” is a steep limestone hillside broken by cliffs and strewn with collapse blocks. The southern (upslope) side of the “Big Rift” is very close to the brecciated zone of McKeowns thrust, giving the appearance of vertical bedding with vertical to overhanging walls. The “Big Rift” contains some unstable vertical caves, which are little visited and contain loose flat boulders, similar to the “Big Rift” itself.

### **Geological Setting**

The geology near Serpentine Cave, a few hundred metres to the south of Wiburds Lake Cave, was described by Cooper (1993). The geological setting of Wiburds Lake Cave is similar to that of Serpentine Cave (Figures 3.56 and 3.30) but with more disturbance to the stratigraphy due to faulting. Wiburds Lake Cave is developed in Silurian Jenolan Caves Limestone. West of

Wiburds Lake Cave, black and red cherts crop out. These are thought to be part of the Ordovician Adaminaby Group. The western boundary of the limestone is faulted against the eastern boundary of the chert. The fault boundary is characterised by a chert and limestone breccia, about 100 m wide, containing black chert nodules (Cooper 1993). The nature of the north-striking thrust fault (McKeowns thrust) is such that the Ordovician cherts partly overly the Late Silurian limestone, with possibly some strike-slip faulting as well.

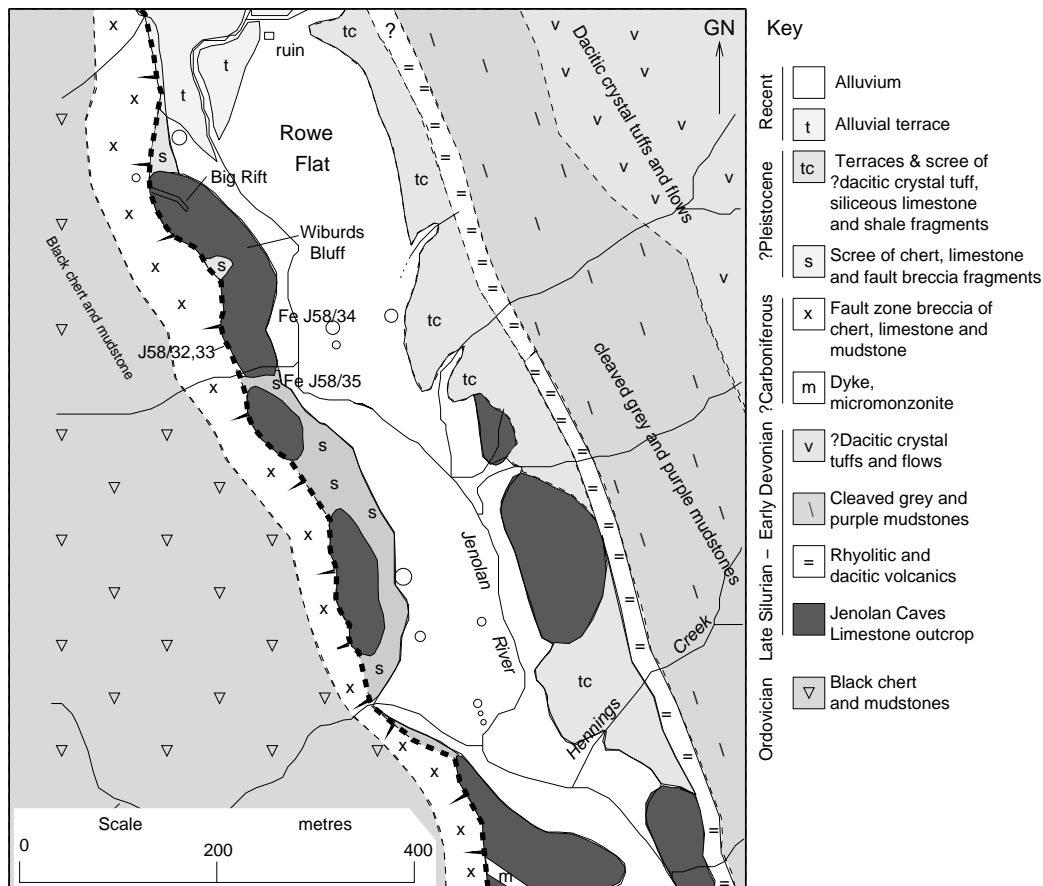


Figure 3.30: Geology of Rowe Flat and Wiburds Bluff, Jenolan Caves showing features and sample points. Geology based on work by Allan (1986), Cooper (1993) and this study.

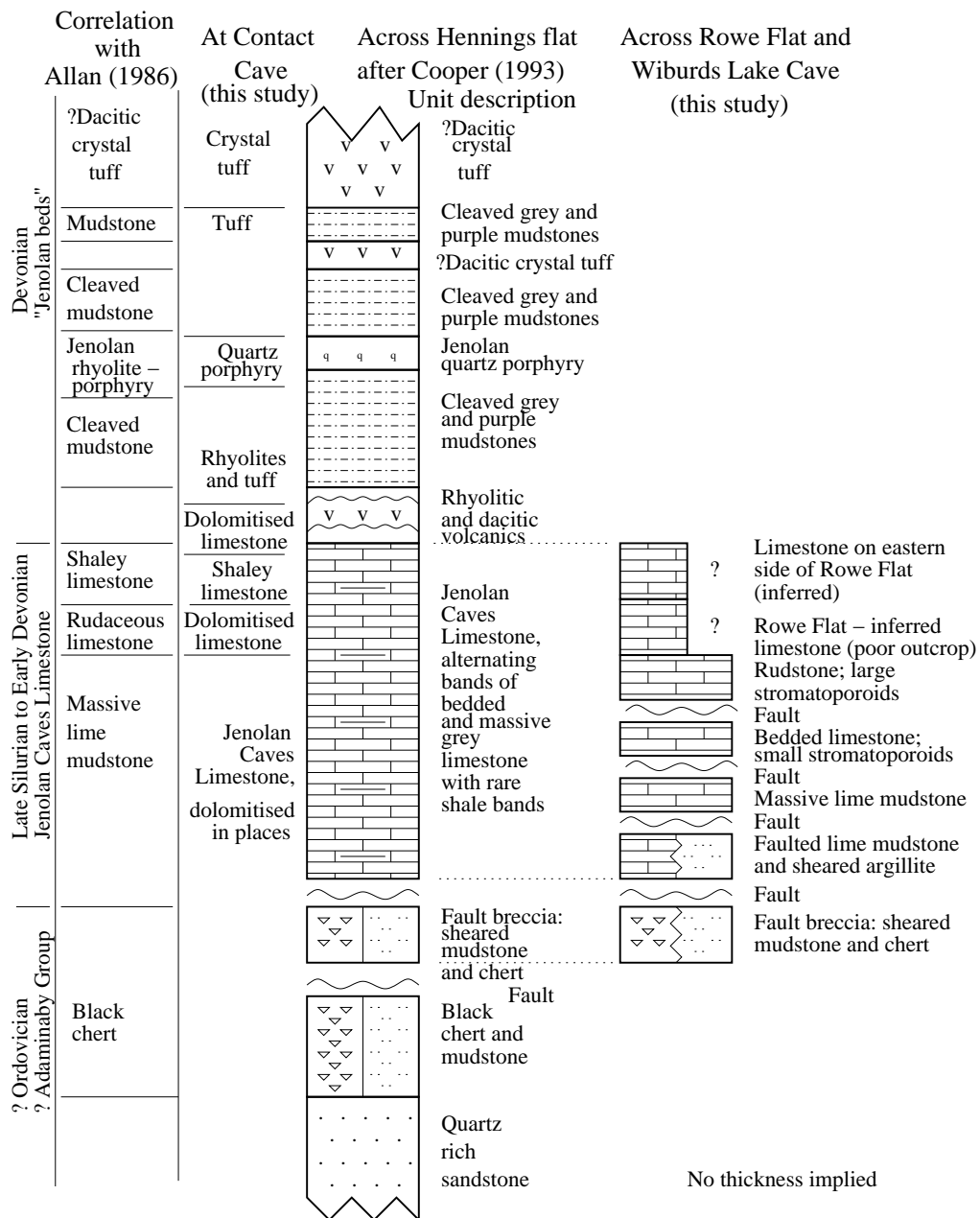
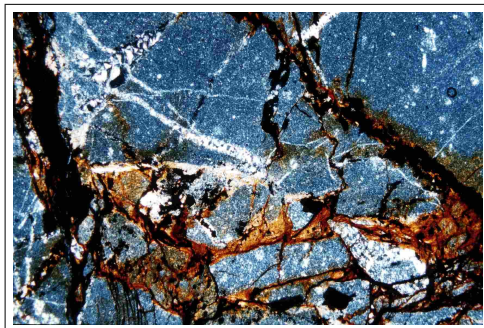


Figure 3.31: Stratigraphic sequence near Wiburds Lake Cave. Based on work by Allan (1986), Cooper (1993) and this study.

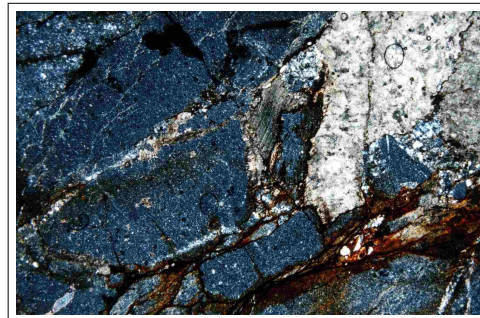
North of Wiburds Lake Cave, the Jenolan Caves Limestone crops out sporadically up to about 600 m north of Wiburds Bluff, with most of the valley buried by unconsolidated sediment. The northernmost karstic features are terminated by an abrupt change in creek direction, where dark purple slates and light grey phyllites dip with a north-west facing (top border of Figure 3.5). It

is suggested that these may be an unmapped, disconformal outcrop of the Silurian Campbells Formation (Smc, Figure 3.1). Karstic features a few km to the north near the Jenolan pine forest may be developed in the Campbells Formation.

At Wiburds Lake Cave, the dip of the limestone ( $32^\circ$  to the SW) is much gentler than it is at Contact Cave, but the bedding is overturned and distorted due to shearing. The limestone is not uniform; there are at least three different types of limestone exposed in the cave and there are shear zones of soft, cleaved argillite. The sheared limestone outcrop on Wiburds Bluff extends from The Big Rift in the north, to a few metres south of a steep gully south of Wiburds Bluff (Figure 3.30). A hill to the south of Wiburds Bluff has limestone cropping out on its eastern side bedded similarly to Wiburds Lake Cave but without the tectonic features or sheared rock. Between these two limestone outcrops is a scree slope comprising fragments of chert and quartzite with crystalline quartz veins. Ironstone crops out in this gully, and in the creek bed at the base of Wiburds Bluff. The relationship between the ironstone and the limestone is unclear as much of it is buried under alluvium or scree. An approximate stratigraphic column for the area near Wiburds Lake Cave is shown in Figure 3.31. It was difficult to determine the exact stratigraphic relationships at Wiburds Lake Cave due to structural complexity. The following notes refer to the rocks in the stratigraphic sequence, Figure 3.31.



TS J58/32 N36516 XN x13. Fault-zone breccia: fractured radiolarian chert with iron-rich veins and some tridymite.



TS J58/33 N36517 XN x13. Fault-zone breccia containing fractured radiolarian chert and sheared limestone.

Figure 3.32: Thin Sections J58/33: Fault-zone breccia west of Wiburds Lake Cave

#### **Fault zone breccia of sheared chert and mudstone**

Sheared black and red chert and mudstone crops out in a north-south band about 100 m wide at the top of Wiburds Bluff, adjoining the limestone with an irregular boundary (Figure 3.30). This comprises light and dark grey angular chert clasts in a matrix of red, orange and dark brown ochrous material. There are two types of breccia: a small-grained variety with 5 mm diameter angular clasts containing radiolarians and a large grained variety with 20 mm diameter angular

clasts. The larger-grained variety occurs both north and south of the limestone outcrop. The small-grained variety occurs immediately west of the top of Wiburds Bluff. Thin section of the small-grained variety shows sheared clasts of fractured radiolarian chert with opaque iron-rich veins, some calc-silicates and small amounts of tridymite (Figure 3.32, Thin Section TSJ58/32, 33). Occasional limestone clasts sheared from the main body of the limestone include crinoid fragments.

#### **Faulted lime mudstone and sheared argillite**

This rock comprises sheared clasts of massive lime mudstone, thinly bedded limestone and sheared argillite. It crops out near the J92 entrance, the J243 entrance and the walls of Dyke Chamber (Figures 3.38, Thin Section TSJ58/24, 3.34). The order of the bedding is unclear due to shearing, and the sequence may be repeated due to faulting, making the unit resemble a large scale deck of cards.

#### **Jenolan Caves Limestone**

In Wiburds Lake Cave, several different textures were noted in the Jenolan Caves Limestone, ranging from a fine-grained light coloured lime mudstone to a dark wackestone. Some of these textures are described here and others are described in the detailed Neddys Knock studies (e.g. Figure 3.43). All the units appear to be faulted with respect to each other.

The limestone facies exposed in a corner formed by 22 Passage and the bottom (western end) of Lake Chamber reveal several different limestone textures. Nearest to the dyke, the layers are upturned slightly. The limestone layers have an angular unconformity with each other and may be sheared. The following measurements were taken along the plane separating two limestone units: Strike  $113^{\circ}$ , dip approx.  $32^{\circ}$  to the south. This is a different orientation compared with the dip in the rest of the cave.

Several different faunal groups and limestone textures were seen. Referring to Figure 3.33, beyond the white alteration zone near the dyke, numerous large fossils (stromatoporoids and brachiopods) occur in a rudaceous limestone (A: the “rudstone” in Figure 3.31). A large boulder with this texture also occurs on the western side of Rowe Flat. By examination of the preliminary cave survey data, it is thought that the rudstone unit is continuous from 22 Passage to the western side of Rowe Flat.

Layer (B) has dolomitised micrite and undolomitised bioclasts. Layer (C), flagged W2002 is also a rudstone with numerous fossils, smaller than those of (A). It has partially dolomitised micrite and undolomitised bioclasts. These two units are suggested to be part of the “bedded limestone with small stromatoporoids” in Figure 3.31. Its relationship with the other units is unclear as it appears to be faulted.

Layer (D) is the “massive lime mudstone” (Figure 3.31) with rarer bioclasts. A brown layer (E) is slightly resistant to weathering and may be dolomitised. It is thought to be also part of the “massive lime mudstone” unit.

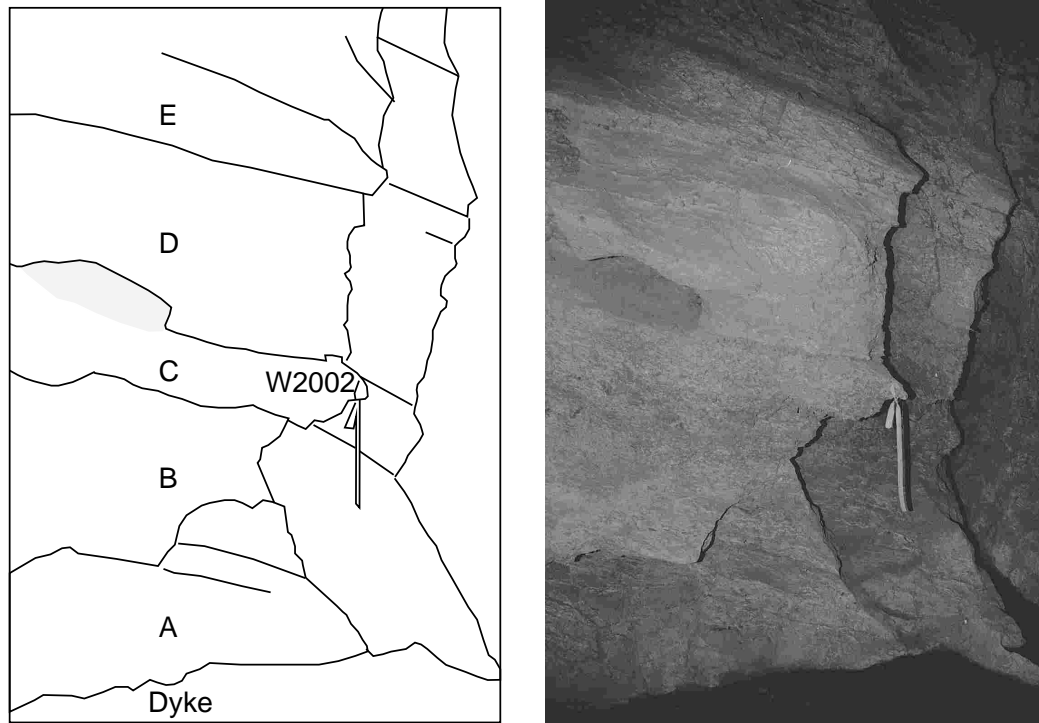


Figure 3.33: View looking south-east towards 22 Passage / Lake Chamber, Wiburds Lake Cave, showing the different limestone facies. Flagging tape marks survey point W2002 (see text). Width of view is about 5 m.

### Limestone on Rowe Flat

Most of Rowe Flat is covered with alluvium. Limestone occurs on Rowe Flat as partially buried boulders including a grey crinoidal limestone and a grey massive limestone. The presence of dolines on Rowe Flat infers that there is karst drainage, so it is assumed that limestone occurs at the base of the alluvium. It may also occur up to 5 metres (approx) to the east of the oldest eastern side terraces, judging by the lime-loving vegetation that occurs there (blackthorn and stinging nettle).

### Cave Description

Wiburds Lake Cave has about 7 km of passages, comprising some large down-dip passages interconnected by long narrow passages aligned along the strike, superficially similar to the “Halls and Narrows” morphology described by Osborne (2001). At Wiburds Lake Cave the passage orientation is guided both by tectonic features and the strike of the bedding, although the difference between the two strikes is only about  $20^\circ$ . One of the features of the long passages in Wiburds Lake Cave is the tendency for them to be developed parallel to one another but at different topographic levels.

