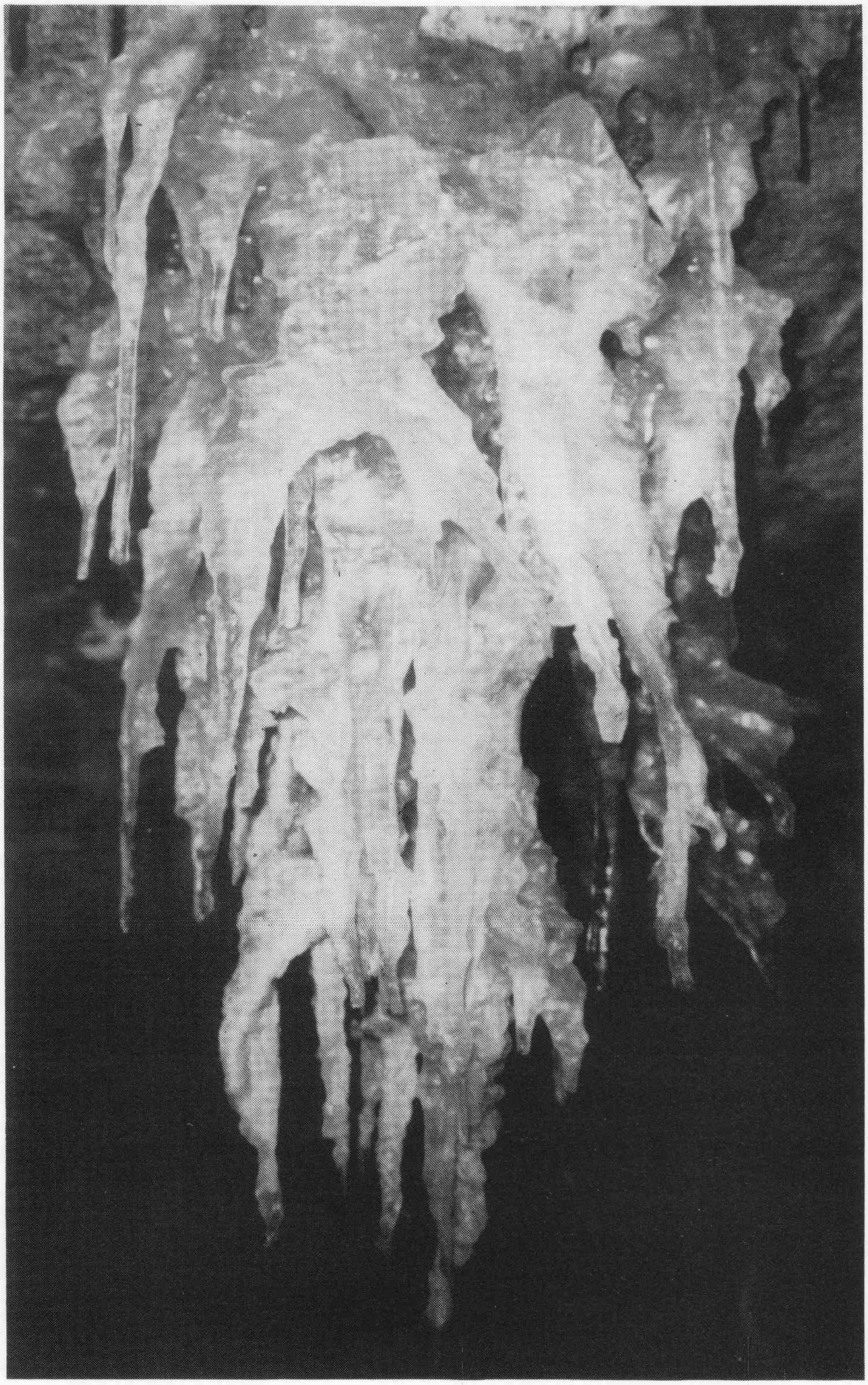
VOLUME 29(1) 1991

Helictite

JOURNAL OF AUSTRALASIAN CAVE RESEARCH



Julia M. James **Gypsum Stalactites**

HELICTITE

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Cover: Massive gypsum stalactites in Thampanna Cave, Nullarbor Plain, Western Australia

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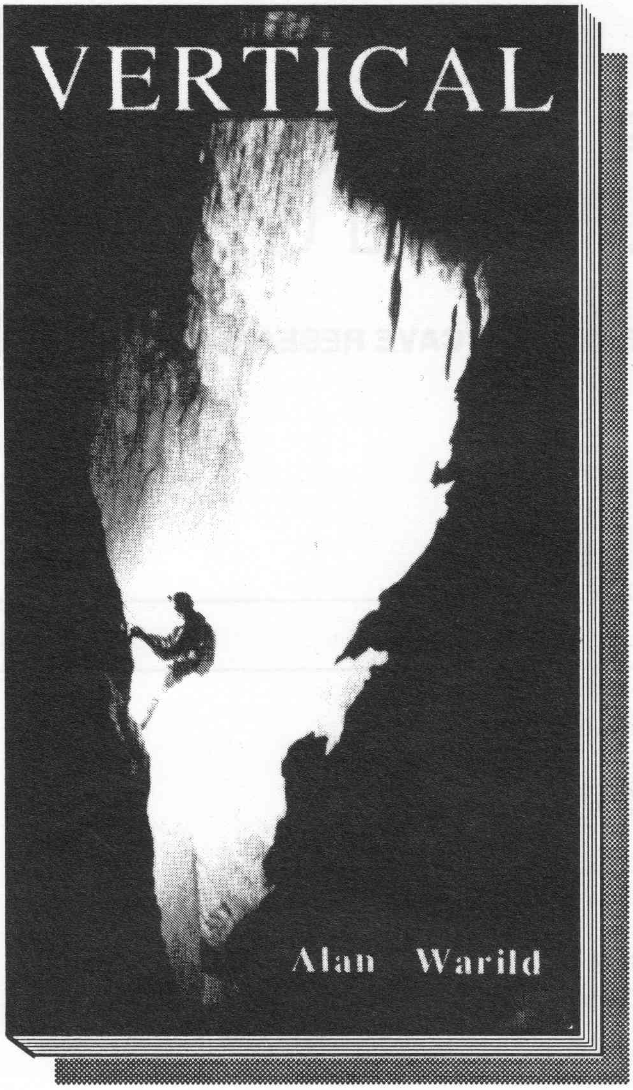

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"MT CRIPPS" Helictite 29 (1) : 3 1991

THE MOUNT CRIPPS KARST NORTH WESTERN TASMANIA

Henry Shannon, Bevis Dutton, David Heap and Frank Salt

ABSTRACT

The Mt. Cripps karst is currently being explored systematically by cavers for the first time. The karst is characterised by large scale closed depressions and a high density of caves with limited surface drainage. The evolution of this karst in an area that was subject to multiple Pleistocene glaciations and the presence of well-developed polygonal karst terrain is of particular note. The area is one of very few south eastern Australian Palaeozoic limestone karsts with its original forest cover still intact.

INTRODUCTION

The area referred to as the Mt. Cripps karst is situated to the north of Lake Mackintosh in the north west of Tasmania (Figure 1). Detailed exploration to date has centred on an area a little over 4 km^2 and has yielded approximately 76 caves of various types. The total area of limestone in this region is approximately 20 km^2, (estimated from Mt. Read Volcanics survey conducted by the Tasmanian Department of Mines). The probability of further finds in the area is very high.

Since Tasmania is positioned on the northern edge of the Roaring Forties and the terrain is mountainous, the Mt. Cripps area experiences a wet cool temperature climate. The Hellyer Mine to the west of Mt. Cripps has an annual average rainfall of 2050 mm. The southern boundary of the karst is covered by Lake Mackintosh, an impoundment formed when the Hydro Electric Commission flooded the Mackintosh and Sophia river valleys. The maximum supply level of Lake Mackintosh is 229.5 m above sea level. The highest point of the limestone is about 500 m.