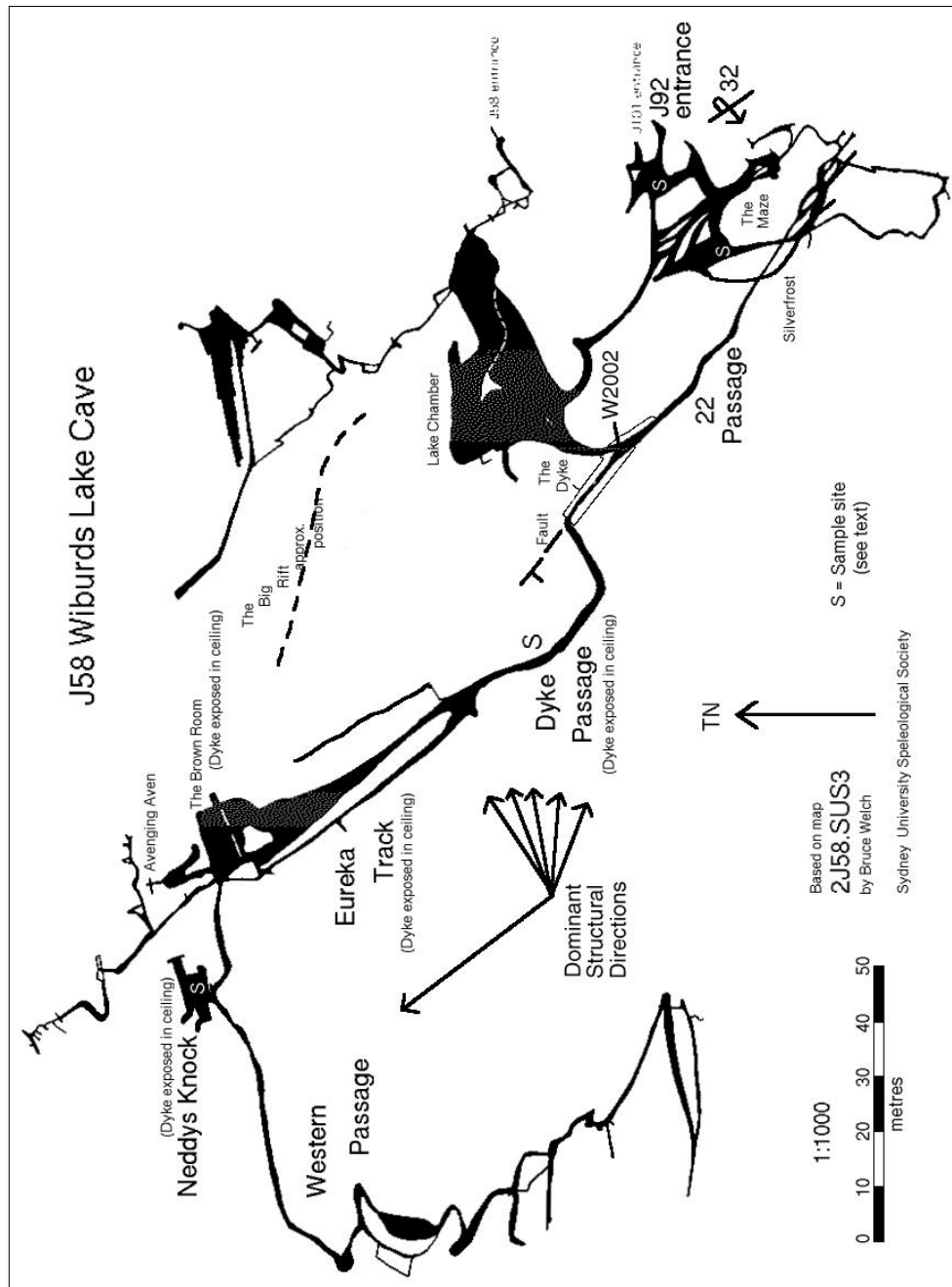


Figure 3.34: Outline (plan) of Wiburds Lake Cave, based on map by Welch in Dunkley (1976), overlaid with sample points and dominant structural directions. Position of the Big Rift and Boomalakka Wee passage drawn from comments by I.Cooper and P.Maynard (pers. comm.); position of Silverfrost based on cave surveys by members of Sydney University Speleological Society.

Parts of “The Maze”, “22 Passage” and “Silverfrost” all present a good example of this configuration (Figure 3.34). Connecting passages between these long passages generally trend down-dip. The NW-SE passage orientation is common for caves in this part of the Jenolan Caves Limestone, compared to the approximately N-S passage orientation of the northern show caves. Superimposed on this northwesterly strike are a number of faults which also trend northwesterly although at a different angle compared with the bedding. “22 Passage” appears to be developed along the strike of such a fault. The net result is a diamond shape formed by the two angles: the bedding and the faulting.

Wiburds Bluff contains several entrances to the cave on its eastern side. The more popular entrance (J92) is developed down dip.

Although much of Wiburds Lake Cave passages have smooth walls with solutional features such as phreatic tubes, areas of rockpile are relatively common. Loose, flat boulders and regions of unstable rock occur in various parts of Wiburds Lake Cave, e.g. the J92 entrance area, “Avenging Aven” and “Neddys Knock”. In some cases wedged limestone / argillite layers are probably broken apart by crystal wedging, although slickensides and diamond-shaped cleavage fragments on many of the argillite slabs would infer that much of this instability is a consequence of penetrative foliaceous shears.

### **J92 Entrance area**

Loose, flat slippery boulders are a feature of this area. The limestone strikes  $153^\circ$  and dips approximately  $32^\circ$  to the west. The dip is distorted in places due to shearing. Parts of the J92 entrance area exhibit smooth walls but other parts are unstable. The entrance passage has an elongated figure-8 cross-section in places and is floored with slippery mud, argillite, claystones and thinly bedded limestones. Rocks jutting from the ceiling of the entrance have slickensides and are poorly cemented in place. The argillite appears to be part of the sequence “faulted lime mudstone and sheared argillite” (Figure 3.31) based on preliminary elevation data from cavers’ surveys.

### **Lake Chamber**

Lake Chamber is one of the largest chambers in the cave and occasionally fills with water up to the base of “The Maze” (approximately the level of the creek outside the cave). There is a general lack of speleothems in the areas flooded by the intermittently present lake and it appears that the lake water is slightly aggressive to calcite.

### **Dyke outcrops and faults**

At the junction of Dyke Passage and 22 Passage, a large and highly weathered basic dyke is exposed. This is displaced by faulting (Figure 3.35). In this area, red lines in the bedrock may be

dolomitised veins. Details concerning the dyke were recorded during this study. The three parts of the dyke exposed at the passage junction are numbered from 1 to 3, south to north.

Part 1 strikes  $163^{\circ}$ , dips  $35^{\circ}$  to the east.

Part 2 strikes  $156^{\circ}$ , dips  $40^{\circ}$  to the east.

Part 3 strikes  $153^{\circ}$ , dips  $30^{\circ}$  to the east.

The displacement between parts 1 and 2 is about 1.5 m, and the fault plane strikes  $126^{\circ}$ , dips  $65^{\circ}$  to the west. “22 Passage” is developed along this plane. The displacement between portions 2 and 3 of the dyke is about 2.7 m, and strikes  $153^{\circ}$ , dips  $41^{\circ}$  to the west. Near portion 1, the limestone alteration zone is white for about 1 m from the dyke.

Dyke outcrops of similar composition occur in Wiburds Lake Cave in the following areas: Dyke Passage, base of Lake Chamber (portion

1 crops out), the footing of the north-eastern end of 22 Passage (a continuation of portion 1), the ceiling of Neddys Knock, the ceiling of the Brown Room (the most northerly part of Dyke Passage), the eastern end of Western Passage and along Eureka Track. They all appear to be faulted portions of the same intrusive event. A sample (JEN-11) has been taken of the micromonzonite dyke cropping out between Serpentine and Hennings Cave, and compared with the one in Wiburds Lake Cave (Figure 3.37). The sample site is shown in Figure 3.56. JEN-11 contains pyrite grains, often surrounded by iron oxides. The Wiburds material is highly altered by chemical weathering, however there are similarities in texture, such as diamond-shaped zones and a high proportion of dark minerals. This would infer that the two dykes were originally of similar composition.

### Dyke Passage

Dyke Passage is a northern continuation of 22 Passage (Figure 3.34). Like 22 Passage, it is a long chamber developed along the strike of a fault. At its southern end, there is a very small speleothem (possibly aragonite) in the ceiling near the dyke (portion 3), associated with a crack and some red veins. This speleothem has developed since the last flooding, and has been observed to get gradually larger over several visits. Rhythmic bands of limestone and a crumbly fault zone breccia occur on the ceiling and walls. Dark mud adheres to the porous breccia but not the limestone. Sometimes cold dry air pools in the lower part of the chamber, creating a moist ceiling and dry floor (Figure 3.36).



Figure 3.35: View looking north in northern 22 Passage. The dyke is exposed at this point, and displacements can be clearly seen.

Portion 1 is on the right hand side; portion 2 is on the left. Width of view is about 5 m

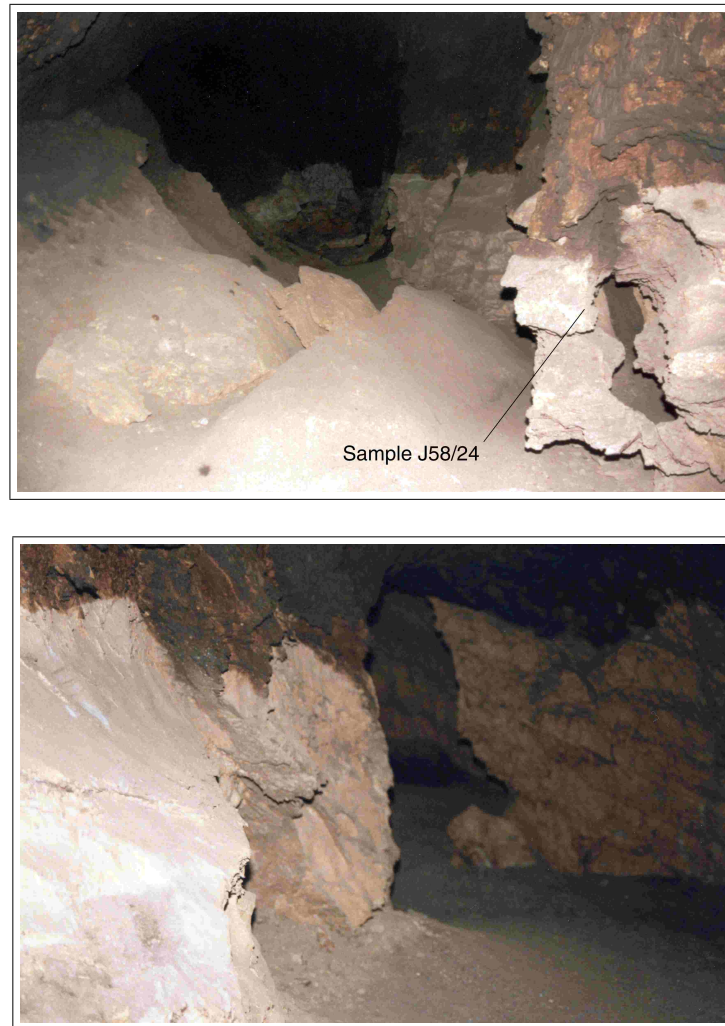
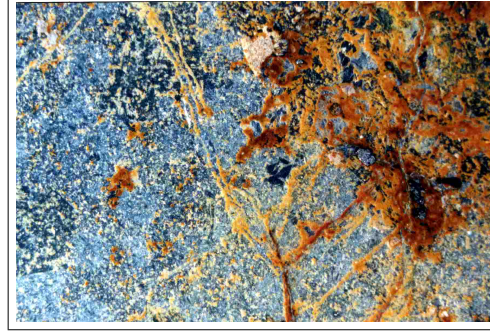


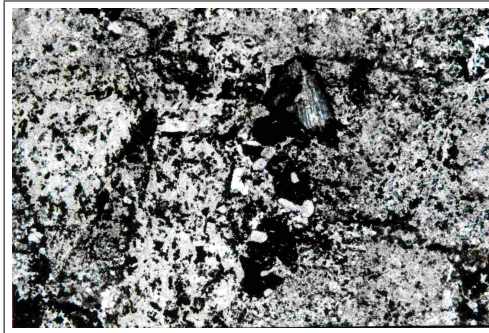
Figure 3.36: View of Dyke Passage looking North-West (top) and South-East (bottom) showing moist ceiling area and dry floor area, 2nd August 2003. This area is inundated by the lake when it fills. Sample J58/24 site indicated.



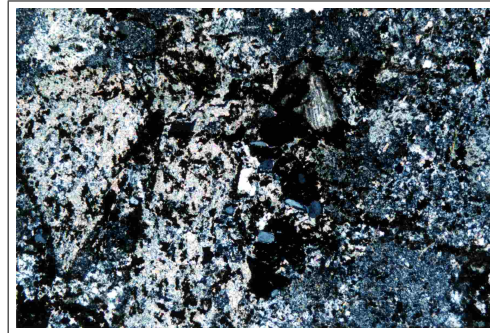
TS JEN-11 N35852 XN x13. Dyke rock between Serpentine Cave and Hennings Cave.



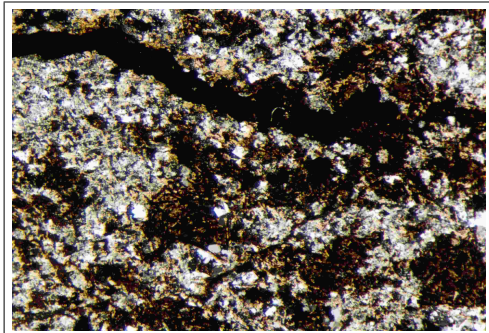
TS JEN-11 N35852 refl x13. Dyke rock between Serpentine Cave and Hennings Cave (reflected light).



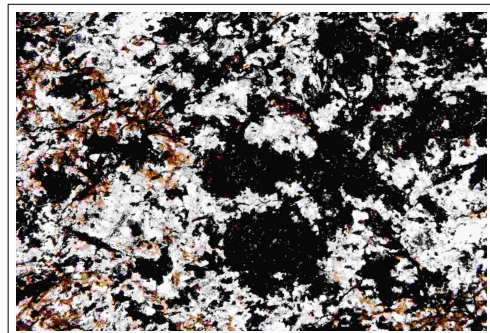
TS JEN-11 N35852 PPL x25. Dyke rock between Serpentine Cave and Hennings Cave.



TS JEN-11 N35852 XN x25. Dyke rock between Serpentine Cave and Hennings Cave.

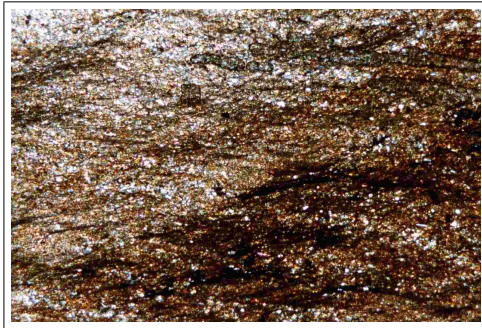


TS J58/3 XN x13. Dyke rock in Neddys Knock, Wiburds Lake Cave (note dolomite).

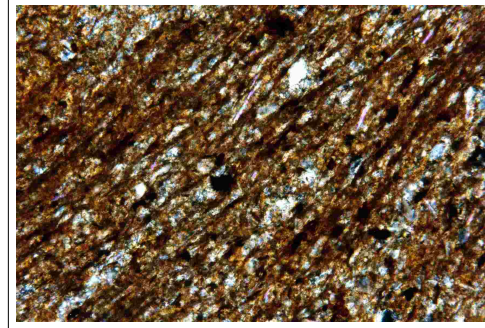


TS J58/14 N35852 PPL x13. Dyke rock exposed in Neddys Knock, Wiburds Lake Cave.

Figure 3.37: Comparing thin sections of dykes.



TS J58/22 N35754 XN x25. Stretched argillite with mica (bright pink flakes). J92 entrance.



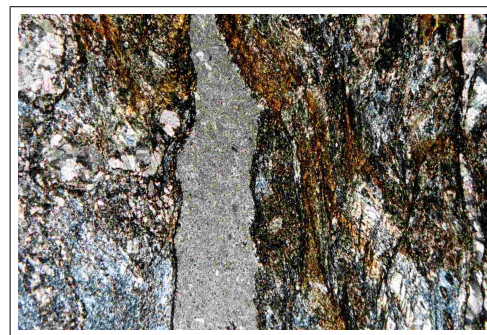
TS J58/22 N35754 XN x100. Stretched argillite with mica. Possible grain rotation. J92 entrance.



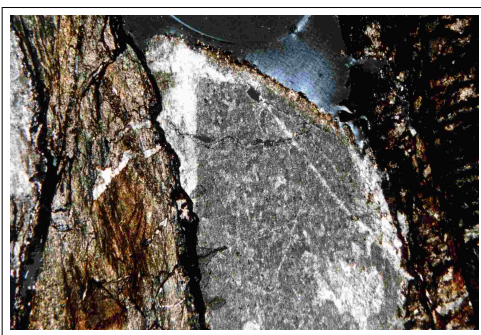
TS J58/24 N35755 PPL x13. Fault zone breccia with stretched argillite and limestone



TS J58/24 N35755 XN x13. Fault-zone breccia with spar and suspected chert fragments.



TS J58/24 N35755 XN x13. Fault zone breccia with chert, limestone, argillite.



TS J58/24 N35755 XN x13. Fault-zone breccia with cleaved argillite, limestone and suspected dyke fragment.

Figure 3.38: Thin sections: Stretched argillite (J92 entrance) and fault breccia (Dyke Chamber).

## **Sample Sites and Observations - Bedrock**

### **J92 Entrance area**

In the J92 entrance area, two bedrock samples were taken of typical slippery rocks found in the entrance passages. Sample J58/22 is highly cleaved along three planes, creating angles of about 30° and 45°. Mica flakes could be seen in thin section (Figure 3.38), with some grain rotation. It contained major muscovite, quartz and lepidolite, minor glauconite and calcite as determined by XRD although a test with HCl was not positive for carbonate. It was interpreted as a sheared argillite.

Specimen J58/23 was a small tan flake from one of the loose, flat limestone blocks near the entrance. It frothed with HCl, leaving a brick-red residue. It is mainly calcite, with minor kaolinite, wollastonite-2M and muscovite as determined by XRD (Appendix, Figure D.9) and is interpreted as sheared, thinly-bedded limestone.

### **Dyke Passage**

The crumbly, flakey breccia exposed in the walls of Dyke Passage occurs in bands with the same strike and dip as the fault along 22 Passage. A sample (J58/24) was taken of this material from behind a pendant about half way between the southernmost part of the chamber and the turnoff to the small passage called “Boomalakka Wee” – see pendant in Figure 3.36. The hand specimen resembles a fractured boxwork. It was interpreted as a fault zone breccia (Figure 3.38). Limestone clasts occur as two types: one is a light stone with fossils (crinoid and brachiopod) and the other is a darker stone. Brecciation occurred after the dyke was already emplaced. This material is in an area which gets inundated by the lake, and exhibits some solution of the limestone. The other components of the breccia are highly weathered. There are a number of components to the breccia: an altered rock resembling fragments of the dyke; dark limestone clasts; light limestone clasts; cleaved and stretched argillite; void-filling spar; chert and opaques. Some dolomite was noted as small clasts, so it is assumed that dolomitisation occurred before brecciation. The tiny aragonite speleothem near the dyke may be associated with dolomite.