The forest on the limestone is spectacular with large eucalypts emerging from the rainforest canopy, and an open

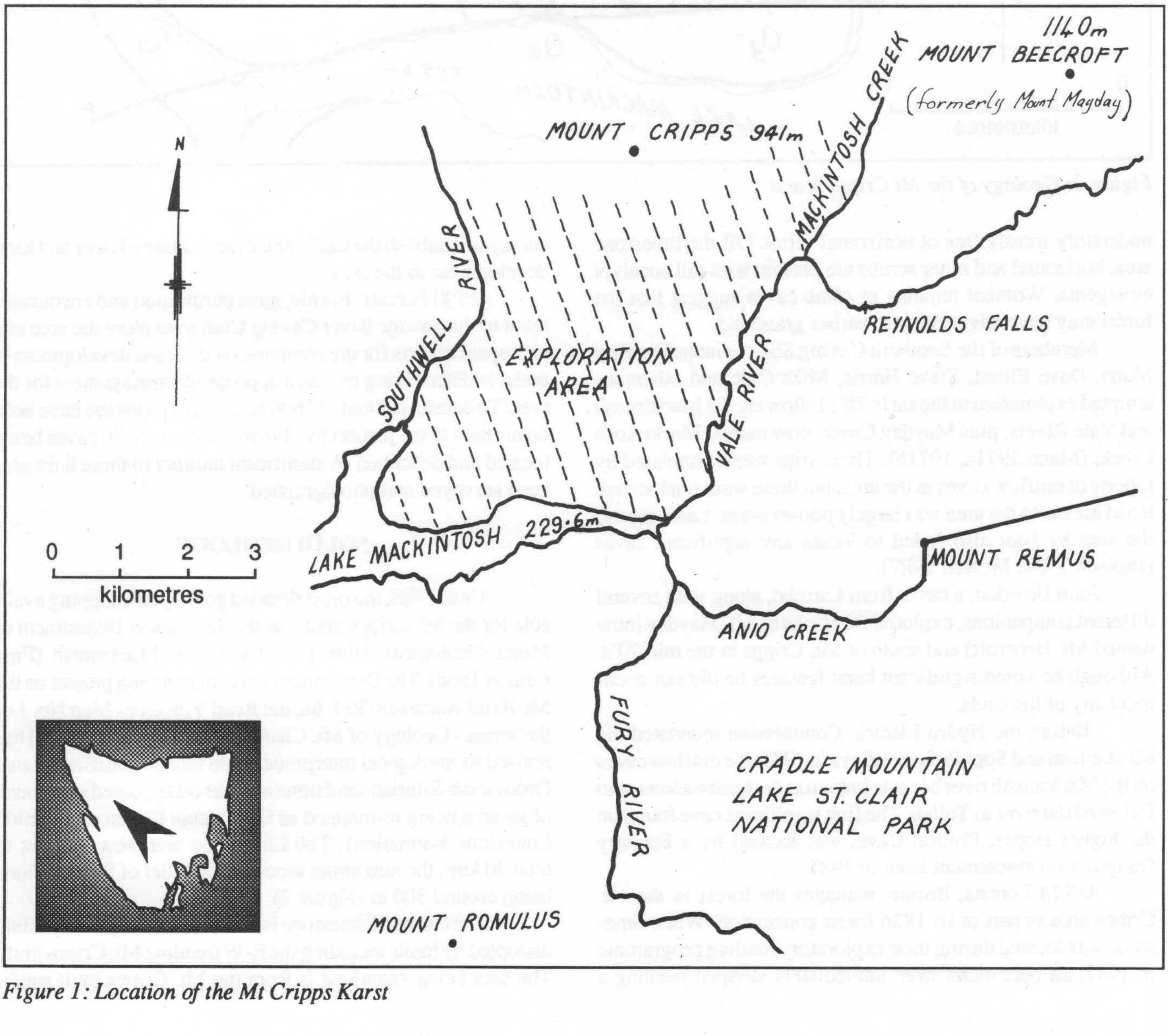

Figure 1: Location of the Mt Cripps Karst

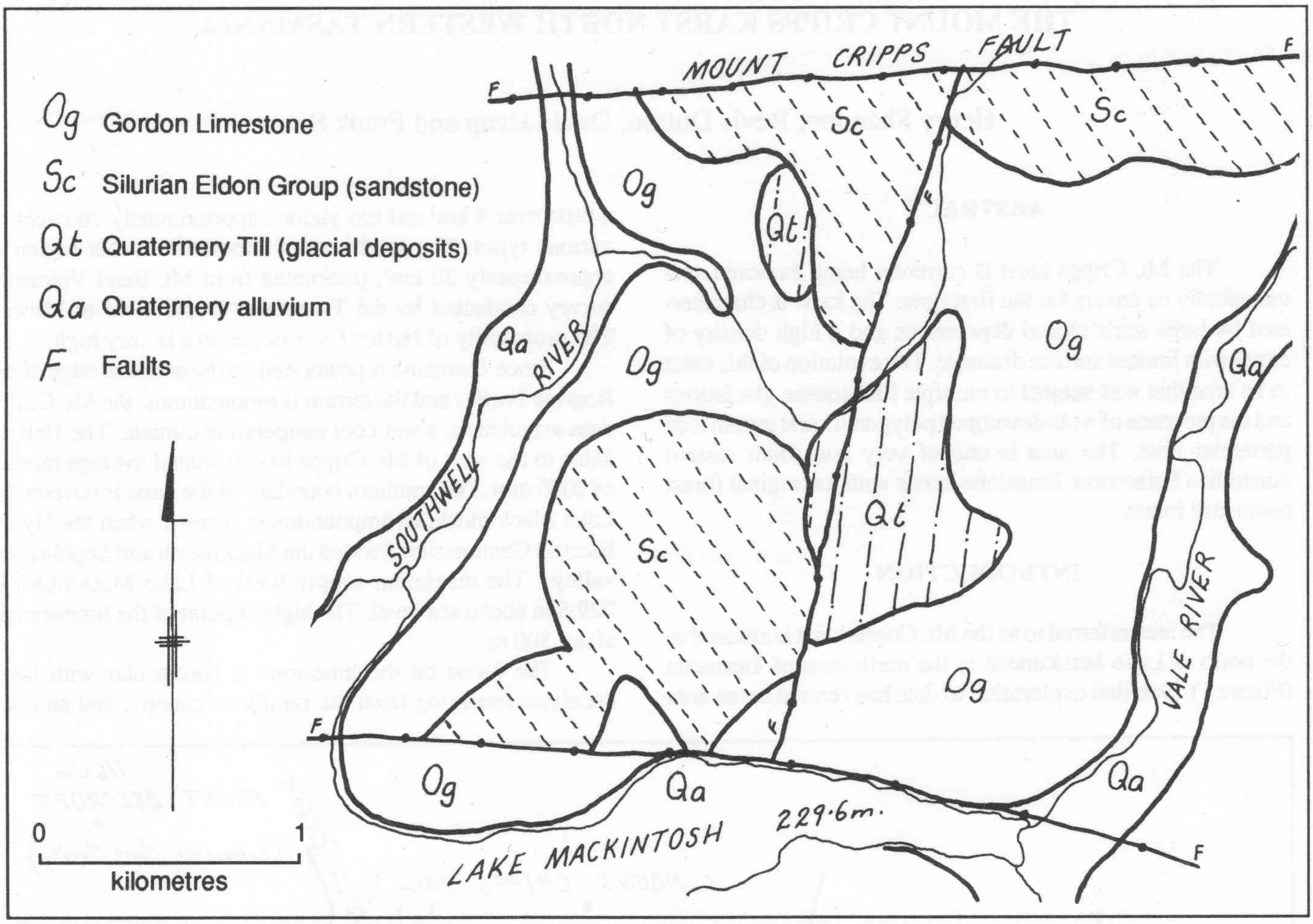

Figure 2: Geology of the Mt Cripps Karst

understory mostly free of horizontal scrub. Off the limestone area, horizontal and other scrubs are present with tall eucalypt emergents. Wombat remains in some caves suggest that the forest may have advanced into earlier grassland.

Members of the Southern Caving Society including Ron Mann, Dave Elliott, Steve Harris, Mike Cole and others attempted exploration in the early 70's following the Mackintosh and Vale Rivers, plus Mayday Creek, now named Mackintosh Creek. (Mann 1971a, 1971b). These trips were stimulated by reports of outflow caves in the area, but these were not located. Road access to the area was largely non-existent. Later trips to the area by boat also failed to locate any significant caves (Jackson 1984; McNeil 1987).