## **Sample Sites and Observations - Aragonite**

### **Silverfrost**

Above and to the west of “The Maze” is an area of the cave called “Silverfrost” after the silvery colour of its flowstone and rimstone dams. This area has one anthodite and other (calcite and possibly phosphate) speleothems and areas of soft hemispherical deposits, probably phosphatic in origin. Soft and fluffy material developing on the surface of the hemispherical deposits has the consistency of cottage cheese, and is thought to be the “lublinite” variety of needle form calcite. Similar material in the show caves has been analysed by Osborne et al. (2002) and found

to contain ardeallite. Silverfrost is more sheltered from external weather influences because of more restricted air flow compared to The Maze.

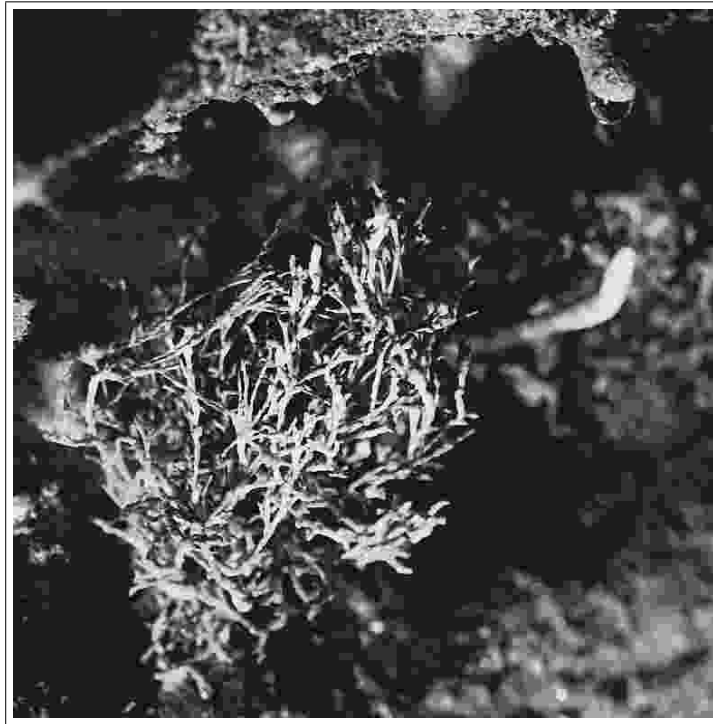


Figure 3.39: Flos Ferri helicites in The Maze. Width of view: about 60 mm.

### **The Maze**

Immediately to the west of the entrance chambers is a section called “The Maze” (Figure 3.34). There are some fine helicites here resembling Flos Ferri (Figure 3.39) and some irregular stalactites that appear to be partially recrystallised aragonite anthodites. The helicites are deposited at the edge of a bedding or joint plane. Where the helicites occur, there is considerable dark surface discoloration resembling manganese oxides but the helicites themselves are white to light grey. The helicites take various forms. The finest form (pictured) may be aragonite; there are thicker (vermiform) types which branch symmetrically, and an irregular fine form that resembles a tight mass of dirty cotton waste. Apart from the helicites, this part of the cave is dry, even during wet periods. Near the helicites, the floor is made of reddish silt with broken shards of darkened calcite, apparently heaved from the silt, possibly by the action of swelling clays under a thin calcite covering. The resulting deposits resemble tepees. A dusty area to the south west of the helicites has very small aragonite hemispheroids on the ceiling (verified with XRD), small upturned helicites and microscopic radiating clusters. In the northern end of “The Maze” some of the speleothems are coated with dark hemispherical deposits of suspected calcite overlying a

white chalky material, giving the effect of a black and white bubbly pattern. This part of the cave is close to the J92 entrance. Temperature and humidity are influenced by outside changes (Table 3.3).

Anthodites in The Maze include irregularly shaped stalactitic and helictite forms, with a prickly and powdery surface and generally poor form compared with anthodites elsewhere in the cave. In the Maze, a very small sample (J58/31) of the ceiling speleothem coating near the anthodites was examined with XRD and found to contain major gypsum and aragonite, minor pyrolusite, kaolinite and hydromagnesite, and trace calcite and huntite.

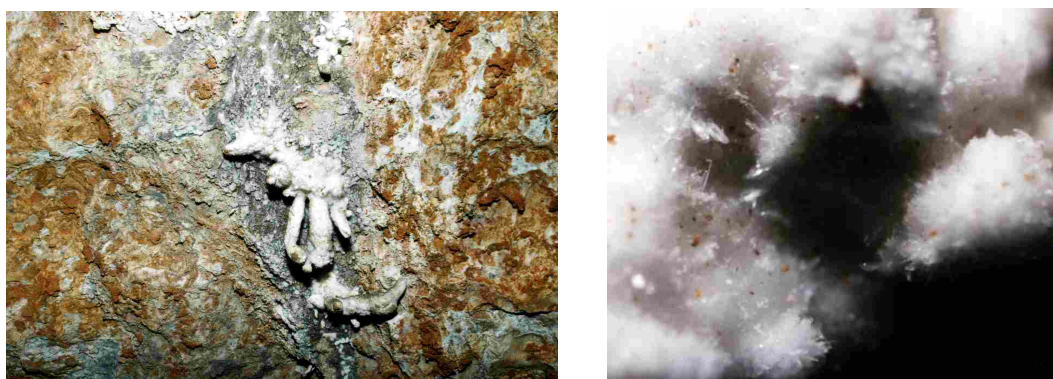


Figure 3.40: Sample J58/31. Left: Area with helictites, The Maze. Area of view is about 0.5 m. Right: A small piece of aragonite from ceiling scrapings, approx. 50x

Long persistence (1 second) green-blue light was emitted from the area after excitation with a flashgun. Normally, calcite emits a green light after such excitation. The speleothems appear to be formed from seepage from fine cracks in the sloping bedrock ceiling. The poor form may be related to low humidity, resulting in the deposition of gypsum and aragonite.

### **Eureka Track**

“Eureka Track” is a passage lying parallel to and above Dyke Passage, that is only accessible using aid-climbing techniques. Climbers have reported extensive aragonite speleothems associated with the dyke in this area, above the highest level that the lake reaches, and that the forms taken by the aragonite speleothems were similar to those seen in “Neddys Knock” (P. Maynard, pers. comm.). There are no samples and no photographs from this area.

### **Western Passage**

Western Passage (Figure 3.34) appears to be joint guided. There are two occurrences of aragonite off Western Passage: one is Neddys Knock (see below) and the other is a small passage trending northwest. Aragonite (unchecked) in this small unnamed area is in the form of a drusy surface

coating (speleothem) deposited on the limestone. The origin of the material was unclear. Its proximity to Neddys Knock would suggest a similar influence for both.

### **Neddys Knock**

Neddys Knock was chosen as a study site for its aragonite. Neddys Knock is a chamber above and to the north of Western Passage – see NW corner of Figure 3.34 and detailed plan, Figure 3.41, connected to Western Passage by a steep solution tube. A lower extension to this tube on the north-eastern side contains aragonite in the form of radiating clusters about 5 cm long along joint lines or cleavage foliations in the ceiling. There are two sets of anthodites in this lower tube. The set closest to the main passage appears to be partially recrystallized. During inspection on 2nd August 2003, they were very wet, and the ray-fan crystal facets were visible. The second set comprised a seam with aragonite speleothems. These are white to brown radiating clusters, each aggregate about 4 cm long. They were drier than the first group.

During the course of study it was discovered that the site is located within a shear zone. The site contains aragonite, bat guano and a variety of bedrock types. The main passage trend is about  $93^\circ$ . It comprises two chambers: a narrow, tall chamber partly filled with large boulders originating from the walls and ceiling, and another chamber to the north, floored with collapse blocks and fractured rock. A dyke forms the sloping ceiling of the two chambers. Some boulders have been wedged part way across the rift. The main part of Neddys Knock is floored with dark brown to reddish mud containing abundant broken rock shards.

Aragonite has been found on the walls, ceiling, boulders and as shards. A lower western chamber (Figure 3.41) is very muddy and does not contain aragonite. It appears that the lowest level fills with water when the nearby lake in Lake Chamber fills. Vertical solution holes along the western wall of the main chamber were noted to be dolomitised and falling apart internally. The lower eastern side of Neddys Knock is mostly filled with muddy boulders. The south wall of Neddys Knock is sheer, with fresh-appearing (uncoated) grey limestone apparently spalled from the walls (possibly by crystal wedging) and intersecting earlier reddish-coated solution hollows.

Some of this wall bedrock appears to be dolomitised, as it has a brown colouration in parts, contrasting with the grey limestone. Aragonite occurs as anthodites and a white spathite near the ceiling of this wall (Figure 3.42). Some of these speleothems are associated with a vertical crack down the wall from which limestone flakes are spalling away. On the lower side of the southern wall are fine white and black coatings over the fluted bedrock. The flutings have a radius of about 10 cm and are oriented vertically. These indicate that the walls were wet and dripping during an earlier period of the cave's development.

A large collapse block forms the north wall of the first chamber. Its upper surface is covered with mud. However under the mud aragonite occurs as a surface coating. The upper western part of this chamber contains crumbly red and yellow ochre in which there are aragonite “stars”, as well as a gelatinous red organic substance thought to be from bat guano.

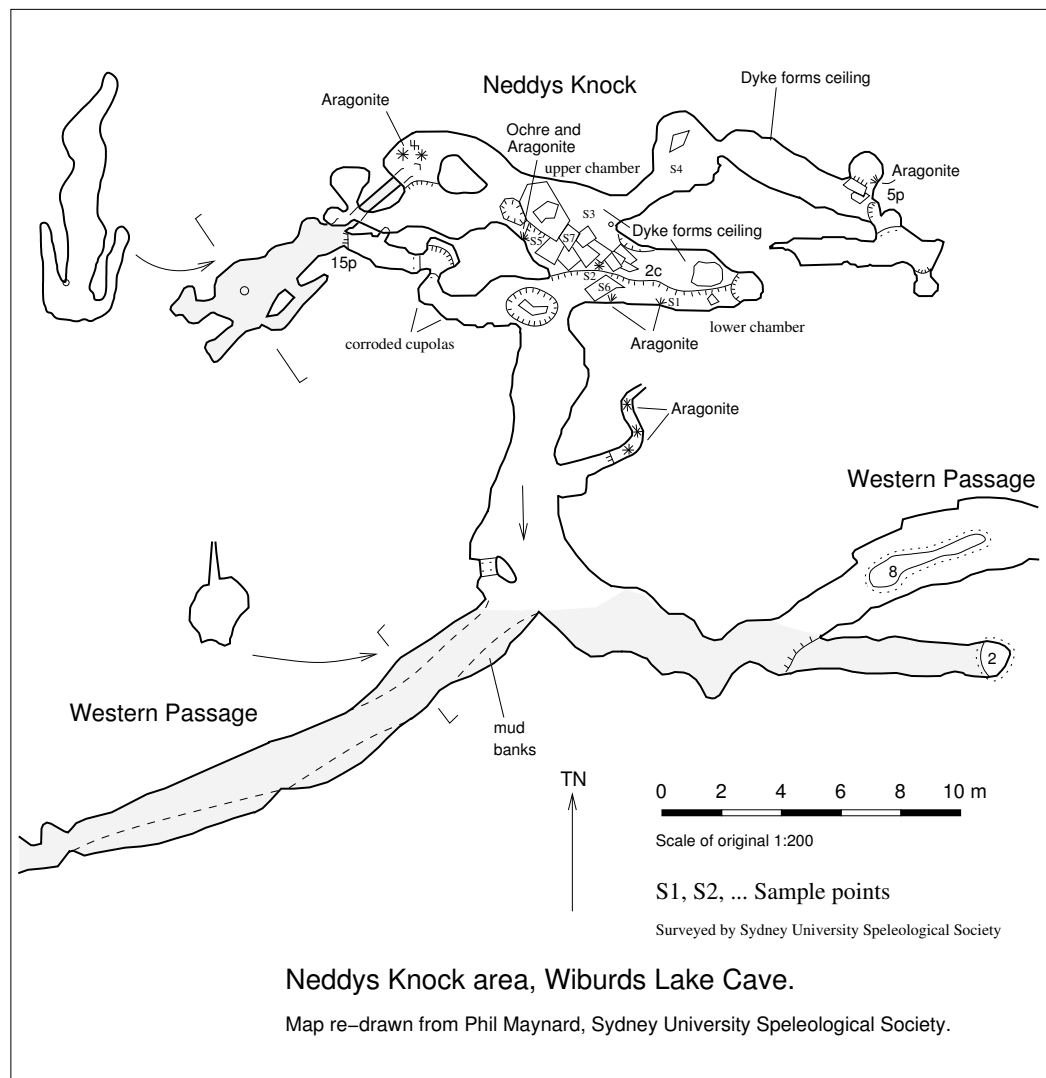


Figure 3.41: Detailed map (plan) of Neddys Knock, showing features, speleothems and sample points. Based on work in progress by members of the Sydney University Speleological Society.

In the top of this part of the chamber there is an aragonite anthodite which is apparently growing from yellow - brown ochre (see Figure 3.42). It takes the form of an array of white and yellow spikes, radiating outwards from the ochre. The black coating on the ochre is thought to be manganese oxides. Nearby are small radiating spheroids of probably aragonite growing on reddish ochre with reddish gelatinous organic material. To the west is a smaller chamber, with aragonite anthodites and helictites in the ceiling.

The more northerly chamber of Neddys Knock was difficult to access. Cavers report aragonite from the chamber's north-east is not as extensive as that seen in the first chamber.

At Sample Site S1 (Figure 3.41), there were small broken pieces of aragonite speleothem



One of the aragonite speleothem fragments in sample J58/1, about 15 mm long.



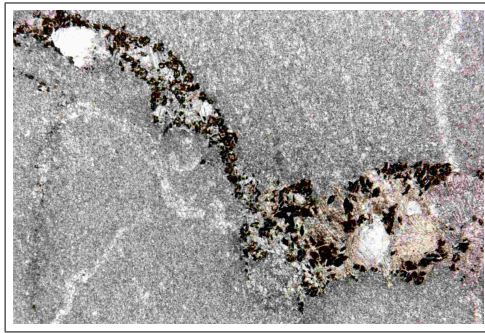
Anthodite in Neddys Knock.



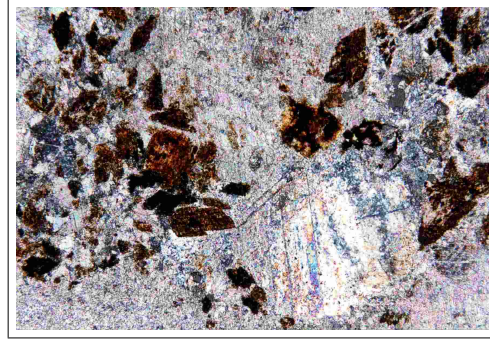
Spathite in Neddys Knock.

Figure 3.42: Views and samples from Neddys Knock.

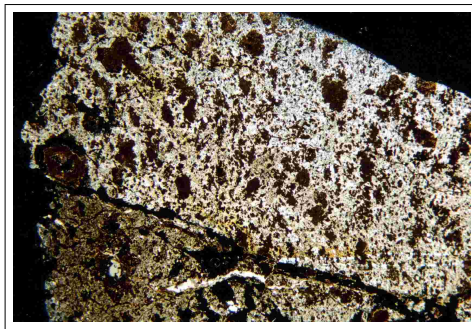
loose on the floor. XRD of Sample J58/1 indicates major aragonite, minor braunite and pseudorutile. Forms taken by the speleothem fragments include a ray-fan shape (probably part of a spheroid), a vugh with ochrous substrate, a vermiform helictite with aragonite surface and a branched aragonite helictite with twisted, twinned and slightly flattened appearance (Figure 3.42). The twinning is axial, so that the helictite appears to be formed from two flattened halves with individual crystallites radiating from the centre and directed at about 45 degrees towards the tip.



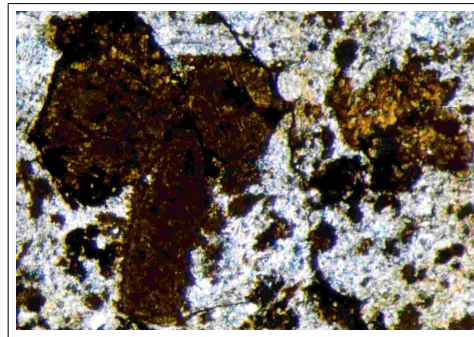
TS J58/6 PPL x13. Lime mudstone with dolomitic vein.



TS J58/6 PPL x50. Detail of dolomitic vein.



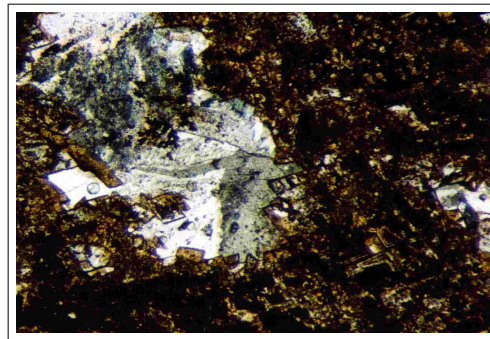
TS J58/2 XN x3.2. Weathered carbonated dyke.



TS J58/2 XN x20. Altered mineral, possibly pyroxene, in a quartz and carbonate replacement background.



TS J58/5 XN x3.2. Breccia of dolomite, possible dyke fragments and pyrolusite.



TS J58/5 XN x20. Zoned ferroan dolomite and spar.

Figure 3.43: Thin sections, Neddys Knock site S1

Chips of limestone were sampled from S1. They feature invasive dolomite and a white powdery coating with black speckles of manganese oxides. Generally these white coatings resemble moonmilk, are easily dislodged and can be washed off samples. Thin Section J58/6 was a lime mudstone with dolomitic veins and sparse biomicrite texture (Figure 3.43). The bioclasts are unaltered by dolomitisation. The white speleothem coating was analysed (XRD) and found to comprise major calcite, with minor aragonite, trace todorokite and pyrolusite.

The fine white coating on the lower side of the southern wall was sampled (area S1, J58/27). It was analysed using XRD at the Australian Museum and was found to be mainly calcite with traces of quartz, possibly magnesite and possibly hydroxylapatite (Ross Pogson, pers. comm.).

Pieces of weathered, carbonated dyke which had fallen from the ceiling were sampled at S1 (Figure 3.43, Thin Section J58/2). Sample numbers are J58/2, J58/3 and J58/8. Thin section shows a highly porous rock, with a groundmass of quartz and altered ferro-magnesian silicate phenocrysts. Opaques include pseudomorphs after pyrite. XRD of J58/3 shows major quartz, minor todorokite, muscovite and lepidolite. XRD of J58/8 shows major quartz, minor todorokite, trace aragonite and calcite (Appendix, Figure D.6). J58/3 had small rhombs of clear and brown dolomite associated with a dark brown vein (Figure 3.37). This shows that dolomitisation occurred after emplacement of the dyke.

A loose dolomitic shard was sampled (J58/4 and J58/5) from the floor at S1 (Figure 3.44). The shard had a soft clayey orange coating and brown, black and blueish interior. The orange coating became much firmer once the sample dried out. The blue was an optical illusion, actually being thin coatings of white minerals over



dark ones. Thin section (Figure 3.43, Thin Section J58/5) shows a breccia of altered dyke rock, dolomite and void-filling spar. XRD results indicate that the material is comprised of (major) dolomite, calcite, manganocalcite, pyrite and quartz with minor aragonite and other minerals (Appendix, Figure D.4). This was interpreted as a portion of dolomitised fault zone breccia of limestone and dyke material with secondary void filling spar. Aragonite is associated with magnesium and manganese minerals.

Sample J58/7 is also from the floor below S1 and comprised laminated unlithified sediment coated with a white powder and some bat guano. Minerals present in the surface powder (XRD data) include major quartz, minor lepidolite, albite, kaolinite-1Md and aragonite (Appendix, Figure D.5). It was interpreted as comprising broken down bedrock with aragonite as a secondary surface powder, like sample J58/6.

A loose piece of breccia was sampled (J58/30) from the floor below S1. It is a tan to red rock, comprised of several fine-grained different rock types and interpreted as a fault zone breccia. One of the veins analysed using XRD indicated major calcite, with minor orthoclase, letovicite, muscovite (Appendix, Figure D.10). Minor amounts of letovicite (ammonium sulfate) was attributed to the presence of bat guano.

Sample site S2 was taken from beneath the wedged boulders in the middle of Neddys Knock (Figure 3.41). On the underside of one of these boulders, small aragonite anthodites grow from an ochreous gossan substrate. Below the anthodites were loose pieces of gossan with aragonite and mud (presumably crystal wedged). One of the boulders has stripes of dark minerals, probably manganese oxide dendrites. A small amount of aragonite has grown from this surface.

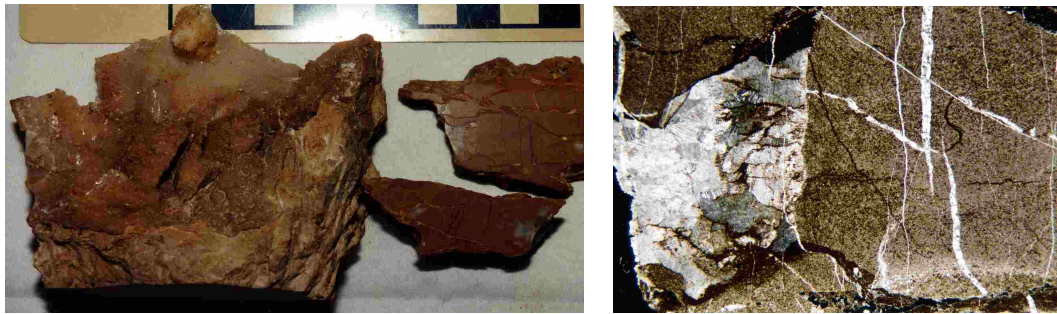


Figure 3.45: Sample J58/9: Aragonite speleothem on lime mudstone. Left: Width of view: 14 cm. Right: TS J58/9 XN x3.2. Mudstone with sparry and dolomitic veins.

A portion of a dense vugh was loose in the sediment below site S2 (Sample J58/9 Figure 3.45). One end has aragonite crystals where the needles are aligned parallel to the surface, rather than the usual perpendicular alignment of most speleothems. It also has a small aragonite stalactite at one end, with conventional crystal alignment. The vuggy aragonite has been partially engulfed by calcite (verified by XRD as major aragonite and minor calcite). The substrate is a fine lime mudstone, lithified, with sparry veins postdating a void-filling spar followed by a series of darker veins. It is unclear what relationship this lime mudstone has with the Jenolan Caves Limestone as all samples were sheared.

Sample J58/10 was loose in the sediment at S2. This is a vuggy ochre with aragonite “stars” – rosettes of aragonite crystals set in a reddish-orange matrix (Figure 3.46).

Aragonite crystals are deposited in veins through-



Figure 3.46: Sample J58/10: Aragonite rosettes in ochrous matrix.

out the porous ochre. XRD of J58/10 indicates major muscovite, calcite and goethite with minor aragonite. This was interpreted as a weathering product (possibly including some dyke material) with secondary aragonite. The rosettes are both aragonite and calcite (inverted from aragonite). The ochre is goethite and muscovite.

A red gelatinous material was sampled in the sediment below S2 (Sample J58/11). It dried to dark red flakes and mud. XRD indicated major diadochite, quartz, biotite, epsomite and minor aragonite and montmorillonite-21A, with other organics and phosphates (Appendix, Figure D.7). It was interpreted as the effect of bat guano on clays, broken down dyke rock and impure limestone.

Sample J58/12 was loose in the sediment below site S2. It was another dense vuggy material similar to J58/9, with calcite and aragonite speleothem coating. The aragonite crystals were aligned parallel to the surface. It has veining similar to J58/9 except that the dark veins appear to be of ferroan dolomite (Figure 3.49, Thin Section J58/12). XRD of the fine lime mud substrate indicates major calcite, manganoan calcite and sylvite, minor aragonite and orthoclase, and possibly trace rhabdite (a manganese uranium carbonate) (Appendix, Figure D.8).

Sample J58/25, from the floor below site S2, was a rusty-looking rock that had apparently fallen. This was a brecciated rock, mainly marble with orange stylolites and deep red pseudomorphs after pyrite. Some of the calcite twin lamellae are bent. XRD shows major calcite, minor scawtite, quartz and manganocalcite, trace aragonite. Interpreted as fault zone breccia.

Sample J58/26, from site S2, was chipped from the side of the boulder which has aragonite speleothems, about 200 mm from the aragonite. This porous rock contains quartz phenocrysts and pseudomorphs of goethite after pyrite, both as a seam or vein fill, as cubes and framboids. XRD showed some of the minerals present to be major quartz, muscovite, calcite, minor biotite, illite-2M1. Interpreted as altered dyke rock, carbonated.

Sample J58/28 was from site S2, on the side of the boulder. It was two small slivers of aragonite speleothem. The cleavage was straight across the slivers, characteristic of aragonite. The sample was analysed with XRD by R. Pogson from the Australian Museum, who determined it to be aragonite.

Sample J58/29, from site S2, was the rusty coloured substrate in which some of the aragonite speleothems were embedded. This was analysed using XRD by R. Pogson at the Australian Museum and determined to be mainly illite with minor quartz and minor kaolinite. No aragonite was observed in XRD.

An exposed portion of the dyke forms the ceiling of Neddys Knock. It has patches of small white crystals assumed to be either aragonite or calcite paramorphs after aragonite. The ceiling strikes about  $150^{\circ}$  ( $\pm 10^{\circ}$ ) and dips at about  $45^{\circ}$  to the east.

Sample site S3 is the ceiling area above site S2, sampled by P. Maynard (Figure 3.41). A piece of the dyke from this site, Sample J58-14, had a laminated texture and numerous pseudomorphs of probably goethite after pyrite. Acicular secondary crystals occurred in small pockets of clay and probably goethite. Minerals present (determined by XRD) include major quartz, muscov-

ite, minor melilite, sapphirine, lepidolite, kaolinite-1Md trace todorokite. The rock has equal quantities of dark and light minerals (Thin Section J58-14, Figure 3.49).

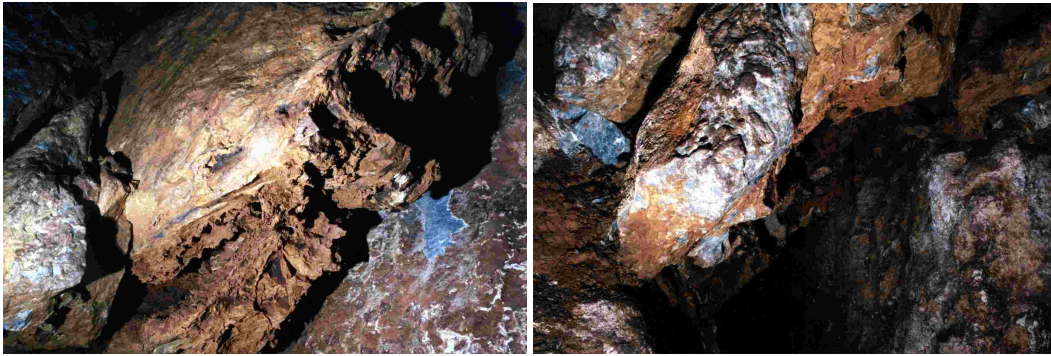


Figure 3.47: Scenes in Neddys Knock, taken from photo site S7. Left: Area below S3. Right: area near S5. Width of view in each case is about 2 m.



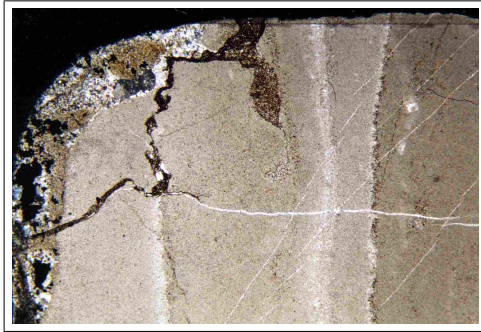
Area S3 near dyke. W=Wall between upper and lower chambers; C=Altered contact zone between wall and dyke on ceiling. Field of view is about 5 m.



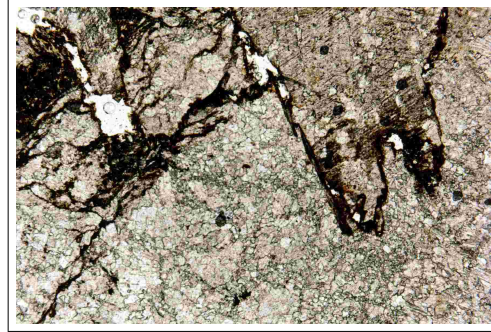
Sample J58/15: Close-up of crystal coating. Field of view is about 5 mm.

Figure 3.48: Area S3, near ceiling of Neddys Knock

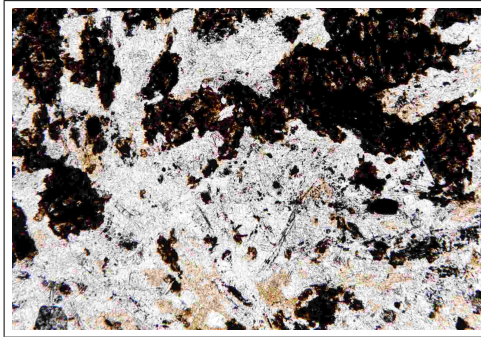
Sample J58/15 is from S3 where the material appears in the field as dark crystals on the ceiling. The colour is an optical illusion due to the shape and orientation of the crystals. The material is actually clear. This was interpreted as a thin coating of apparently length-slow calcite paramorphs after dolomite, coating an ochreous, weathered, carbonated dyke (Figure 3.48). XRD of these crystals with some of the substrate gives mostly calcite, with minor wollastonite.



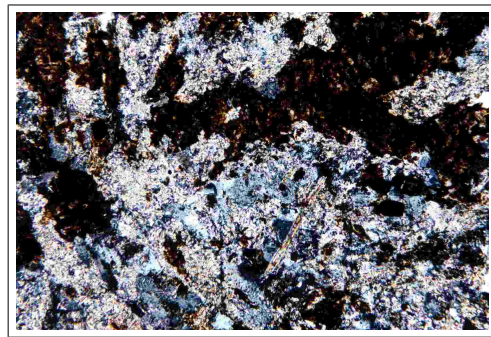
TS J58/12 XN x3.2. Substrate of aragonite-coated vugh shows dolomitic vein.



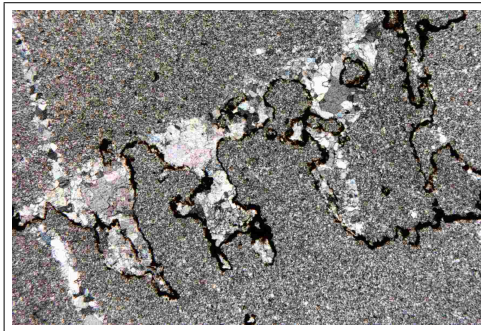
TS J58/25 N35756 XN x13. Stylolite, altered rock.



TS J58/14 N35852 PPL x50. Dyke rock exposed in Neddys Knock.



TS J58/14 N35852 XN x50. Dyke rock exposed in Neddys Knock.



TS J58/16 N35853 XN x13. White limestone with stylolite, Neddys Knock.



TS J58/19 N35855 XN x13. Fragments of trilobite, echinoderm and brachiopod. Neddys Knock.

Figure 3.49: Thin Sections from sites S2 and S3 in Neddys Knock

Sample J58/16 from S3 (Figure 3.49) is from 10 cm below the ceiling-limestone contact area (Figure 3.48). It is a white stone and appears to be baked with no original structure left. There are some stylolites and some sparry veins. Interpreted as contact metamorphic. On the surface was a white powder, similar to the surface coatings elsewhere in Neddys Knock.

Site S4 is near the northern (second) chamber above the rockpile. Sample J58/17 is a piece of the dyke from the ceiling at S4, obtained by Phil Maynard. It contained some well-preserved pseudomorphs after pyrite as chamfered cubes with face striations.

Its thin section is similar to the other dyke samples with some plagioclase, quartz phenocrysts and dark minerals. Some birefringent needle crystals resembled secondary gypsum.

Site S5 is directly above S2, on top of the large boulders. Sample J58/19 is from Site S5. It is a rock chip taken from the lower side of a large dolomitised boulder next to some boxwork (Thin Section TS J58-19, Figures 3.49 and 3.50). It had a white powdery coating, similar to



Figure 3.50: Sample J58/19: Partially dolomitised wackestone with white coating. Specimen is about 3 cm long.

other rocks from Neddys Knock. The hand specimen was partly dolomitised. Thin section shows the material is a dense wackestone with bioclasts, sparry veins and opaque veins. It is a dark mudstone with trilobite, echinoderm and brachiopods.

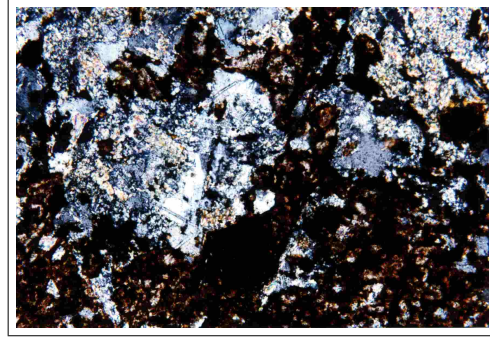
Sample J58/20 is from site S5. It is a chip from a boulder which had a striped pattern on its surface. The striped pattern was thought to be manganese oxides. There were aragonite crystals on the surface. It appeared to have aragonite engulfed in calcite. The substrate appears to be a mixture of marmorised wackestone, dolomitic material and a green shaley rock. The substrate was similar to J58/24 (the crumbly boxwork from Dyke Passage) and therefore interpreted as a fault breccia.

Sample J58/21 is a chip from the lower edge of a cupola shape on one of the large boulders. It has some boxwork with dark minerals, probably manganese oxides, some dolomitised zones and possibly dolomitised veins, partially dedolomitised. Some calcite, apparently speleothem breccia, appears in thin section. It was interpreted as a weathered breccia, similar to J58/24 (Figure 3.51).

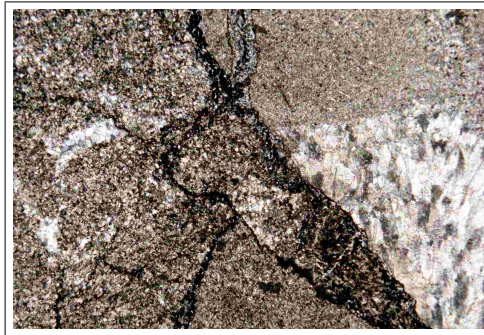
Site S5 is in the rockpile. Sample J58/18 was from the side of the access hole to the west of S5, collected by P. Maynard. It is red material similar to J58/11, thought to be the action of bat guano on clay. XRD of this material indicates major quartz, aragonite, minor muscovite and illite-2M1 and other minor minerals.



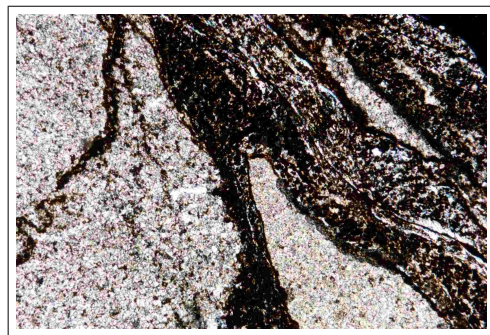
TS J58/17 N35854 PPL x13. Dyke, Neddys Knock Site S4.



TS J58/17 N35854 XN x50. Dyke, with acicular crystals (centre) and possibly dolomite (lower left).



TS J58/21 N35856 XN x13. Breccia, possibly with speleothem, Neddys Knock S5.



TS J58/21 N35855 XN x25. Dark mineralised veins around breccia fragments, Neddys Knock S5.

Figure 3.51: Thin Sections from sites S4 and S5 in Neddys Knock

Although there is fresh bat guano at Neddys Knock, it is not a large deposit so one assumes the bat occupation of the area is only opportunistic and dependent on water levels. The reddish deposits infer that in the past, conditions may have been more favourable to bats than at present.

Site S6 is on top of the large boulder. Sample J58/27 was from near location S6, on the south wall. The sample comprised scrapings of the white pasty substance on the wall. The material was granular (unlike “moonmilk” which is powdery). This sample was analysed by Ross Pogson at the Australian Museum using XRD and found to be mainly calcite with minor quartz, very minor magnesite and minor hydroxylapatite.