John Bowden, a caver from Latrobe, along with several different companions, explored the flanks of Mt. Mayday (now named Mt. Beecroft) and south of Mt. Cripps in the mid 70's. Although he noted significant karst features he did not document any of his finds.

Before the Hydro Electric Commission inundated the Mackintosh and Sophia river valleys in 1981, the outflow caves on the Mackintosh river became known to the bushwalkers who followed the river to Tullah. The first significant cave found on the higher slopes, Philrod Cave, was located by a Forestry Commission assessment team in 1987.

APPM Forests, Burnie, manages the forest in the Mt. Cripps area as part of its 1926 forest concession. When limestone was located during their exploratory roading programme in 1987, all operations were immediately stopped pending a survey to establish the likely extent and nature of cave and karst development in the area.

APPM Forests, Burnie, gave permission and encouragement to the Savage River Caving Club to explore the area and to prepare reports for the company on the karst development to assist in determining the most appropriate management for the area. To date an estimated 1600 hours of exploration have been committed to the project by club members with 76 caves being located and described. A significant number of these have also been surveyed and photographed.

SOLID GEOLOGY

Until 1988, the most detailed geological mapping available for the Mt. Cripps area was the Tasmanian Department of Mines Geological Atlas 1:63 360 Series Mackintosh (First Edition 1966). The Department's recent mapping project on the Mt. Read volcanics (Ref. Mount Read Volcanics Map No. 1 of the series - Geology of Mt. Charter/Hellyer area 1:25,000) has revised its geological interpretation so that an undifferentiated Ordovician-Silurian sandstone unit has disappeared with much of its area being re-mapped as Ordovician limestone (Gordon Limestone Formation). The Limestone area now appears to total 20 km^2, the maximum topographic relief of the limestone being around 300 m (Figure 2).

The Gordon Limestone is contained locally in a syncline disrupted by faults including the E-W trending Mt. Cripps fault. The area being examined is from the Mt. Cripps fault south-

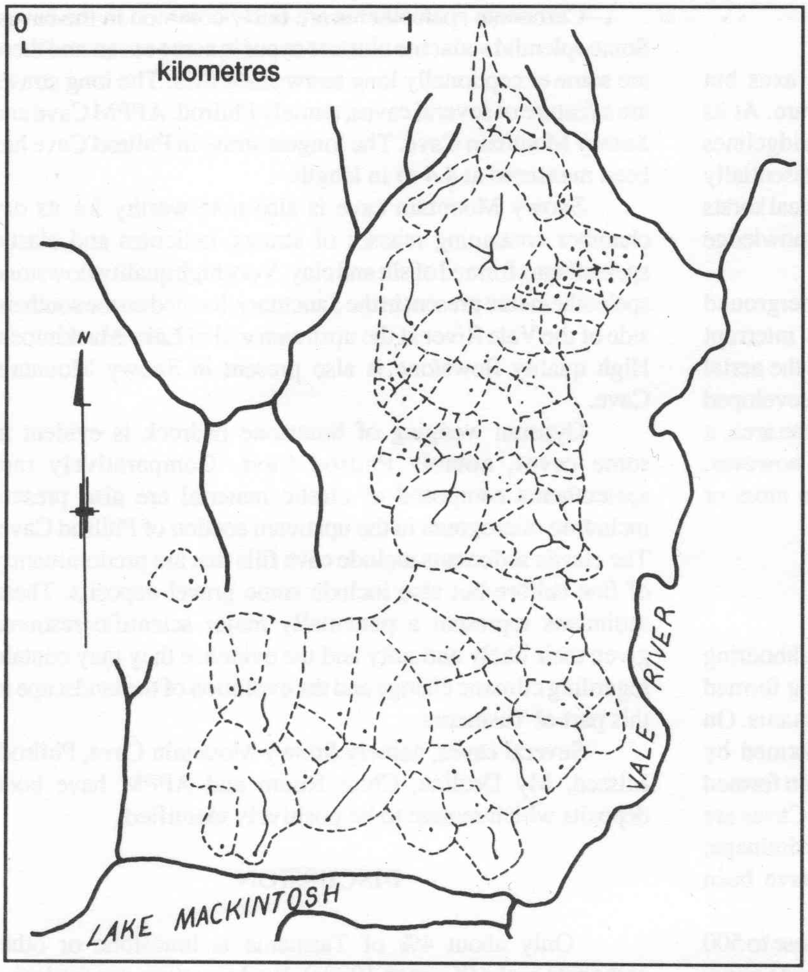

Figure 3: Drainage divides in the Polygon karst

wards to Lake Mackintosh. In this area the new official map (Ref. Mount Read Volcanics Map No. 1 of the series - Geology of Mt. Charter/Hellyer area 1:25,000) recognises Eldon Group sandstones overlying limestone but some of this material has proven to be quartzite gravel and may be thick glacigenic sediment of Pleistocene age.

South of Lake Mackintosh the Crotty Quartzite and higher units of the Eldon Group make up a large syncline core. Most of the limestone area to the west was bevelled off under the Sophia River button grass plain which is now submerged beneath the Mackintosh impoundment. Part of the eastern limb is still accessible at White Hawk Creek and upstream along the Mackintosh and Vale river valleys to Fury Flats, with interruptions to the outcrop because of talus, till or basalt cover. Upstream of Fury Flats the limestone on the eastern limb can be followed to the head of Mackintosh Creek (formerly Mayday Creek) where it goes below basalt cover. The western limestone belt follows the Southwell River to the Mt. Cripps fault. Limestone may also exist to the east of Mt. Cripps. Further limestone occurs in the Vale of Belvoir 18 km to the north east of the Mackintosh-Southwell confluence, but this latter outcrop is in a different syncline and is not discussed in this paper.

SUPERFICIAL DEPOSITS

Surface exposure of the limestone is generally limited due to the presence of soil cover. The limestone is bare on some steep slopes and hill crests and it is also exposed in dolines and creek banks. Most of the limestone observed contains mudbands spaced a few centimetres apart that are a common feature of the Gordon Limestone.

At a logging road intersection on the Western slope of Mt. Cripps (grid reference 965945 Charter 1:25,000) superficial gravel cover with erratics over bedrock and older gravels is exposed. The bedrock is Crotty Quartzite which provided the bulk of the clasts in the gravels.

The top unit is a widespread cover of breccia with an earthy matrix. Clasts are up to boulder size and where the cobbles from the older gravel are included they are normally fragmented.

In contrast to the loose earthy matrix of the top unit, these older gravels have a compact weathered matrix and includes diamicton that may be a till or a mass movement deposit like the top unit.

The cobbles in the older gravels include sandstone clasts which are more blocky, smooth and well rounded, than the cobbles in present day creeks.

It is thought that this gravel was deposited in a torrent running alongside a glacier. Rudimentary bedding, inbrication and cross bedding are exposed in a section at (grid reference 965945 Charter 1:25,000).

A major outlet glacier extended down the Pieman River Valley (Augustinus and Colhoun 1986) but detailed patterns of ice movement in the upper reaches of this glacier system have not yet been determined. Glacial sediments are widespread in the general area and extend into the karst area. Unequivocal erratics, most notably granite, have been observed underground as well as on the surface.

Several granite erratics occur at 550 m altitude on the SW slopes of Mt. Cripps (grid reference 965945 on the Tasmania 1:25,000 Series Charter sheet Edition 1 1986) the largest being a car-sized boulder that has broken into two. An isolated granite boulder occurs in Chamber Pot Cave and there are several in Quasitomo Cave. Other rock types found as erratics in Quasitomo Cave include sandstone of non-Crotty aspect, quartzite, schist and vein quartz. The source of the dolerite erratics is from Barn Bluff or Cradle Mountain while the granite is from Granite Tor well south and on the opposite side of the Macintosh valley. This implies the extension of a distributary lobe of the Macintosh Glacier up the Southwell Valley.

The characteristic sandstone cobbles give clues to the extent of the gravel cover in areas without outcrops since they may be observed in pluck holes where trees have fallen over. The gravel is most prominent in the areas where horizontal scrub or bauera grows on ground which should be underlain by limestone bedrock. This association between the vegetation and the Quaternary sediments facilitates appraisal of the likely distribution of the gravel.