### Cave Weather Measurements

The cave’s temperature and relative humidity were measured at various places and times (Table 3.3). Lake Chamber often has cold dry air pooling in winter, after sunset. As Neddys Knock is far away from entrance area climate variations, it is expected to be the average annual temperature

for the region and close to 100% relative humidity. During this study in Wiburds Lake Cave, CO<sub>2</sub> concentrations did not rise to levels where classic physiological symptoms become noticeable.

| Date            | Location                        | CO <sub>2</sub> % |
|-----------------|---------------------------------|-------------------|
| 11th June 2001  | Neddys Knock, site S2           | < 0.1             |
| 2nd August 2003 | Neddys Knock, 3pm               | 0.03              |
| 2nd August 2003 | Side passage below Neddys Knock | 0.06              |

Table 3.2: CO<sub>2</sub> measurements, Wiburds Lake Cave, using the MSA pump with Dräger tubes on the 5 pumps range.

| Location                  | Av. wet bulb °C | Av. dry bulb °C | Depression °C | RH % |
|---------------------------|-----------------|-----------------|---------------|------|
| 12th July 2002            |                 |                 |               |      |
| Ent Chamber J92, 4 pm     | 9.0             | 9.7             | 0.7           | 93.8 |
| Lake Ch. - 22 Pass., 5 pm | 5.4             | 6.4             | 1             | 90.3 |
| 2nd August 2003           |                 |                 |               |      |
| Outside J92 ent, 11:30 am | 6.61            | 14.56           | 7.95          | 26   |
| Ent Chamber J92           | 9               | 10.2            | 1.2           | 86   |
| Maze                      | 8.75            | 9.58            | 0.83          | 93   |
| Dyke betw. 2 & 3          | 6.41            | 7.4             | 0.99          | 87   |
| Dyke Passage Nth of dyke  | 8               | 8.66            | 0.66          | 94   |
| Neddys Knock 3pm          | 11.9            | 12.2            | 0.3           | 98   |

Table 3.3: Temperature measurements at Wiburds Lake Cave and calculated humidity, with three measurements taken at each site.

### Synthesis - Wiburds Lake Cave

Aragonite deposits in Wiburds Lake Cave are associated with minerals containing magnesium, manganese, sulfate and phosphate. In contrast with Contact Cave, most of the aragonite speleothems at Wiburds Lake Cave are not coated with hydromagnesite. Instead, there are two associations: one with biological material, and one with inorganic minerals. Aragonite (as small “stars”) is associated with sulfate and phosphate (and possibly heavy metals) in red gelatinous material derived from bat guano. Aragonite (as anthodites) is associated with magnesium, manganese and possibly sulfate in other areas. The source of magnesium in Neddys Knock is dolomitised breccia. The source of phosphate is bat guano. Sulfate may be derived either from the bat guano or from oxidising pyrite in the dyke. Some speleothems are a mixture of both aragonite and calcite, inferring that the mechanisms for preserving aragonite are not always active. Substrates for aragonite speleothems include porous ochres and dolomitised bedrock (either dyke rock or limestone). In two areas of the cave, The Maze and Dyke Passage, aragonite may be influenced by the drying effect of cold air pooling during winter.

### Glass Cave

The Chevalier Extension of Glass Cave was visited twice (Rowling 1999b) prior to this study commencing. This work is based on photographs taken during these two brief visits. Access to this area is difficult, and restricted to 6 people per annum as a conservation measure.

#### Location

Glass Cave is situated on the western side of the Jenolan River valley. Its entrance is about half way between the river bed and the western edge of the limestone, near the base of a prominent bluff of massive limestone (Figures 3.2, 3.5 and 3.6).

#### Geological Setting

Glass Cave is located in the same general area as Contact Cave, albeit in a more westerly position, with the cave lying above and to the west of the Jenolan Underground River, therefore the geological setting for Contact Cave applies also to Glass Cave. The cave entrance is developed in the middle massive lime mudstone component of the Jenolan Caves Limestone (grey wackestone) with two gravel deposits nearby. The western part of the cave is developed in a partially dolomitised rudstone. The bedding near Glass Cave is near-vertical, striking  $340^\circ$  with one joint set striking  $10^\circ$  (Figure 3.52). A prominent joint set strikes  $310^\circ$  and dips at about  $12^\circ$  to the south-west.

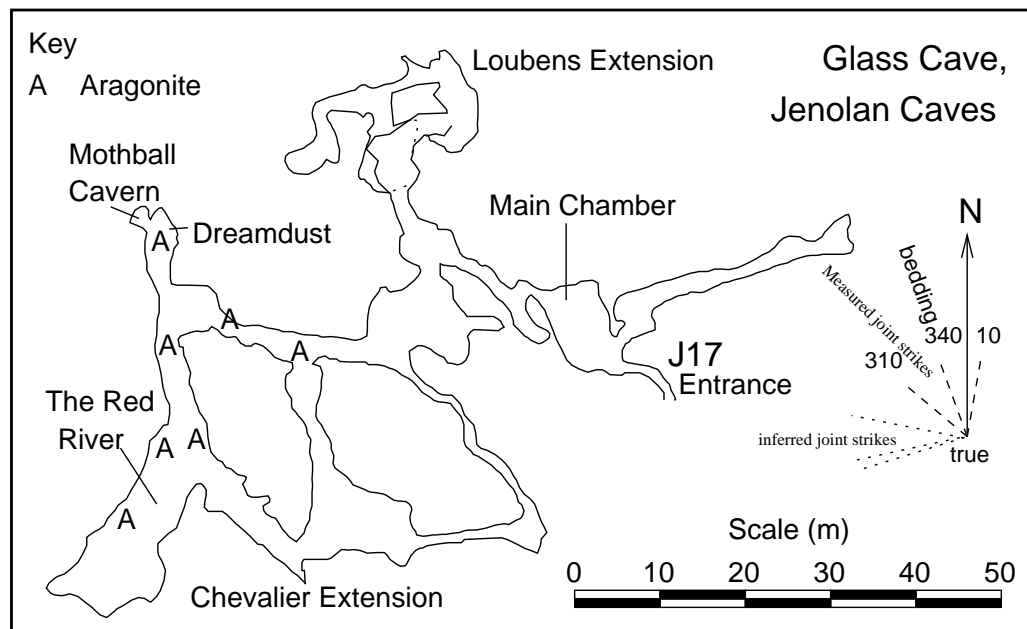


Figure 3.52: Outline (plan) of Glass Cave overlaid with strike of bedding and joints. Based on map in Dunkley (1976) and from photographs.

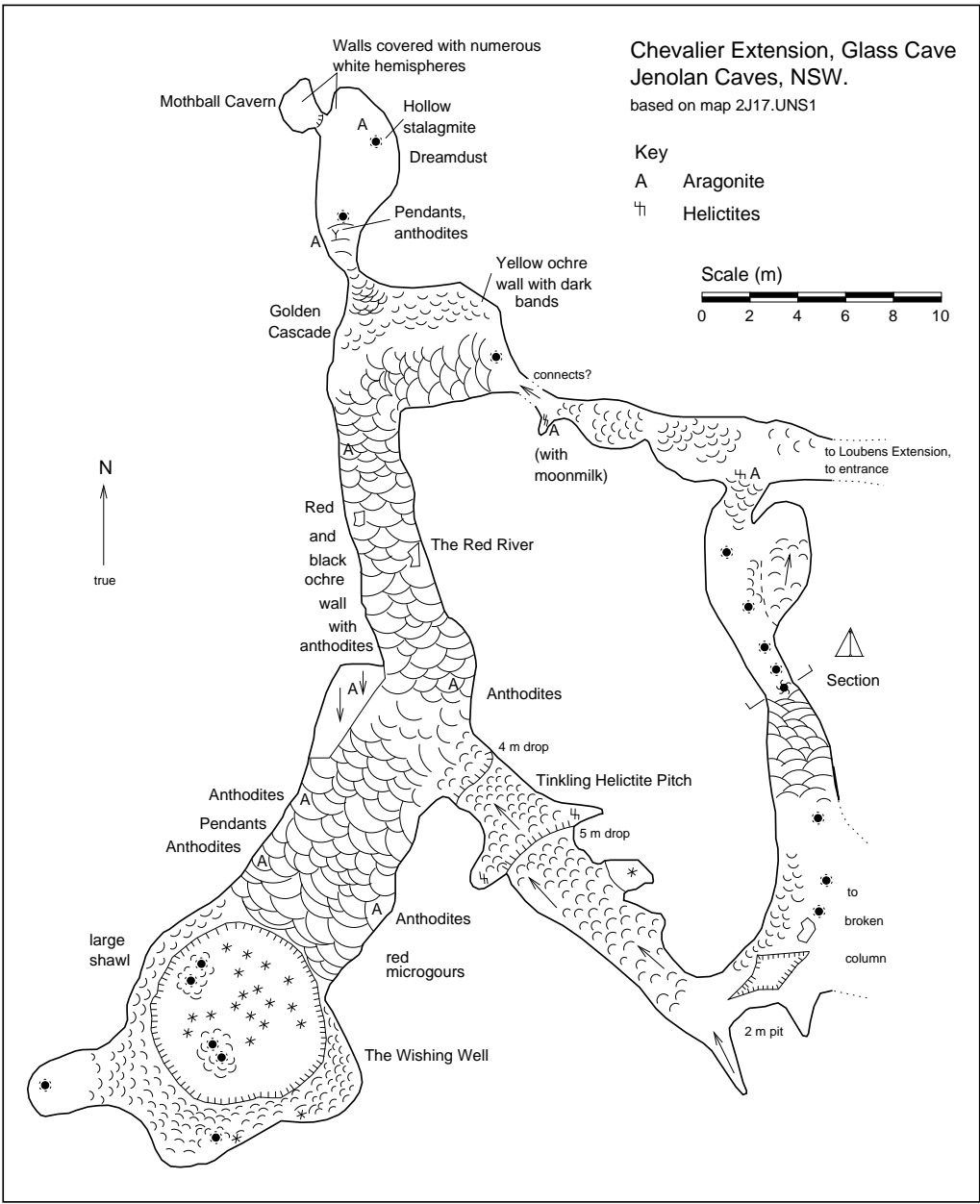


Figure 3.53: Plan of Chevalier Extension of Glass Cave overlaid with aragonite notes. Based on map in Dunkley (1976).

### Cave Description

Glass Cave is a series of interconnected cavities (chambers), mainly joint and bedding guided. Near the entrance is a tall, roughly cylindrical “Main Chamber” (Figure 3.52) with a deep rock-pile at the bottom and a high ceiling. All other chambers in the cave are accessed via an upward-sloping tube near the ceiling of the W. end of the Main Chamber. The Loubens extension is a curving, mainly joint guided chamber with a steep floor terminating in a small crystal pool. The flat ceiling features deckenkarren, and is at the same level as the Main Chamber ceiling. Deckenkarren are often a sign of a past water filled chamber, with water above sediment. Deckenkarren also occur in the low parts of the connecting passage between this point and the Chevalier Extension, as well as “The Red River” and “Dreamdust”. Bedrock pendants about 1 m long occur along the walls of “The Red River”. The most easterly chamber of the Chevalier Extension has a ceiling devoid of speleothems, with numerous brachiopod fossils visible. Some brown colouring of the rock may indicate dolomitisation. The ceiling of this area is the same height as that of the Main Chamber. Scallops (about 10 cm long) on the walls of the 9 m deep “Tinkling Helictite Pitch” (Figure 3.53) indicate that in the past, water flowed through this section of cave. The floor of the “Red River” is approximately the same height as that of the Main Chamber.

### Speleothems

Most speleothems in Glass Cave are calcite. Chevalier Extension contains aragonite-like speleothems in the form of helictites, anthodites, coralloids, surface coatings, “moonmilk” and a small hollow stalagmite. Such forms are associated with gossans, manganese oxides, hydromagnesite and/or huntite deposits. In a wall niche on the northern passage, anthodites and helictites are associated with a thick deposit of soft pasty moonmilk (Figure 3.54). The substrate is unknown. A small brown stalagmite in the eastern passage has a coating of white aragonite-like popcorn and directed coralloids, possibly associated with barometric air movement along this passage. Nearby, aragonite-like helictites have spread across a low ceiling. The helictites’ lengths are about 300 mm.

“The Red River” is a dry passage with orange-red microgour flowstone on the floor. Around the sides of this passage, there are several anthodites. Moonmilk and aragonite-like coatings occur on both (ceiling) deckenkarren and (walls) metre-long bedrock pendants. The floor also has patches of very sticky red clay with white moonmilk and black minerals, most likely manganese oxides. The Wishing Well is a circular pit in the south west end of the cave. Around its edges are many unusual speleothems, including small anthodites. Embedded in the south wall are rounded cobbles of either porphyry or dacitic crystal tuff, partially cemented and coated with a fibrous mineral that resembles either gypsum or aragonite (Figure 3.54).

Along the northern and western sides of the “Red River”, the walls are very reddish and ochreous but this may be only a surface coating. Deckenkarren and metre-long bedrock wall pendants are often grey with moonmilk. Anthodites have developed on a rusty red coloured,



Glass Cave: niche with helictites, anthodites and “moonmilk”.



Cobble partly coated with fibrous speleothem.



White helictite and anthodites with probably hydromagnesite tips, reddish ochre and wedged bedrock near the Red River, Glass Cave.



Dreamdust area of Glass Cave with anthodites in the ceiling. Field of view is about 4 m.

Figure 3.54: Aragonite-like speleothems, Glass Cave.

porous substrate. Near one of the anthodites, there appears to be a dark limestone under the red ochre (Figure 3.54), visible by crystal-wedged flakes. The northern end of the Red River has a wall with red, black and yellow-brown banding resembling wood. This was interpreted as an eroded ironstone, possibly comprising goethite and dark manganese-rich minerals and looks similar to a coated version of the ironstone in the “Diamond Mines” area of Imperial Cave.

In the area called “Dreamdust” (Figures 3.53 and 3.54) some of the deckenkarren are covered with anthodites and white moonmilk. The walls are also lightly coated with moonmilk and a black material.

### Sample Sites and Observations

Two small samples were taken from the cave, both from the “Dreamdust” area. Sample J17-1, from the floor near a hollow stalagmite, was a match-head sized coralloid. Under the microscope it appeared to be a mixture of hydromagnesite, aragonite and calcite with possibly gypsum. It had small opalescent bubbles and had a general coralloid or popcorn appearance. XRD analysis showed the presence of (major) aragonite, minor calcite, gypsum, huntite, hydromagnesite, mel-lite (organic), diadochite (a phosphate), magnesian calcite (Appendix, Figure D.3). The hollow in the stalagmite may be a result of high (soluble) gypsum content.

The other sample, J17-2, was a white pasty substance collected from clothing used in this part of the cave. This pasty material was mainly from the “Dreamdust” area. The sample had the consistency of cottage cheese when first collected, but lacked the fibrous nature of typical moonmilk. It was kept dry for four years before analysis and minerals may have altered since collection. Optical analysis showed it comprised small brown and white grains. Some crystals with aragonite form appeared to be present.

XRD analysis of the powder showed major calcite, as expected for moonmilk, minor aragonite, todorokite, huntite and hydromagnesite. There were traces of birnessite, pyrolusite, hausmannite and a clay. This is unlike the findings of England & Smith (2000) who found only fibrous calcite in Glass Cave “moonmilk”. Possibly both polymorphs are present in different areas of the cave.



Figure 3.55: Crystal coating contains aragonite. Near hollow stalagmite in Dreamdust area of Glass Cave. Field of view is about 20 cm

**Synthesis: Glass Cave**

Glass Cave seems to have originated as phreatic, joint guided cavities, with larger chambers formed first and then connected later. Later, there appears to have been a stage with slowly flowing water. Larger cavities appear to have formed in more pure limestone, and the dolomitised limestone has remained as narrow connecting passages, strike oriented. At some stage, gravel has been deposited in the cave. There have been at least two phases of cave development, as it appears that some cave passages have intersected older cavities, e.g. two passages connecting to the large entrance chamber are near the ceiling of the chamber.

Aragonite in the Chevalier Extension of Glass Cave seems to be mainly associated with magnesium-rich minerals (huntite and hydromagnesite), as well as manganese. It is proposed that the origin of the magnesium is breakdown of dolomitised bedrock. Red ochre forms the substrate for a number of aragonite speleothems. Like Contact Cave, it is thought that these minerals are being slowly released by strong acids in the oxidation of pyrite in dolomitised limestone, forming red ochre and releasing magnesium and manganese. Some “moonmilk” in this cave has a high proportion of magnesium and manganese-rich minerals.

There may be some influence from phosphate (assumed to be from bats), however the aragonite produced from this origin has a different speleothem appearance compared with inorganic processes. These possibly organically derived speleothems tend to be small and fine grained, whereas the mineral-derived ones (e.g. anthodites and helictites) have larger crystals and presumably deposit more slowly. It would appear that larger numbers of bats may have roosted in this cave than at present. The initially released acids from bat guano may also have assisted the release of magnesium from bedrock in areas close to bat guano.

## **Mammoth Cave**

### **Location**

Mammoth Cave is a large cave with about 13 km of passages located under Mammoth Bluff and South Mammoth Bluff on the eastern side of the Jenolan River valley (Figure 3.5). Mammoth Cave lies about half way between Contact Cave and Wiburds Lake Cave. The entrances are a few metres above the normally dry creek bed. The southern extremities of Mammoth Cave lie to the north-east of Playing Fields, and the most northerly extent lies to the east of Serpentine Cave.

### **Geological Setting**

The geology of this area has been mapped by Allan (1986) and Cooper (1993) (Figures 3.6 and 3.56). The geology is similar to that of Contact Cave. Like Contact Cave, Mammoth Cave is developed in Late Silurian Jenolan Caves Limestone. Its eastern extremities lie close to the easterly boundary between the Jenolan Caves Limestone and the “Jenolan beds”. The limestone in the cave varies from a light grey colour with occasional dark stromatoporoids to nearly black with white calcite veins (e.g. the North West Passage area). Dolomitisation occurs parallel to bedding, with veins and yellow-brown zones. Cooper (1990) has described hydrothermal veining in Mammoth Cave near Snakes Gut.