Residual soil derived from weathering of the limestone consists of yellowish-orange silty-clay studded with rare relicts of limestone up to boulder size. This soil is prone to severe erosion, as shown by the exposure of rounded solution runnels that probably originated beneath a soil cover. Another geomorphic hazard is posed by clay-rich sinkhole fills that may pose some landslip hazard for road construction.

SURFACE KARST

Chains of dolines extend along the valley axes but streamsinks that engulf large permanent creeks are rare. At its most extreme the surface karst comprises a net of ridgelines above large complex karst depressions. The form is essentially polygonal karst similar to that described from the tropical karsts of New Guinea (Williams 1985) but not to our knowledge mapped in Australia until now (Figure 3).

The less extreme surface karst has full underground drainage diversion through abundant dolines that interrupt gully lines. The big depressions show up clearly on the aerial photographs. On one of the exploration tracks well developed rundkarren are apparent. Despite the dense forest in the area, it is possible that some former soil cover has been lost, however, some rounded karren forms may develop beneath a moss or lichen cover.

CAVES

The lack of drainage concentration from neighbouring impermeable rocks prevents large stream caves being formed such as are common in the other major karsts in Tasmania. On the other hand the area is rich in cave systems formed by autogenic percolation. Some caves may also have been formed by meltwater when glaciers filled the major valleys. Caves are not exclusively accounted for by the modern sinkhole drainage; older and often larger sections of cave passage have been accidentally cut by the modern surface valleys.

At present the largest cave systems found are close to 500 m in length. These include Philrod Cave, Stettle Pot, and Snowy Mountain Cave. Of the remainder, the largest are Chamber Pot at 100 m and Quasitomo Cave at 125 m in length. The remaining caves of any significant length average between 30 to 40 m. This group includes Missed Cave, Protocol Cave, APPM Cave and the Choir Room.

Significant vertical development is present in several of the systems. Stettle Pot, the deepest at approximately 80 m deep, contains the longest single shaft at 25 m. Missed Cave is 40 m deep with a pitch of 20 m, Chamber Pot and Snowy Mountain Cave are in the order of 35 m deep.

The first caves were found more or less accidentally. Several of these are not in obvious dolines and appear unrelated to the drainage patterns suggested by the surface topography. Examples include Choir Room, My Decline, Narrow Scrape and APPM Cave. The last named does have a streamsink of sorts but has upper level passages that do not seem related to streamways. The largest caves found later in the polygon karst also show features indicating that modern streams are more or less accidentally occupying older passage; for example in some places passages end suddenly at a cliff face of fill. Paragenetic passage enlargement above cave fill is common in caves such as Quasitomo. The initial crawlway of Snowy Mountain Cave is wide with a level flat ceiling indicating a water table stream but indicating a larger flow than could be provided from the present catchment. Given the history of glaciation in the area it is possible that glacial meltwater produced some of these old series passages. However, the erratics in the caves are not really in locations that demand primary transport by meltwater. For those with more experience in glaciated karst the evidence may already be sufficient.

Carbonate speleothems are fairly common in the caves. Some splendid stalactite clusters occur in some caves and there are some exceptionally long straw stalactites. The long straws are a feature of several caves, namely Philrod, APPM Cave and Snowy Mountain Cave. The longest straw in Philrod Cave has been measured at 4.4 m in length.

Snowy Mountain cave is also note-worthy for its dry chamber containing masses of straws, helictites and clastic speleothems formed of silt and clay. Very high quality flowstone speleothems are present in the Sanctuary, located on the southern side of the Vale River at the upstream end of Lake Mackintosh. High quality flowstone is also present in Snowy Mountain Cave.

Gypsum wedging of limestone bedrock is evident in some caves, notably Philrod Cave. Comparatively rare speleothems composed of clastic material are also present including microgours in the upstream section of Philrod Cave. The clastic sediments include cave fills that are predominantly of fine calibre but also include some gravel deposits. These sediments represent a potentially major scientific resource given their likely antiquity and the evidence they may contain regarding climatic change and the evolution of the landscape in this part of Tasmania.

Several caves, namely Snowy Mountain Cave, Philrod, Missed, My Decline, Choir Room and APPM have bone deposits which remain to be positively identified.

DISCUSSION

Only about 4% of Tasmania is limestone or other carbonate rocks (Kiernan 1989a). By Australian standards that is quite a lot, but the world average is perhaps three times that figure. The relatively limited extent of karst in Australia enhances the importance of the resource that is present

The Mt. Cripps area is particularly significant since it is the only large east Australian Palaeozoic limestone karst with its natural forest cover (in this case Eucalyptus/Nothofagus forest) intact over the whole karst area.

From a scientific viewpoint, this glaciated karst area has the potential to be of major interest. From a geomorphological perspective, the interaction between glacial and karst processes, the form and evolution of the polygon karst, and the palaeoenvironmental information that may be contained in the cave sediments are potentially of very great interest. Some aspects of this karst including the multiglacial context in which it has evolved, may be without parallel in Australia. Up to six glaciations may have affected western Tasmania (Kiernan 1989b). Other aspects may be of considerable interest including the unstudied cave biology, mineralogy and subfossil bone deposits.

Future management of the surface environment is presently being addressed by APPM Forests, Burnie. However, management of the subsurface environment also requires consideration. Track marking and care is required if notable areas of speleothems, including clastic speleothems are to survive traffic by cavers. The guiding principle that has been adopted in route delineation is that no more disturbance should be contemplated than a tourist track would produce. Some lessons have been learnt from earlier efforts at people-proofing sensitive parts of other caves such as Kubla Khan Cave at Mole Creek. The route over the flowstone in Snowy Mountain Cave was marked on the first trip after discovery, but more mud-proofing of boot and clothes changing areas will be necessary. Sand bag routes are to be installed as well as conventions for going no further (e.g. signs). However, while it is essential that track marking be undertaken to centralise damage the advent of a defined route should not be viewed as permission to cause unnecessary damage within the defined area. Rather, the same standards of extreme care, including the removal of boots and dirty clothing are imperative whether or not tracks have been marked. These measures are essential since the caves at Mt. Cripps will inevitably become more popular in due course.

ACKNOWLEDGEMENTS

The attitude adopted by APPM Forests, Burnie, to the karst in its forest concession represents a real breath of fresh air. Their encouragement of our activities as an aid to forest planning stands in stark contrast to the attitude adopted by at least one other forest manager in Tasmania.

In these times of often acrimonious debate on conservation and forest issues, it is reassuring to be working with a company that is obviously, genuinely committed to implementing a forest management philosophy that is pragmatic but which strives to meet the often conflicting demands and aspirations of the various interest groups.

The authors and the Savage River Caving Club members wish to thank Dr. Kevin Kiernan of the Forest Practices Unit of the Tasmanian Forestry Commission and the management of APPM Forests, Burnie, for their assistance with this project. In particular, the help given by Mr. Andy Warner, the Forest Management Superintendent, has been deeply appreciated.

Address for correspondence:
P.O. Box 806, Burnie 7320 AUSTRALIA.

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"ABERCROMBIE" Helictite 29 (1) : 8 1991

A GEOLOGICAL REVIEW OF ABERCROMBIE CAVES

R.A.L. Osborne

ABSTRACT

Abercrombie Caves have developed in a regionally metamorphosed marble forming part of the Upper Silurian Kildrummie Formation. The limestone precursor of the marble was probably deposited as a shoal or bank deposit and is not an ancient coral reef. Geological structure and changes in lithology have strongly influenced cave development with pyritic thinly bedded units in the marble being preferentially eroded. The topographic relationships of a dated basalt flow suggest that the Abercrombie Arch originated as a through cave in Pliocene times, between 4 and 5 million years ago.

INTRODUCTION

This paper reviews the bedrock and cave geology of the Abercrombie Caves Reserve. It is based on a report produced as part of the information gathering process for the Reserve's Plan of Management. Information presented here is based on an extensive literature survey, limited field work and micropetrographic study. Although information on the bedrock geology is somewhat derivative, geological observations in the caves are original and the interpretation presented are those of the author.