Two samples of limestone were taken from the surface, near the northern end of Mammoth cave. Sample JEN-9 is a light coloured fossiliferous wackestone, taken from the side of the hill (northernmost Mammoth Bluff, Figure 3.56 and 3.57). A thin section of this rock shows fossils of echinoderm fragments, brachiopods and algae. The limestone contains broken bioclasts, with mixed areas of fine micrite and biosparite. The junction of the micrite and biosparite is sutured. Veins are mostly spar-filled, with a brown mineral resembling goethite. Some small vein crystals resemble paramorphs of calcite after aragonite. The fauna is a little different to that normally seen in the Jenolan Caves Limestone and may be compared with that in Figure 3.8.

Sample JEN-10 is a grey and purple coloured wackestone, taken from the rockpile on the flat between the creek and the base of the northernmost hill on Mammoth Bluff (Figure 3.56). A thin section of this rock shows fossils of brachiopod, stromatoporoid and crinoid in a lime mud. Limestone textures vary from a sparse biomicrite to a coarse sparite. Acicular spar has developed epitaxially, possibly from a biological precursor such as a shell, shortly after deposition. The junctions between the two textures is in part invaded by a vein of ferroan dolomite.

Throughout most of the cave, the bedding dips to the west and is overturned. Towards the top of Mammoth Bluff, a recumbent fold can be seen in the exposed limestone. Below this fold, the limestone (closer to the creek) dips to the west. A loose scree slope, mostly comprised of rocks of the Jenolan Beds, covers much of the steep hillside between the cliffs of Mammoth Bluff and the creek bed. Both the eastern and western banks of the creek are steep. Smashed limestone boulders in the usually dry creek are mainly massive grey limestone, with some veining and colouring from dolomitisation.

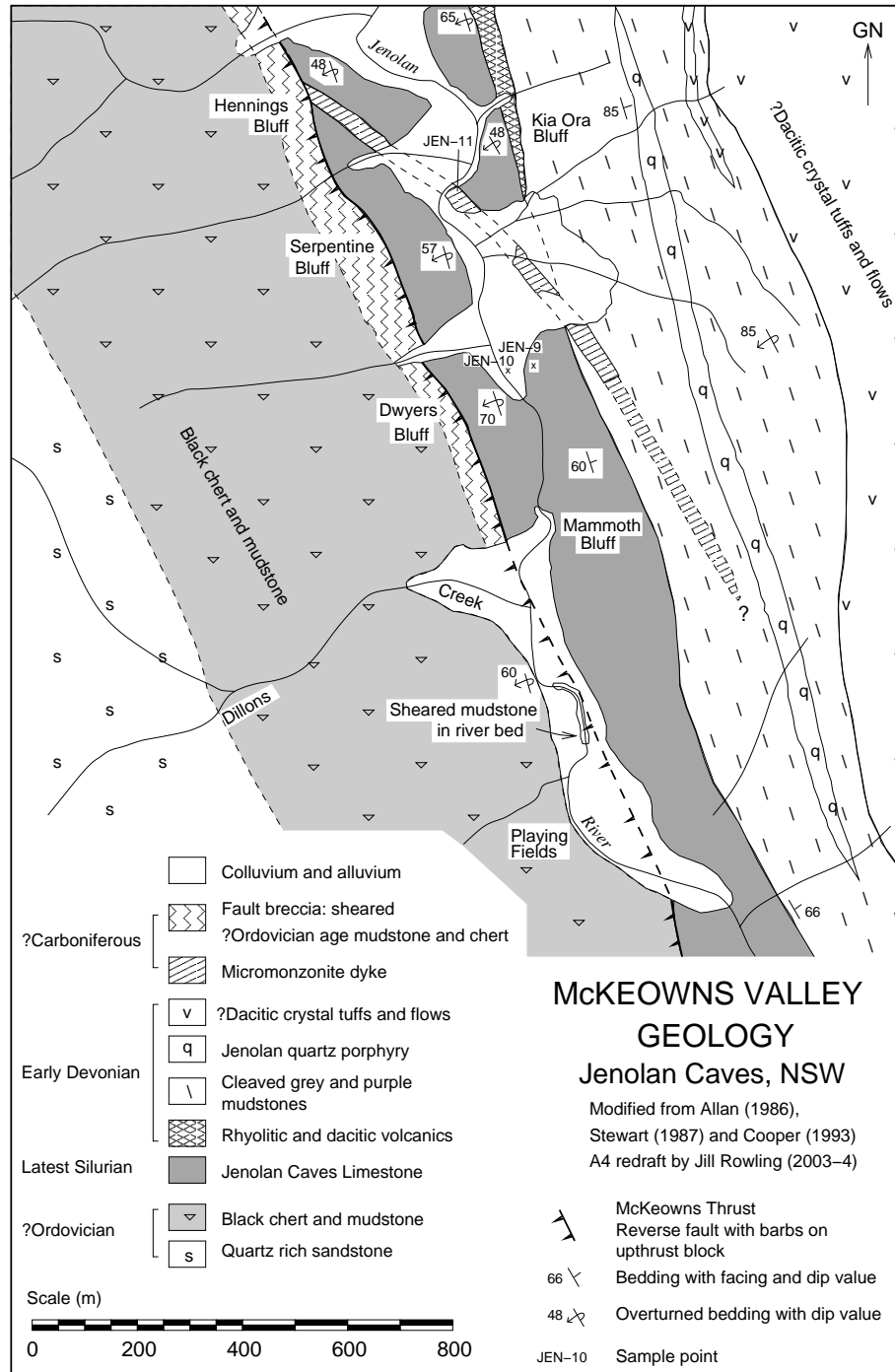
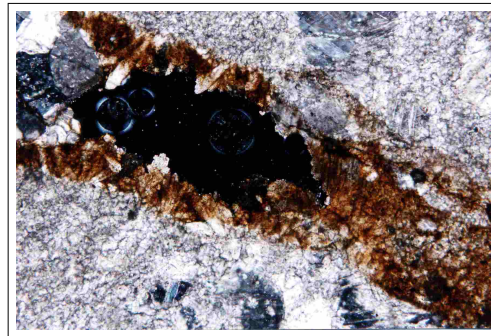


Figure 3.56: Geology of the Serpentine Cave area, Jenolan Caves. Outcrops traced from Cooper (1993), then overlaid with sample points JEN-9 and JEN-10. For cave positions, see Figure 3.5.



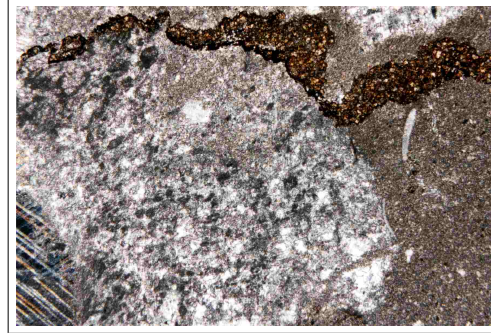
TS JEN-9A N36450 PPL x13. Wackestone with fossils (probably dasycladacean algae).



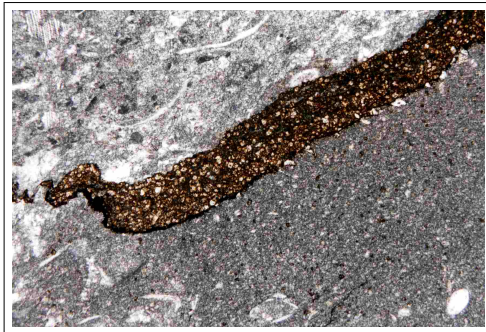
TS JEN-9B N36450 XN x50. Vein detail, with acicular crystals.



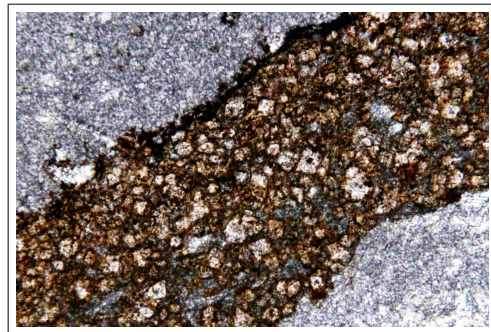
TS JEN-10A N36451a PPL x13. Acicular (calcite) cement (LHS) may have been originally aragonite or gypsum.



TS JEN-10A N36451a XN x13. Limestone textures vary from partially dolomitised sparse biomicrite to coarse sparite.



TS JEN-10B N36451b PPL x13. Dolomitic vein between different limestone textures.



TS JEN-10B N36451b PPL x50. Dolomitic vein detail.

Figure 3.57: Thin Sections JEN-9 and JEN-10: North Mammoth Bluff

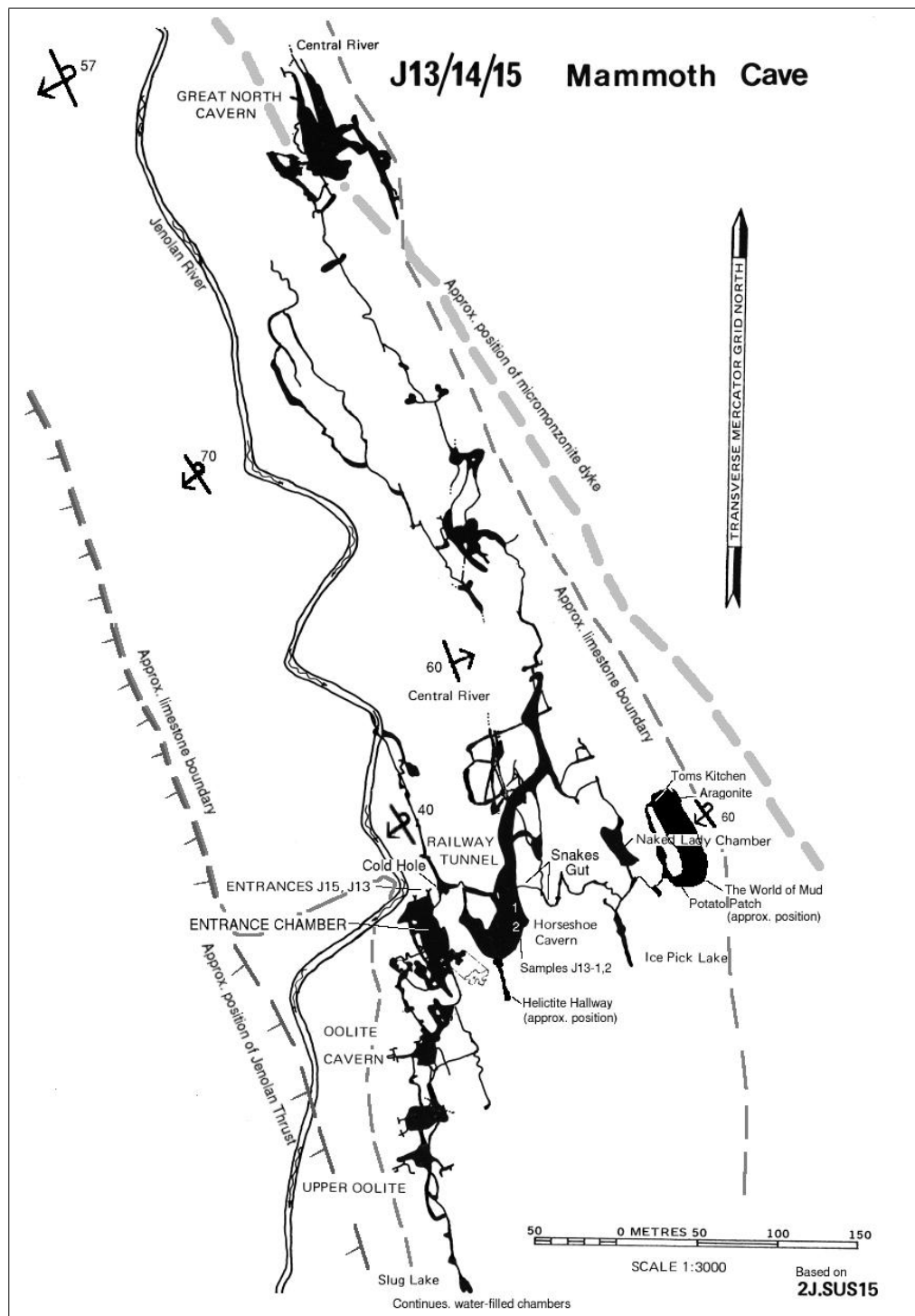


Figure 3.58: Outline (plan) of Mammoth Cave. Based on Dunkley and Anderson (1978), overlaid with approximate geological boundaries from Cooper (1993). Approximate position of the World of Mud from preliminary field trip.

### **Cave Description**

Mammoth Cave consists of a set of large chambers interconnected at various levels by narrow, strike-oriented tubes forming a branching network. The large chambers are of two types: long, box-shaped, or tall with circular plan (avens). There is an arc of large chambers in the southern part of the cave (Figure 3.58).

Large chambers in the central and northern part of the cave include the Entrance Chamber, Horseshoe Cavern, Railway Tunnel, Great North Cavern, Naked Lady Chamber and the World of Mud.

The Entrance Chamber has a roughly circular outline. It is a large, deep cavern with a flat topped ceiling channel and a steeply sloping floor piled with room-sized boulders. Horseshoe Cavern is a large semicircular chamber with three avens (vertical shafts). The larger of these rises at least 40 m from the cavern floor and its upper region is inhabited by bats. Railway Tunnel is a northerly continuation of Horseshoe Cavern. It is mainly strike-oriented, with large holes in the floor connecting to the more hydrologically active areas of the cave. It has a roughly rectangular plan and cross-section. A ribbed shape in its flat ceiling corresponds to dolomitised regions of the limestone. Parallel to Railway Tunnel and at different levels to it are a series of long, tall passages mainly developed along the strike of the limestone. In the south eastern part of the cave is a large chamber discovered recently called the “World of Mud”. This contains aragonite and is described in more detail below.

Cross-sections of small interconnecting passages vary from roughly circular, metre-diameter tubes with small scallops to deep vertical slots with circular tops (e.g. Snakes Gut). Some tubes take water and gravel during floods.

The southern half of the cave is developed mainly in a north to south orientation following the strike of the limestone. Passages in this area are often circular tubes, long but small in cross section. These occasionally intersect avens such as near Lower River and Oolite Cavern. The Jenolan Underground River appears in Mammoth Cave for a short distance. There are also small intermittent side creeks and small lakes in the cave. A lake in the southern end of the cave, Slug Lake, forms part of a large, water-filled cavity, estimated to be at least 90 m deep. According to the divers (Keir Vaughan-Taylor, pers. comm.), the cavity has a roughly triangular cross section with the apex at the top and north-south orientation. Ice Pick Lake is another large water-filled cavity with roughly north-south orientation.

In the northern half of the cave the passages trend more towards the north-west following the strike of the limestone. Passages in this area are also usually long, narrow phreatic tubes.

Aragonite occurs in the aven, “Helictite Hallway” near Horseshoe Cavern, according to cavers. Photos show large (possibly recrystallised) helictites associated with anthodites. This possible aragonite is associated with a particular layer of the bedrock or a joint. Prominent lines in the ceiling, parallel to bedding, correspond to more resistant, possibly dolomitised, limestone.

### **The World of Mud, Mammoth Cave**

Observations in The World of Mud are the result of photographs taken on a single reconnaissance visit. No sampling has been undertaken and no map has been published. This area is to the south east of Naked Lady Chamber (see Figure 3.58). The World of Mud is shaped roughly like a rounded rectangular prism with approximate dimensions as follows: length: 40 m oriented north-northwest (strike  $160^\circ$ ), width: 15 m, height: 100 m. The nature of the ceiling is unknown. The floor of the World of Mud is partly rockpile and partly gravel with connecting tubes to other parts of Mammoth Cave. Dip of walls: about  $60^\circ$  to the west. The southern wall was blank above the lower connecting passage. The northern wall is a rockpile with deep (possibly corrosion) pits connecting to the lowest levels. The sloping eastern wall has loose blocks of limestone and possibly corrosion furrows several metres deep. The hanging western wall, where seen, was flat and devoid of features. The general shape resembles a “hall” (Osborne 2001).

In the lower, western part of The World of Mud, are small tunnels. the ceilings are arched and ribbed as the bedrock is alternately banded with dark grey limestone and brown stone, possibly dolomite, parallel to the bedding and similar to that seen on the hillside near Contact Cave. These possibly dolomitised regions are more resistant to weathering than the limestone, and create a gothic arch appearance in the ceiling. One small chamber in this lower area has a type of orange velvet flowstone on the floor. Known as the “Potato Patch”, the flowstone was thought to be aragonite due to its unusually spiky surface texture. Near the “Potato Patch” and in “Toms Kitchen” directly above it, there is a lot of boxwork on the walls and boulders, wherever there is dripping water.

There is a loose scree slope of dark coated cobbles (not limestone) resembling a rock stream near the “Potato Patch”. It was thought to lie close to the contact between the Jenolan Caves Limestone and the “Jenolan beds”. A steep wet and muddy slope has small possibly aragonite anthodites protruding from flowstone. One smooth flowstone canopy, called the “Blue Lady”, is orange, blue-grey and white and is thought to be partially aragonite because of the colour. At the top of this slope is a rockpile of room-sized boulders at the bottom of a very large, steeply-sloping chamber. Some boulders in this rockpile have aragonite in the form of drusy surfaces like “stars” or in seams like the boulder examined in Neddys Knock, Wiburds Lake Cave.

“Toms Kitchen” is one of the largest chambers in the north of “The World of Mud” with a flat floor comprised of breakdown blocks. Some small muddy anthodites are in the south western part of “Toms Kitchen” (Figure 3.59). One of them looked slightly greenish. The bedrock in this area consists of grey limestone with a brown colouring, possibly a dolomitic replacement of lime mud which has left most bioclasts intact. One anthodite (Figure 3.60) had developed on a brown / red substrate of altered limestone. The dip visible on the eastern wall is about  $60^\circ$  to the west. The eastern wall is deeply incised by a slow trickle of water, leaving large limestone blocks perched on mud. In some areas, holes in the bedrock are square with proud residual material resembling boxwork. These structures are interpreted to be due to corrosion resulting

from aggressive dripwater, confined by insoluble zones in the bedrock.

To the north-northeast and above “Toms Kitchen” is a steep chamber with lots of loose muddy and shaley material. The shaley material is interpreted as an impure limestone which strikes about  $160^\circ$  and also dips about  $60^\circ$  to the west. This small funnel-shaped chamber has a gable shaped ceiling and a large sloping block of rock on the wall / floor which is displaced about half a metre downslope from its original position. Upslope of this block is a hanging wall of corroded-looking bedrock blocks. These form the eastern wall, broken down across the strike. The hanging western wall of this chamber is limestone bedrock coated with delicately shaped mud pendants. Large helictites protrude from this wall, apparently from the ends of the corroded blocks. The largest dark, almost black spidery helictite about 300 mm diameter with each 3 mm diameter branch radiating from a central point. The dark coating appeared to be more pronounced on the upper surfaces of the speleothem.