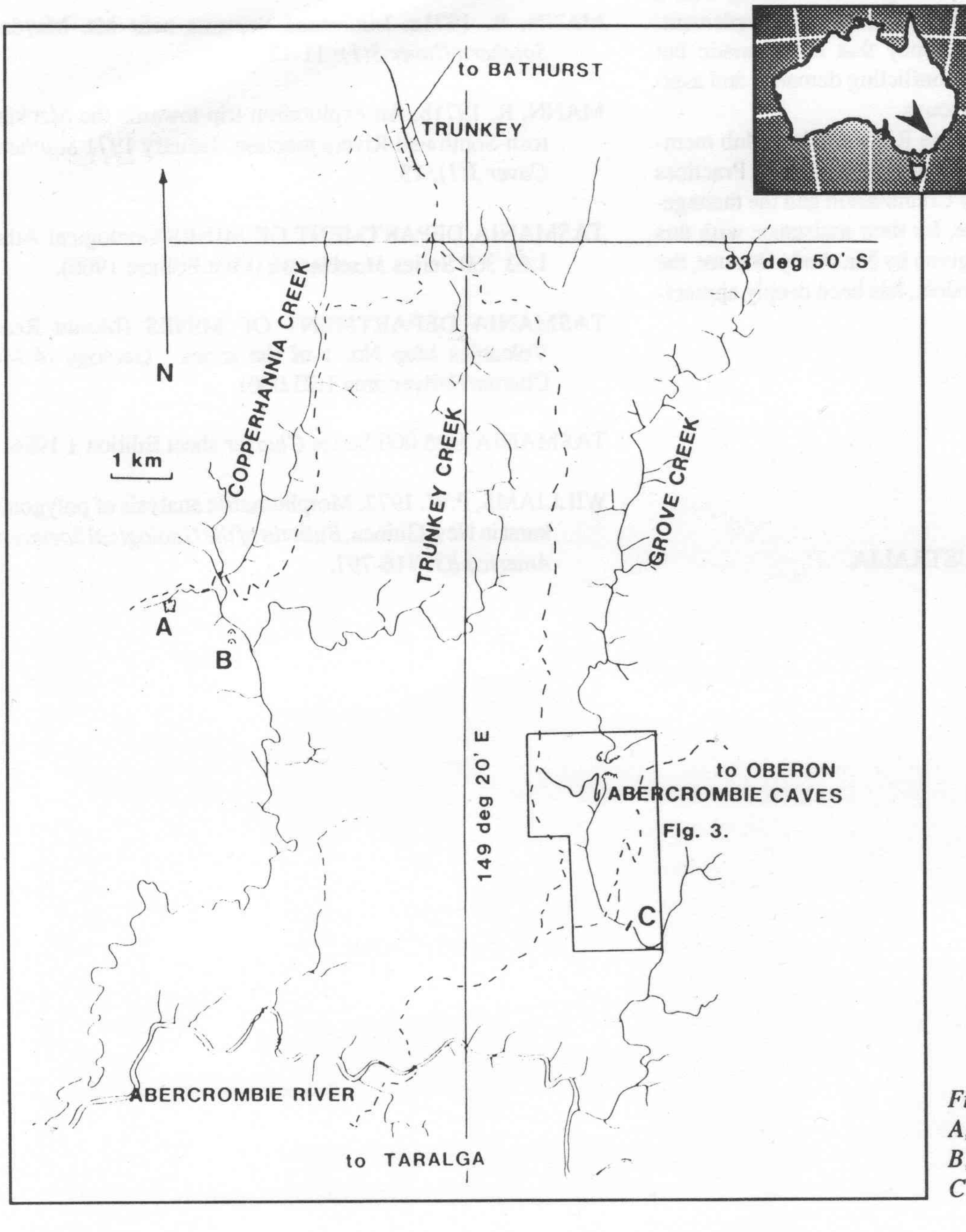

Figure 1: Location:
A, marble quarry;
B, caves at Copperhannia Creek,
C, Grove Creek Falls.

Location

The Abercrombie Caves Reserve (Figure 1), part of the consolidated Jenolan Caves Reserve, is located 10 km south of Trunkey in the western margin of the central highlands plateau of New South Wales. The Abercrombie Caves Reserve encloses a small impounded karst, developed on marble, whose main feature is The Great Arch a through cave some 180 m long which captures Grove Creek.

Another small karst area, containing a few small caves, has developed on similar marble in the valley of Copperhannia Creek, 6 km north west of Abercrombie Caves.

Geological and Geomorphological Setting

The Abercrombie Caves are developed in a regionally metamorphosed limestone unit correlated with the Upper Silurian Kildrummie Formation (De Dekker, 1976). Structurally the area forms part of the Hill End Synclinorial Zone of Scheibner (1976). The Kildrummie Formation (Figure 2) overlies Silurian and Ordovician volcanics.

The region surrounding Abercrombie Caves has been intensely folded. Syntectonic granites were emplaced during the Devonian and post-tectonic granites, related to the large Bathurst Granite, were emplaced during the Carboniferous Period.

Volcanism during the Tertiary produced extensive basalt flows covering a landscape with relatively low relief. Remnants of these basalt flows now occur on many of the higher parts of the landscape.

Uplift in Latest Cretaceous to Early Tertiary times was followed by downcutting, producing an incised plateau landscape. Abercrombie Caves lie in some of the most deeply incised country, where headward erosion of the Abercrombie River and its tributaries have cut deeply into the western margin of the highlands plateau (the "western incised zone" of Osborne and Branagan, 1988).

The Abercrombie Caves are located in the middle tract of Grove Creek. Incision in the middle and upper tracts of Grove Creek has been retarded relative to that of other streams in the area by the presence of a resistant bed of felsic volcanics which have resulted in the development of Grove Creek Falls. Landscape features in this area, including the caves, are therefore older than those in similar parts of adjoining streams.

PREVIOUS WORK

The first scientific description of the Abercrombie Caves and their geology was given by C.S. Wilkinson (Wilkinson, 1878,1879) who visited the caves in 1877 as part of his duties as Government Geologist. His report was quoted by later workers (Trickett, 1906 & Carne & Jones, 1919).

Stonier (1892) described the economic geology of the area, in particular the Mt Gray Mine, while Baker (1915) listed Abercrombie Caves as a locality for marble of "excellent quality".

Carne & Jones (1919) described the limestone outcrop, noting that the rock was intensely folded, had a variable grainsize, and contained chloritic and talcose partings. They provided a chemical analysis (Table 1) and noted that Abercrombie Caves was one of the few localities in New South Wales where *"careful search may possibly locate a good white marble of fine even texture, comparable with the imported Italian marbles"*.

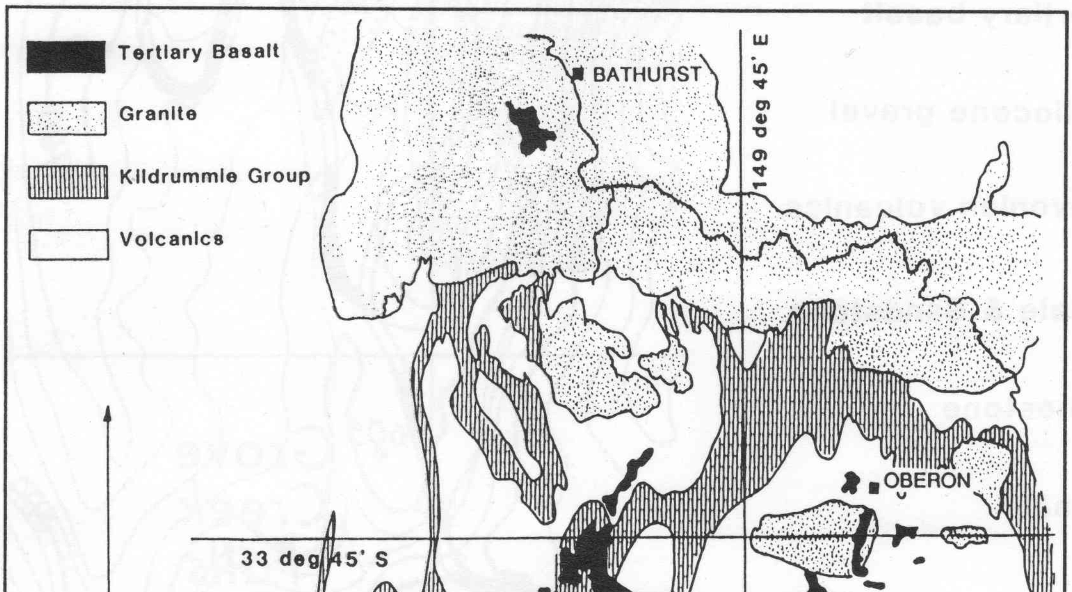

Figure 2: Regional Geology after Packham (1966).

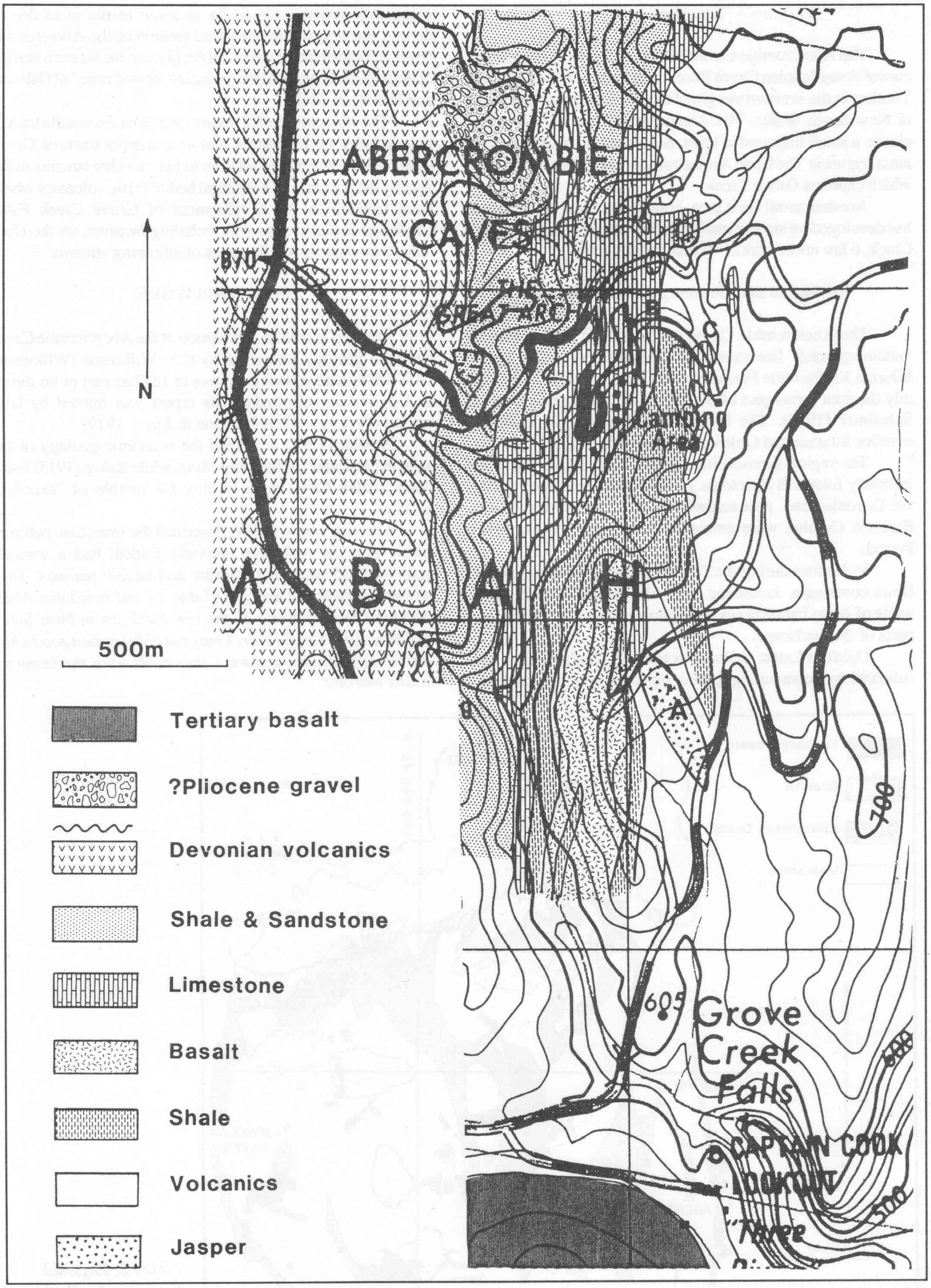

Figure 3: Geology of the Abercrombie Caves Reserve. Based on Morrisey and Green n.d. Field revision by the author 1990.

Chin (1972) provided the first detailed geological map and modern interpretation of the geology.

Abercrombie Caves was one of the areas examined by R.M. Frank between 1966 and 1972 as part of his PhD studies of cave sediments. Frank mapped and described the caves in detail. He proposed a chronology for the development of the Arch based on geomorphic evidence and radiocarbon dating of sediments. The results of this study were published later in association with J.N. Jennings (Frank & Jennings, 1978).

During the late 1970's and early 80's the area was subjected to intensive exploration for base metal deposits. Initial exploration by Jododex included geochemical sampling and resulted in a detailed geological map (Morrissey & Green, n.d.). Further exploratory work was carried out by Teck Explorations (Green, 1983) but failed to find any near-surface deposits of significant size.

Lishmund *et al.*, 1986 presented revised data of Carne and Jones (1919), including a tectonic interpretation of the limestone occurrence based on the work of Scheibner (1976).

BEDROCK GEOLOGY

Stratigraphy

At Abercrombie Caves a prominent and significantly metamorphosed limestone unit strikes north and south. Underlying the limestone is a sequence of felsic volcaniclastics, shales and, in places, spilitic basalts. Overlying the limestone are sandstones, shales and greywackes. (Figure 3). The limestone is mostly massive but contains a few narrow, thinly-bedded units and intercalations of lime-mudstone, chlorite, dolomite and pyrite.

In his regional mapping, Packham (1966) included the sequence at Abercrombie Caves within the Kildrummie Group (Stanton, 1955), a Silurian marine sequence of felsic volcanics and limestones with a wide distribution south of the Bathurst Granite (Figure 2).

In his original description of the Kildrummie Group, Stanton (1955) noted that bedding in the limestone was variable and that the principal impurity was fine shale containing some carbonaceous material and disseminated sulfide.

Chin (1972) correlated the felsic volcanics, shales, spilitic basalts and the limestone with the "Grove formation" of Hobbs (1962) and the sandstones, shales and greywackes with the" Mulgunnia formation" of Hobbs (1962) both of which he considered formed part of the Kildrummie Group of Stanton (1955).

Scheibner (1973) described the Kildrummie Group south east of Abercrombie Caves and noted the presence of minor chlorite, muscovite and pyrite in the limestone.

De Deckker (1976) reduced the status of the Kildrummie Group to the Kildrummie Formation which he defined as follows:

> *"The Kildrummie Formation consists predominantly of thinly bedded to massive impure limestones with intercalations of tuffaceous arenites and minor shale, quartzo-felspathic arenite, dolomite, argillaceous sandstone and breccia conglomerate.*
>
> ***Lower Boundary**: base of lowermost limestone bed, the Kildrummie Formation is conformably underlain by metasiltstones of the Campbells Group (Formation ?).*
>
> ***Upper Boundary**: top of uppermost limestone bed, Kildrummie Formation is conformably overlain by quartzo-felspathic arenites of the Burraga Group (Formation?)."*