One bizarre helictite cluster about 100 mm diameter consisted of dark spines radiating from a central point. Each spine had a white blob at the end. This was interpreted as an aragonite helictite or anthodite with manganese oxides coating the surface and hydromagnesite or huntite on the tips. Another peculiar radiating helictite cluster was similar, but had a hook of aragonite at the ends of each of the 1 to 2 mm diameter spines, pointing back towards the centre at an angle of about  $30^\circ$ . Several spines looked identical and may have a common twinned origin. Other helictites looked like dark hairs or brown radiating clusters protruding from a thick coating of white probable hydromagnesite or huntite – see Figure 3.61. On the upper eastern wall were small (about 5 mm diameter) hemispheres of probably aragonite crystals. These catch the cap lamp light in such a way as to resemble crescent moon shapes and is probably a precursor to velvet flowstone. In the ceiling at the north end of the chamber were small (about 10 mm long) forked anthodites that resembled fish tails. This may be a crystal twinning effect (Figure 3.61). The ceiling of the chamber has a pocket of aragonite-like stars (spherulites), similar to the ones in Ribbon Cave. It also has black (probably manganese oxide) deposits coating pink mud. According to Martin Vizjak (pers. comm.), aragonite above this chamber does not occur in the boxwork but in corners and on rock surfaces. He reported that high above the chamber, aragonite occurs in an extremely muddy area in “scallop and notches” but not actually growing directly from the mud.

### **Sample Sites and Observations**

At Cold Hole, near Horseshoe Cavern, a small speleothem has developed on a brown material which is probably a dolomitised limestone bed. Here, several such beds are visible and are more resistant than the surrounding limestone. The strike is about  $150^\circ$  and the dip is about  $40^\circ$  to the west. The speleothem was a (probably calcite) straw stalactite, with a base of probably aragonite popcorn / coralloids and a fine helictite. Possibly there is sufficient Mg available to prevent calcite from forming directly on the dolomite, but insufficient to prevent a calcite straw from forming.

On the floor, about 6 metres south of the turnoff to “Unsurveyed Connection” in Railway Tunnel (J13-1 on map, Figure 3.58), a fallen block of speleothem had unusual crystal growths resembling aragonite. A sample (J13-1) of this material was found to be calcite (by cleavage and by XRD), although it had aragonite-like external features and is assumed to be a paramorph of calcite after aragonite.

A few metres away from J13-1, the cave wall is very dark limestone with brachiopod and stromatoporoid fossils, reddish boxwork and patches of white “moonmilk”. Sample J13-2 was a very small piece of the boxwork. Although optical microscopy suggested aragonite was present (from cleavage), XRD showed major calcite and todorokite, minor vaterite, hydromagnesite, alunite, alunogen and traces of monohydrocalcite and braunite (Appendix, Figure D.2).

This part of Railway Tunnel / Horseshoe Cavern has a popcorn line about 4 m from the ground.

### **Synthesis – Mammoth Cave**

In Mammoth Cave, aragonite has not been positively identified by XRD methods, but has been identified by morphology alone. Probable aragonite in the World of Mud appears to be associated with minerals containing magnesium, manganese and possibly sulfate ions. The mud is unusually dark-coloured in some areas and appears to contain large quantities of manganese oxides. Unlike the other caves examined at Jenolan, there are no obvious phosphatic deposits: the chamber was discovered by cavers digging, and unlikely to have ever housed bats. No drying effects were noticed, although air movement may be significant in places. The reported pale green and blue colouration of some speleothems may be due to a combination of heavy metals such as copper, and whiteness due to the lack of brown humic / fulvic acids in the aragonite crystal lattice. Orange speleothems (such as the “potato patch”) may be due to rhodocrosite as was found in speleothems at Contact Cave. Sampling in “The World of Mud” was not possible at the time of the visit. The source of the magnesium and manganese appears to be the dolomitised zones of the bedrock. Possibly strong acids from weathering pyrite are eroding the limestone to create the broken down rock and releasing calcite-inhibitors from the dolomitised regions. Aragonite crystal wedging appears to have broken apart large boulders.



Figure 3.59: Anthodites, about 15 cm long, Toms Kitchen, the World of Mud, Mammoth Cave.



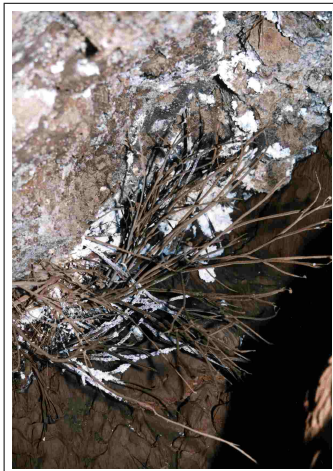
Figure 3.60: Dolomitised limestone (left), micrite replacement (field of view about 0.5 m) and anthodite (right) about 15 cm long, Toms Kitchen area, the World of Mud, Mammoth Cave.



Radiating helictites and filigree mud. Cluster diameter about 10 cm.



Velvet spheroids, manganese, mud and crystal wedging. Field of view about 10 cm.



Brown helictites and "moonmilk". Field of view about 0.5 m.



Dark Radiating helictites and "moonmilk". Field of view about 0.5 m.



Paired or twinned helictites. Each is about 1 cm long.

Figure 3.61: A selection of helictite forms from the funnel shaped chamber, the World of Mud, Mammoth Cave.

## **Spider Cave**

### **Location**

Spider Cave is in the limestone on the western side of the Jenolan River, north of the show caves and about 100 m below Contact Cave (Figure 3.6). Its entrance is about 5 m above the bed of the river near the base of a cliff.

### **Geological Setting**

Spider Cave (Figure 3.63) is mainly developed in the middle massive unit of the Jenolan Caves Limestone. Near the cave entrance, the rock is a fine grey wackestone with sparse brachiopods. One measured joint outside the cave strikes  $326^\circ$  and dips at  $75^\circ$  to the west. Some rudite was noted by Cooper (2001) as a bedding discontinuity in Frustration Chamber between Dingo Dig and Z Squeeze. Limestone on the eastern side of Frustration Chamber contains fist-sized stromatoporoids; the western side appears to be a lime mudstone. Z Squeeze cuts through an impure brown limestone, more resistant to dissolution. Brachiopods and small stromatoporoids on the ceiling near the western side of Z Squeeze may form part of another (rudite) facies. The streamway section of the cave is developed parallel to the strike, with strong north-northwest passage orientation in mainly grey lime mudstone with occasional brachiopod fossils. There are three levels of passage, similar to the northern show caves, with the lowest passages more westerly than the higher ones. The most westerly part of the cave is truncated by a less-soluble, thinly bedded facies. This is exposed in the cave as soft black crumbly material forming the western wall of the area near the Jenolan Underground River. The black colouring is probably due to manganese oxides adhering to the ochrous substrate. Mafic dykes intrude the limestone at the northern edge of Pike Lake (strikes eastwards) and at the entrance chamber (strikes north-northwest).

### **Cave Description**

Spider Cave has about 2800 m of passages and comprises two parts: an entrance series of chambers where the passages are mainly west and northwest oriented, and a streamway area where the main passage orientation is north-northwest. The entrance series comprises a set of chambers connected together by phreatic tubes and rockpiles. The passage orientation appears to be governed by an east-west striking joint. The surface gully between Spider Cave and False Frenchmans Cave may follow the same joint. Many passages in this part of the cave contain sediments with sub-fossils. A large chamber, Helictite Passage, is developed on two levels with mainly east-west orientation. Helictite Passage (Figure 3.64) contains anthodites which are probably aragonite (described below). The western part of Spider Cave is comprised of two parallel passages on different levels, both with mainly north-south orientation. The lower (most westerly) level contains the Jenolan Underground River. This level is the northern continuation of the Imperial show cave, connected via a series of sumps. It is about 50 metres below the bed of the creek outside the

cave, and about 200 m to the west. The underground creek flows close to the sheared contact with the cherts at the western side of the limestone. The Mausoleum is a large chamber about 25 m high through which the Jenolan Underground River flows. Its walls are blocky, partially formed by structural failure of large blocks along zones of weakness, close to the western boundary of the limestone. There are few speleothems in the western part of Spider Cave. Figure 3.63 is the general plan of the cave showing an overall branching shape. The section (Figure 3.65) shows a number of features striking  $355^\circ$  and dipping about  $19^\circ$  to the east. This is not the bedding, as that is nearly vertical, but may be related to a joint set.

### Sites and Observations

No mineral sampling was done in Spider Cave for this study. In Spider Cave, most speleothems appear to be calcite. Speleothems thought to be aragonite (or mixed aragonite/calcite) occur in part of Helictite Chamber, a relatively dry part of the cave. The middle and lower Helictite Chamber contains banks of calcite-cemented cobbles, which have been re-excavated prior to the present dry period. Speleothems (probably aragonite) occur in a steeply sloping passage above this cobbled area (Figure 3.65) (Cooper 2001, Maynard & Rowling 1998, Maynard & Cooper 1998). Speleothems include small beaded helictites on the wall near the western side of “Z Squeeze”. At the junction of Upper and Lower Helictite Chamber are anthodites and thickened straw stalactites with a surface texture resembling the aragonite furze bushes in the show caves. There is also flos ferri and some calcite (stalactites and microgour flow-



Figure 3.62: Anthodites in Spider Cave. With Sue Bonar.

stone). Some fine (probably aragonite) helictites have small white blobs on their ends, resembling hydromagnesite or huntite (Figures 3.62 and 3.66). The bedrock near the anthodites appears to be a blue-grey rudite, with a brown colouring which resembles the invasive ferroan dolomite seen

near Contact Cave. This ferruginised, probably dolomitised limestone forms the substrate to the aragonite in Helictite Chamber. Cracked mud is present in ceiling niches, so possibly the chamber was filled with mud and has been re-excavated. Many aragonite speleothems have a “dirty” appearance and may have developed contemporaneously with the removal of mud. Beaded helictites are generally made of alternating calcite and aragonite.

#### **Summary – Spider Cave**

Some speleothems in Spider Cave appear to be aragonite. Further study of the cave is necessary before conclusions can be drawn.

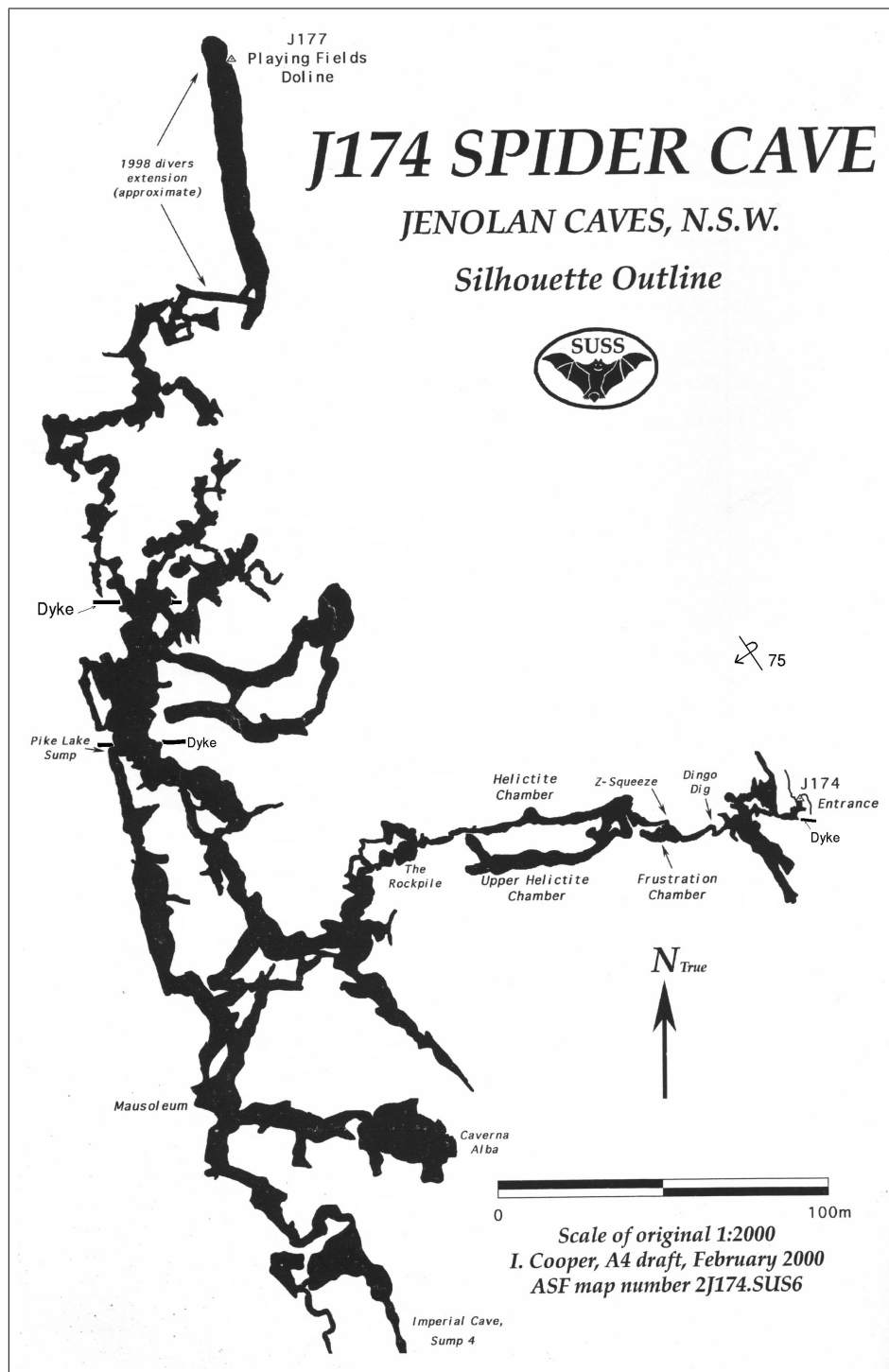


Figure 3.63: Outline (plan) of Spider Cave, Jenolan. Based on map 2J174.SUS6 by Ian Cooper, 2000, in Cooper (2001).

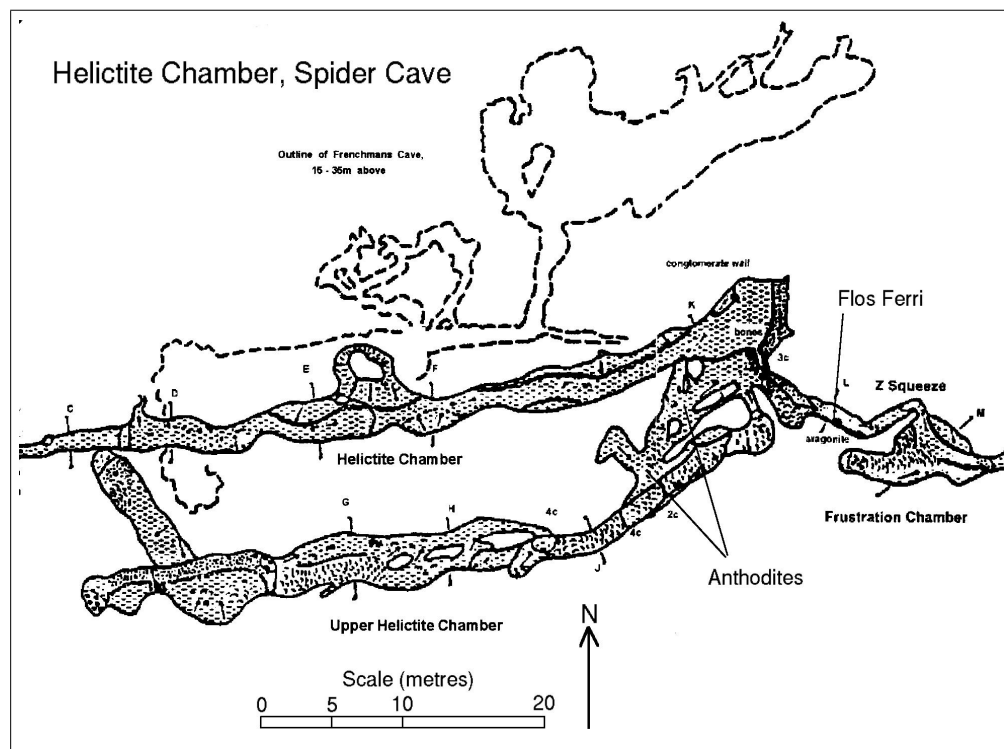


Figure 3.64: Map of Helictite Chamber, Spider Cave, Jenolan. Based on map 2J174.SUS5 sheet 1 of 6 by Phil Maynard and Jill Rowling, 1998.

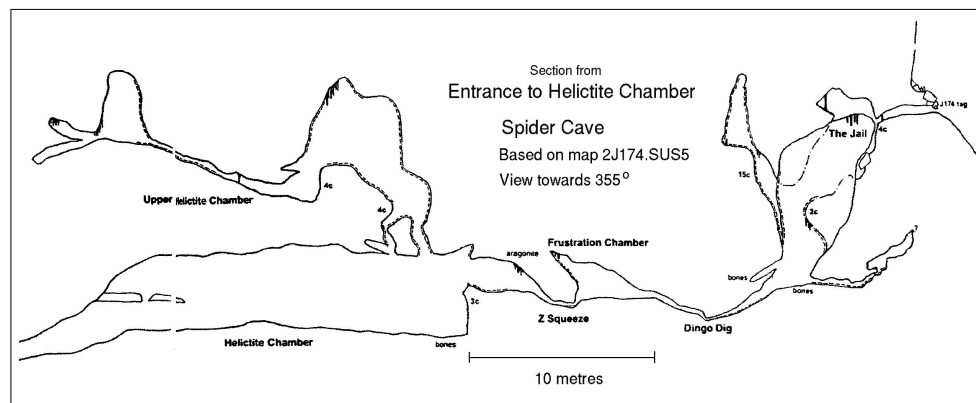


Figure 3.65: Section of part of Spider Cave, Jenolan. Based on map 2J174.SUS5 sheet 6 of 6 by P. Maynard and I. Cooper, 1998.



Flos ferri



Anthodites with straw stalactites



Anthodites



Beaded helictites

Figure 3.66: Anthodites and beaded helictites in Helictite Chamber, Spider Cave.

## **Show Caves**

### **Location and setting**

The show caves are located in the area bounded by Lucas Rocks to the south and the Spider Cave area to the north. The northern extent of the show caves is limited (for tourists) to Imperial and Jubilee Caves, however Spider Cave is hydrologically connected and shares many passage morphologies. Figures 3.2 and 3.5 show the location of the show caves with respect to the limestone. Figure 3.67 is an overall view of the show caves. The overall geological and geomorphological setting for the show caves was described in Section 3.2.