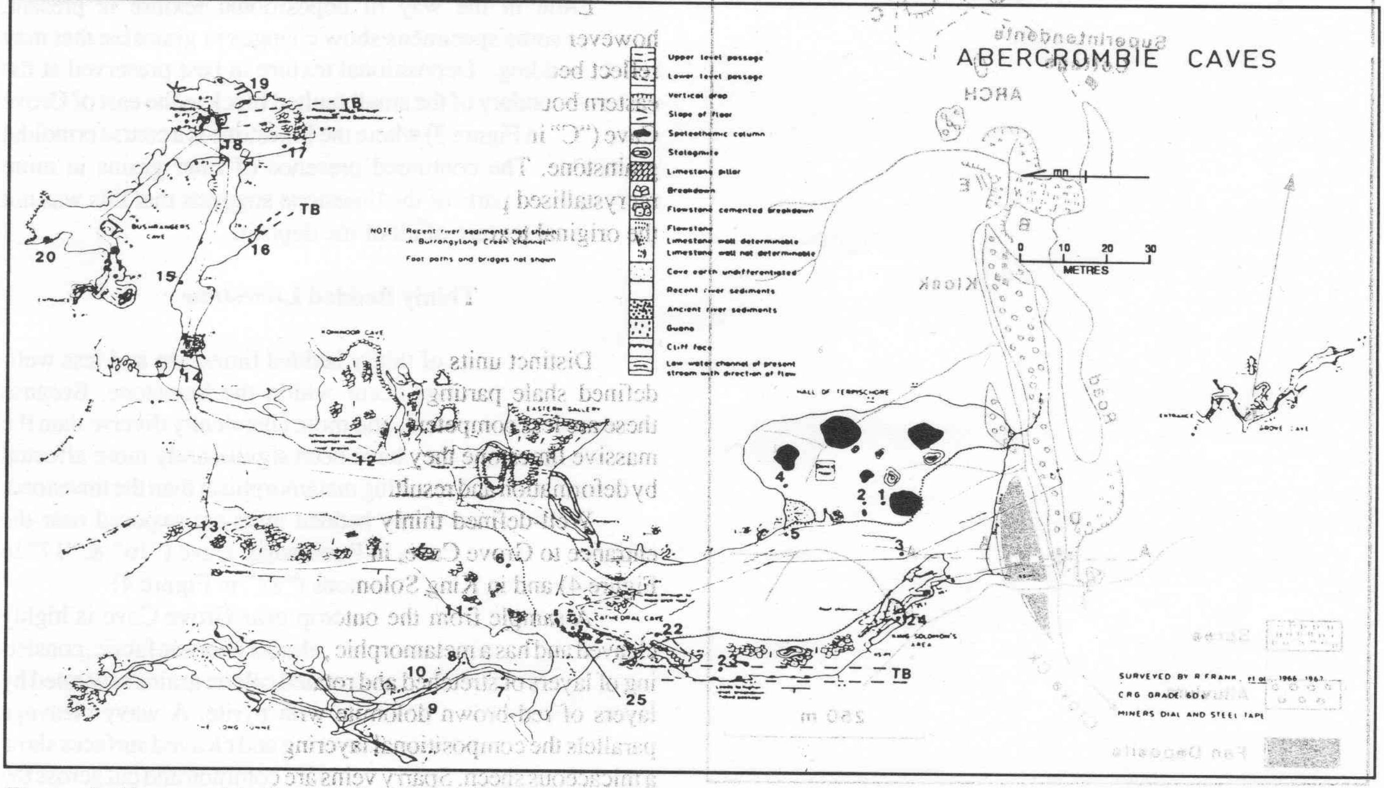

Figure 4: Abercrombie Caves, after Frank & Jennings (1978).

By De Deckker's definition the Kildrummie Formation at Abercrombie Caves would be restricted to the limestone as mapped in Figure 3.

The sequence at Abercrombie (metasiltstone, spilitic basalt, limestone) is similar to that at other Silurian limestone localities in the region e.g. Jaunter {mapped by Packham (1966) as part of the Kildrummie Group (Stanton, 1955), and Jenolan (particularly the "eastern limestone"). Scheibner (1982) noted that the Late Silurian sequence around Jenolan Caves was similar to the Kildrummie Formation.

Although there is no direct evidence at Abercrombie Caves as to the age of the sequence, coral and brachiopod fossil evidence from other limestone attributed to the Kildrummie Formation, and conodont studies at the type section south of Rockley by De Dekker (1976) have clearly established that the Kildrummie Formation has a Late Silurian age (491-428 million years).

Structure

The rocks at Abercrombie Caves have been highly deformed. Chin (1972) recognised five phases of folding. This deformation has resulted in the shales underlying the limestone having a well developed crenulation cleavage and a phyllitic to schistose fabric.

The limestone has been extensively recrystallised, with almost total destruction of depositional texture. The prominent structural feature of the limestone is a westerly-dipping cleavage which roughly parallels bedding in the area of the Arch. Chin (1972) demonstrated that the sequence at Abercrombie Caves both dips and youngs to the west.

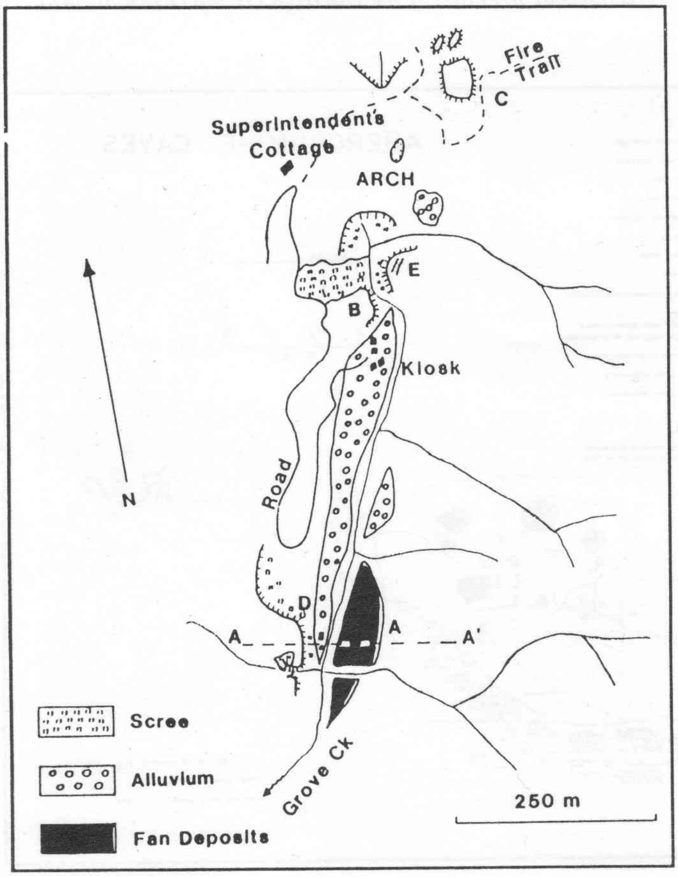

Figure 5: Surficial Geology.

The intensity of the deformation is clearly illustrated in the less competent thinly-bedded limestone units (particularly in the exposure near Grove Cave, Figure 3, "B") in which kink folds are developed.

Small bodies of limestone to the east of the main outcrop appear to have been displaced by faulting.

LIMESTONE

The limestone at Abercrombie Caves is predominantly massive, however, it does contain distinct thinly bedded units.

Massive Limestone

The massive limestone is composed of twinned, interlocking calcite crystals, aligned parallel to the westerly dipping cleavage. Grainsize ranges up to 2 mm with very occasional larger crinoid ossicles reaching up to 4 mm.

As recognised by Chin (1972) the calcite has the form of equant spar, with straight grain boundaries joining in triple junctions. Twinning is often parallel to cleavage. In some cases large skeletal grains show signs of rotation.

Frank and Jennings (1978) noted a variation in the percentage of insoluble quartz residues in the limestone. They believed that these residues represented quartz which had been deposited in microfractures in the limestone, and that the quantity of quartz residues in the limestone was directly proportional to the size and density of microfractures. They concluded that cave development was most pronounced in limestone containing a high proportion of insoluble residues and thus a high density of microfractures. It is not clear, however, whether their data reflects variation in the composition of the massive limestone, or their failure to recognise the presence and significance of thinly-bedded units within the sequence.

Little in the way of depositional texture is present, however some specimens show changes in grainsize that may reflect bedding. Depositional texture in best preserved at the eastern boundary of the small faulted block to the east of Grove Cave ("C" in Figure 3) where the limestone is a coarse crinoidal grainstone. The continued presence of finer grains in more recrystallised parts of the limestone suggests that this was not the original texture of all of the deposit.

Thinly Bedded Limestone

Distinct units of thinly bedded limestone and less well-defined shale partings occur within the limestone. Because these are less competent, and more chemically diverse than the massive limestone they have been significantly more affected by deformation and resulting metamorphism than the limestone.