### **Cave Description**

The main features of the show caves are a series of large chambers, some with domed ceilings. The southern show caves are interconnected at various levels through rockpiles, phreatic tubes and paragenetic loops (e.g. Mons Meg). The northern show caves form a branching pattern and are mainly formed around three levels of north-south trending passages with rockpile interconnections. Large chambers in the northern show caves occur in the Chifley Cave and the Elder Cave. Both have large chambers and are higher in level compared to most of the Imperial or Jubilee Caves. The latter are mainly streamway-developed caves with occasional small domes such as Sydney Smith Chamber and Alabaster Chamber. Large chambers tend to be developed in an east-west arrangement and interconnecting passages tend to be aligned more north-south. All show caves have considerable amounts of calcite speleothems of various colours and shapes.

### **Sites and observations**

The show caves were not examined in as much detail during this study. Observations were made during three visits. Much of the work on aragonite in the Jenolan show caves has been done by Osborne, Pogson and Colchester, discussed earlier (Section 1.3). Aragonite has been confirmed from the following show caves: River Cave, Mud Tunnels and Ribbon Cave. Aragonite-like speleothems have been reported from Cerberus (Skeleton) Cave, Orient Cave, Barralong Cave, Lucas Cave (rockpile connection to River Cave), Temple of Baal and Jubilee Cave.

### **Orient Cave**

In the Persian Chamber, at “The Well” there are several unusual rod shaped helictites with saw edges and some possibly recrystallised speleothems. In the lower “Indian Chamber”, on the far side of a pool (across from the tourist path) is an outcrop of dolomitised rock which contains aragonite “stars” (Figure 3.69).

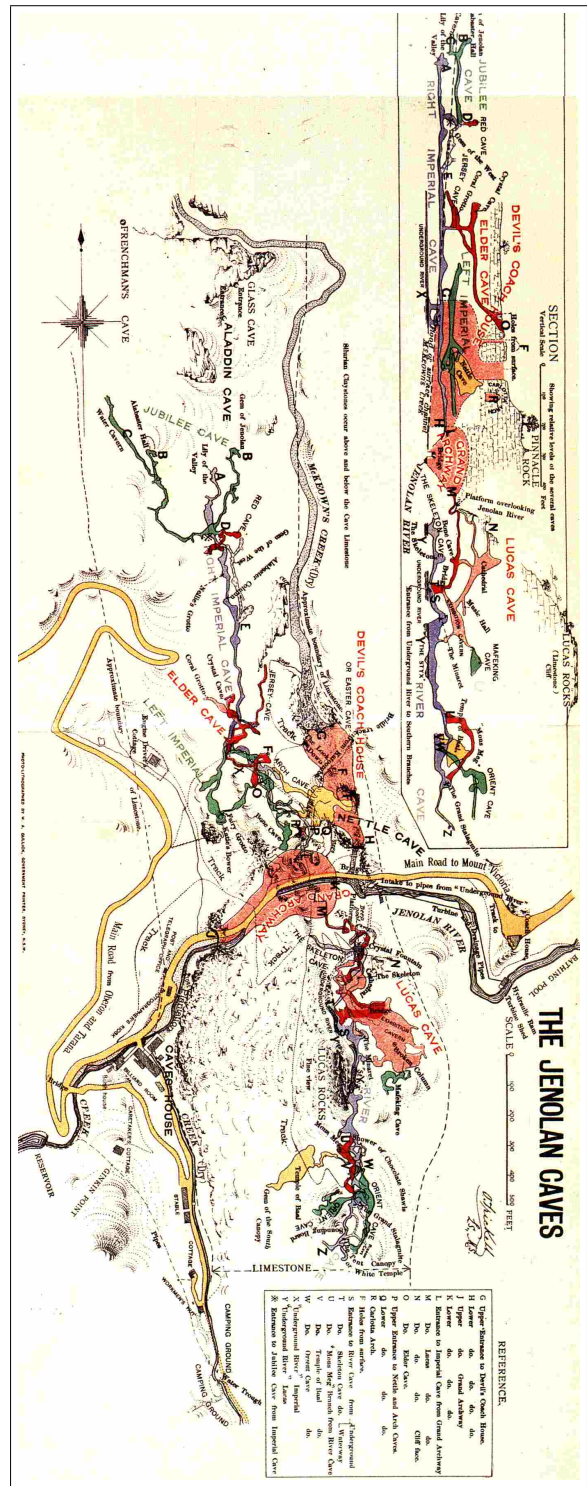
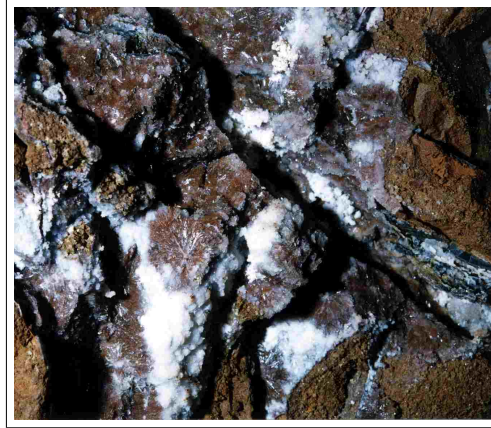


Figure 3.67: Plan and elevation of the Jenolan show caves. Map by Trickett (NSW Government) 1905; reproduced from Middleton (1991).



The Lyre Birds Nest.



Aragonite “stars” in cutting. Field of view is about 12 cm.

Figure 3.68: Aragonite in Ribbon Cave.

### Ribbon Cave

Ribbon Cave contains two main aragonite sites and some minor ones. One is a feature called the Lyre Birds Nest (Figure 3.68) which was discussed in Section 1.3. This contains a couple of long (0.5 m) rod-shaped helictites, floss ferri of various thicknesses and deposits of huntite and hydromagnesite (Osborne 1999, Osborne et al. 2002).

The other aragonite site is more cryptic; it is a mass of reddish dolomitised rock which has been partly cut through to form the path. This has exposed aragonite “stars” or spherulites (Figure 3.68). The red material is iron oxide (materials confirmed by XRD, D. Colchester, pers. comm.).

### River Cave, Mud Tunnels

In an alcove off the mud tunnels, there is a cluster of (broken) aragonite anthodites known as “Furze Bushes” (combination speleothem, comprising an aragonite column or heligmite with numerous branching aragonite helictites). The substrate of these speleothems was dolomitic palaeokarst (Osborne 1993a, Osborne 1994).

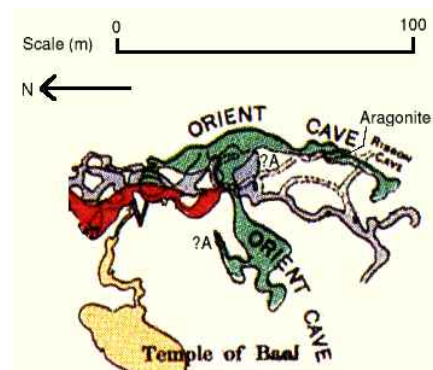
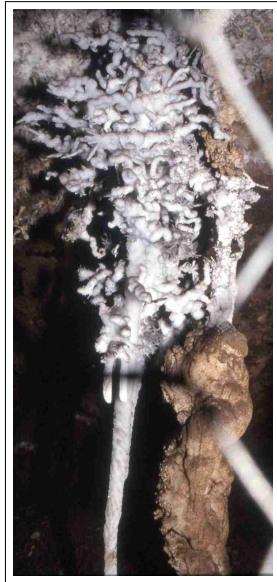


Figure 3.69: Southern show caves: Orient, Ribbon Cave (after Trickett 1905) and Mud Tunnels with location of aragonite and aragonite-like (“?A”) speleothems.



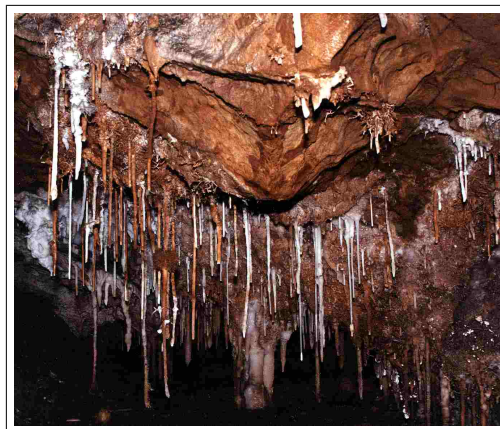
Flos ferri, ribbed stalactite, “knurled” stalagmite. Behind netting.



Flos ferri, ribbed stalactites, beaded helictites.



“Knurled” stalagmite, ribbed stalactite, beaded helictites. Speleothems on far right are probably calcite.



Spathites, anthodites and small brown balls of flos ferri.

Figure 3.70: Aragonite-like speleothems, Cerberus Cave. Top left and right: “The Arabesque”. Bottom: several aragonite-like speleothems on the south-western side of the chamber.

### Pool of Cerberus

The last chamber shown to tourists on the Pool of Cerberus tour has a number of speleothems which are most likely aragonite (Figure 3.70). The best known of these are the Arabesque and Furze Bushes. These are a combination of brown and white beaded helictites, floss ferri, branching speleothems (probably aragonite), and chevron-ribbed brown columns from which branches have developed. In the same area on the other side of the tourist path are some thickened brown and white straw stalactites about 1 m long. In the middle of one of these is a brown ball of floss ferri. Most likely the straw stalactites are a combination of aragonite, calcite and hydromagnesite. Fine helictites protrude from most parts of the straw stalactites. White material deposited at the ends of some of the helictites and stalactites is most likely hydromagnesite and huntite.

### Jubilee Cave

Jubilee Cave is part of the Northern show caves (Figure 3.71) and contains “ribbon helictites” (Rowling 1998a) which resemble aragonite yet are made of calcite with some iron content (determined by Phil Maynard using Raman spectroscopy and EDAX). The active tip of the speleothem was depositing needle-form calcite (“lublinite”). An SEM image shows the surface of one of these speleothems has textures similar to that of aragonite, but with indistinct terminations characteristic of paramorphs of calcite after aragonite

(Figures 3.72, 3.73, 3.74). Diagonal striations on the needles’ sides are consistent with needle form calcite. Etched pits in the surface of the speleothem may be partially aragonite. Rowling (1998a) noted that the substrate for ribbon helictites in Jubilee Cave is cemented gravel and suggested the gravel was reacting with the bedrock. It is also possible that the bedrock is slowly releasing calcite-inhibitors which then permeate the gravel. The humidity in the area is consistently high with little air movement. Ribbon helictites may be a borderline case, where there may be just enough calcite-inhibitors to allow aragonite to form, but insufficient to keep it in that polymorph. In the same area of the cave there are wing-shaped speleothems, reminiscent of aragonite. Many speleothems in Jubilee Cave have a prickly coating. Jubilee cave is also said to have native sulfur near the Water Cavern junction; this appears to have an organic (bacterial) origin and is associated with a blue black mineral, possibly pyrolusite.

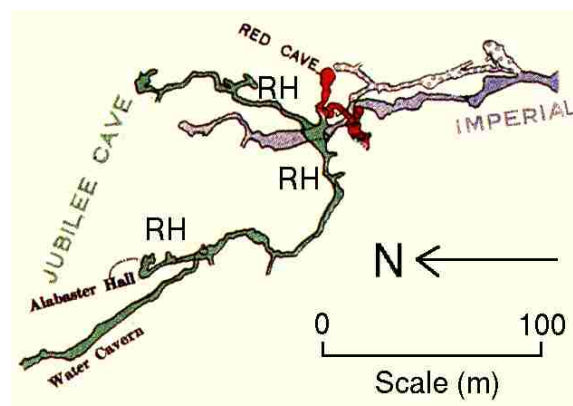


Figure 3.71: Map of Jubilee Cave (after Trickett 1905): RH = ribbon helictites and other aragonite-like speleothems.



Figure 3.72: Jubilee Cave. Ribbon helictites, spiky surfaces and a winged form.

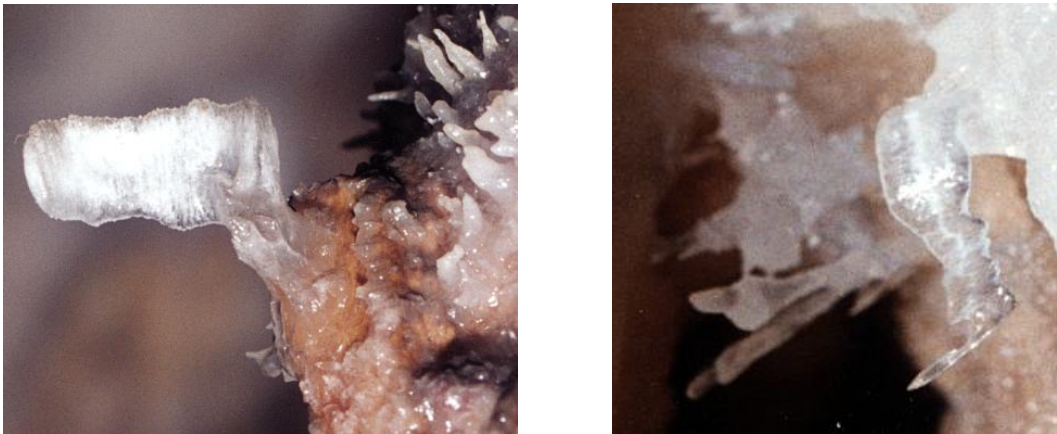
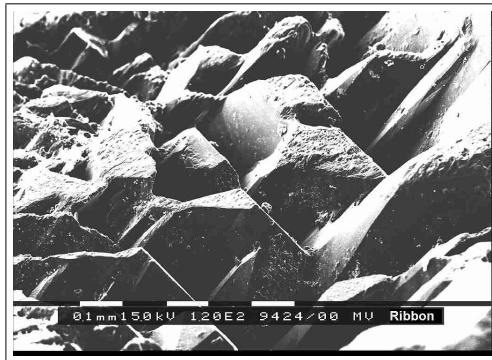
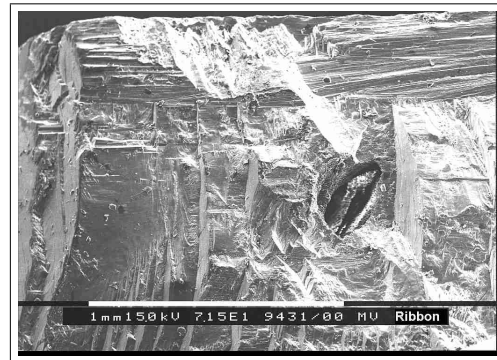


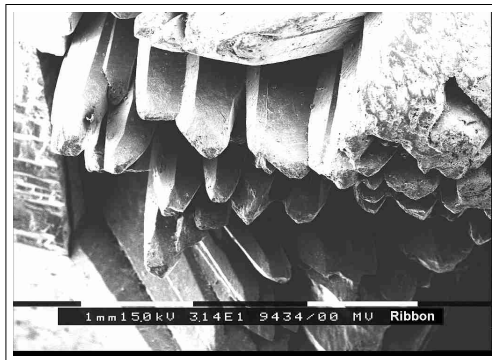
Figure 3.73: Jubilee Cave. Ribbon helictites and spiky surfaces.



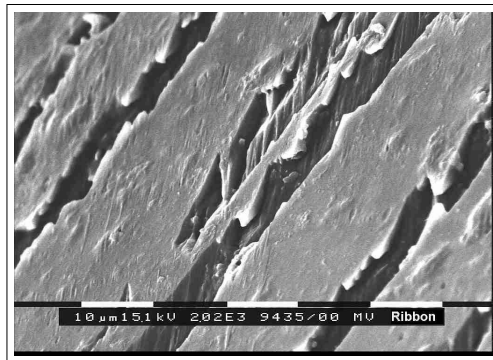
Etched pits and crystal blades similar to aragonite terminations.



Fractured helictite (central canal visible) exhibits both aragonite-like and calcite-like cleavages.



Needle crystals have pitted and corroded terminations. The morphology is like aragonite but the crystals do not flare out like aragonite.



Surface texture of needle crystals have diagonal pits.

Figure 3.74: Ribbon helictite surface textures.

### **Synthesis - Show Caves**

Most occurrences of actual and suspected aragonite in the show caves are associated with dolomitic (or apparently dolomitic) substrates. Some speleothems exhibit aragonite-like appearances and may be paramorphs of calcite after aragonite. Examples include the ribbon helictites and winged forms in Jubilee Cave. This indicates that the calcite-inhibitors are not always present, or are present in insufficient quantities to prevent inversion from aragonite to calcite. In some areas (e.g. Orient Cave), this may be due to the speleothem being engulfed by the large amount of calcite being deposited nearby.

### **Synthesis - Aragonite at Jenolan Caves**

Substrates to aragonite at Jenolan Caves appear to be dolomitic areas and/or ochres. Chemical associations with aragonite at Jenolan appear to be magnesium, manganese, sulfate and possibly phosphate. There are three main factors which may influence the deposition of aragonite at Jenolan Caves:

- Inorganic processes involving the release of magnesium, manganese and sulfate ions from substrates containing ferroan dolomite. the most likely factor responsible for the release of these minerals is the oxidation of pyrite, which releases sulfuric acid in the dolomitised rock. After oxidation, the previously dolomitic substrates are usually re-lithified as an ochre or ironstone. Typical aragonite mineral associations include hydromagnesite, huntite, todorokite and gypsum, with dolomite and rhodochrosite present in one site (Contact Cave). Aragonite speleothems associated with these processes are typically large stalactitic forms such as anthodites, spathites, vein fills, “stars” (spherulites) and precipitates which force the rock apart from crystal wedging. The form taken depends on the amount of water available, whether it is dripping or seepage only. Helictite forms tend to dominate where the water is seeping only.
- Inorganic processes related to lowered humidity and / or air movement which serve to concentrate calcite-inhibitor minerals such as gypsum and huntite. In such cases, both aragonite and calcite can occur. Aragonite speleothems in such cases are typically small cryptic coatings and small, imperfect helictite / anthodite forms.
- Partially organic processes involving minerals in bat guano. Typical mineral associations include aragonite with gypsum, phosphates and manganese-rich minerals. In the cases examined, the bat guano was not fresh (fresh guano is corrosive) but had been allowed to decompose and neutralise with the cave environment. Aragonite speleothems include small stars and cryptic coatings. Bat guano mineral assemblages are discussed in Hill & Forti (1997).