Well-defined thinly bedded units are exposed near the entrance to Grove Cave, in Bushranger Cave ("16" & "17" in Figure 4) and in King Solomons ("23" in Figure 4).

A sample from the outcrop near Grove Cave is highly cleaved and has a metamorphic , almost gneissic fabric, consisting of layers of stretched and rotated calcite grains separated by layers of red-brown dolomite with pyrite. A wavy cleavage parallels the compositional layering and cleaved surfaces show a micaceous sheen. Sparry veins are common and cut across the fabric.

Carne & Jones (1919) and Chin (1972) recognised the presence of shaley inclusions or partings within the limestone. Chin (1972) interpreted these as being the remains of thin layers of shaley sediment that had been disrupted and metamorphosed as a result of deformation. Chin recognised a metamorphic assemblage of muscovite, chlorite, iron-rich opaques and epidote in the shaley partings.

The thinly bedded unit exposed in Bushranger Cave ("16" & "17" in Figure 4) has this composition and is weathering by the oxidation of chlorite.

Small inclusions are also exposed in Bushranger Cave and at one locality ("21" in Figure 4) large pyrite rhombs occur in a chloritic parting.

The thinly bedded units and the chloritic partings are most likely metamorphosed versions of the pyritic and dolomitic lime-mudstones reported from other Kildrummie Formation localities by Stanton (1955), Scheibner (1973), and De Deckker (1976). Some of the sulfides and oxides in the limestone, however, may be the result of mineralisation (see below).

Origin of the Limestone

The high degree of recrystallisation makes it difficult to determine the depositional environment of the limestone.

Wilkinson (1879) described the limestone as being "full of corals, encrinites (crinoids) &c" but then commented that *"The limestone has become so crystalline in structure as to almost obliterate all traces of fossils; but when polished these may be plainly seen."* Wilkinson considered that this and other lenticular masses of limestone in N.S.W. "are no doubt the remains of coral reefs which once grew in the Silurian ocean."

Later workers, e.g. Chin (1972), J. Byrnes (pers comm) and the author have failed to find any coral fossils in the limestone within the Reserve, nor has any evidence been found of a reef structure. Chin (1972) considered that "it is probable that the limestone originated from accumulations of calcareous fragments, particularly crinoid fragments."

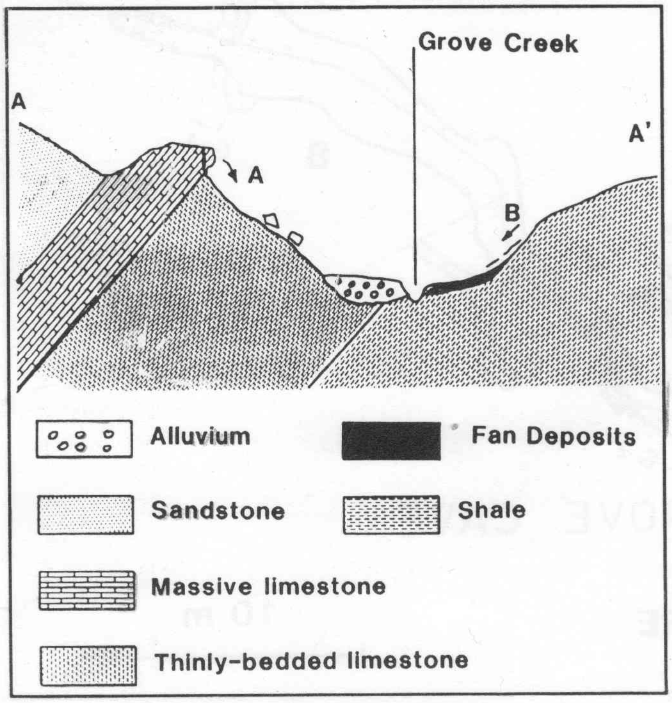

Figure 6: Schematic Section across Grove Creek.

Crinoid fragments are the only identifiable fossil grains that have been observed in this study, either in field exposure, polished blocks or thin-section. In spite of the lack of identifiable fossils and recrystallisation some conclusions can be drawn about the limestone's origin:

1. Prior to metamorphism the limestone consisted of both massive and thinly bedded units.

2. The variable grainsize, noted by Carne and Jones (1919) and observed in thin sections of massive limestone appears to be a depositional texture, rather than a metamorphic one. The grains are most likely fossil fragments which, although they are not identifiable, have never-the-less retained their approximate grainsize through metamorphism.

8. In a few places where the massive limestone is not extensively recrystallised depositional texture is preserved. The rock here is a coarse crinoidal grainstone, suggesting deposition by a fairly fast current that winnowed away finer material.

4. Although now highly deformed and altered, the thinly bedded units and the chloritic partings are the product of periodic low energy deposition of both lime mud and terrigenous fines. The pyrite (also reported from less metamorphosed outcrops of the Kildrummie Formation, see above) is indicative of anoxicconditions during low energy deposition.

5. There is no evidence of any reef structure. The limestone is most likely a bank or shelf deposit.

Metamorphism

The structural and petrographic evidence suggests that tectonic forces, rather than heat, were the main agents of metamorphism responsible for converting the limestone into marble.

The regional metamorphism at Abercrombie Cave is much more intense than that at other major karst localities in New South Wales. The Kildrummie Formation at Abercrombie differs significantly from the marble at Wombeyan Caves, which was recrystallised by thermal metamorphism, in that it

TABLE 1 LIMESTONE ANALYSIS
from Carne & Jones (1919), p 367, Assay No 312
Locality:County Georgiana, Parish Bombah.
Half-mile south of Abercrombie Caves Reserve

calcium carbonate	98.03 %
magnesium carbonate	0.65 %
manganese carbonate	0.03 %
ferric oxide and alumina	0.14 %
phosphoric anhydride	not detected
gangue	1.40 %
organic matter	not detected
moisture	not detected
Total	100.25

has a well-developed cleavage which has influenced both surface weathering and cave development (see below).

Mineralisation

Abercrombie Caves occur in a region of significant mineralisation. In addition to the former mine sites and modern prospects described below the limestone adjacent to the Arch has in places been affected by mineralisation.

The most obvious mineralisation occurs along the eastern boundary of the body of limestone to the east of Grove Cave ("C" in Figure 3). Here the limestone is penetrated by prominent mineralised veins, composed mainly of haematite.

Chin (1972) reported quartzite with pyrite mineralisation and secondary iron oxides along the eastern boundary of the limestone and considered it to be a continuation of the mineralisation at Mt Gray (see below). Chin (1972) observed that the quartzite was cleaved, indicating that the mineralisation predated folding and metamorphism of the limestone.

As indicated above there is some similarity between the composition of the thinly-bedded units and partings and that of the mineralised zones. Further investigation is required before these relationships are understood.

ECONOMIC GEOLOGY

Mt Gray Mine

The Mt Gray Gold Mine ("A" in Figure 3) was worked intermittently between 1888 and 1898 with no evidence of gold being recovered. The geology of the mine was described by Stonier (1892) and Chin (1972).

The shafts have recently been filled as part of a mine rehabilitation program. Surface rehabilitation works involved dozer ripping up and down slopes and planting of exotic grasses.

There is much of archaeological interest at the mine site and clear evidence remains of the infrastructure of the mine and the processing operations that took place there.

Modern Prospects

Prospecting in the Abercrombie Caves region during the late 1970's and early 1980's identified two base metal sulfide prospects in or adjacent to the Caves Reserve.

The Caves East prospect, which includes the Arch was subjected to detailed soil geochemical surveys by Jododex in the 1970's Their analyses and later work by Teck Exploration (Green, 1983) showed the presence of low grade lead, copper and zinc anomalies in the catchment of the caves

The Best Prospect, in the Grove Creek valley upstream of the Arch contains a weak lead anomaly (Green, 1983).

Green (1983) concluded that neither of these prospects were economic, but their presence raises the possibility that mineralisation may have had an effect on cave formation and that groundwater depositing speleothems may be enriched in heavy metals.

Alluvial Deposits

Gold, zircons, sapphires and garnets are reported from alluvium in the bed of Grove Creek. The gold is most likely derived from quartz veins which are common in the area. Zircons and sapphires are frequently derived from basalts and

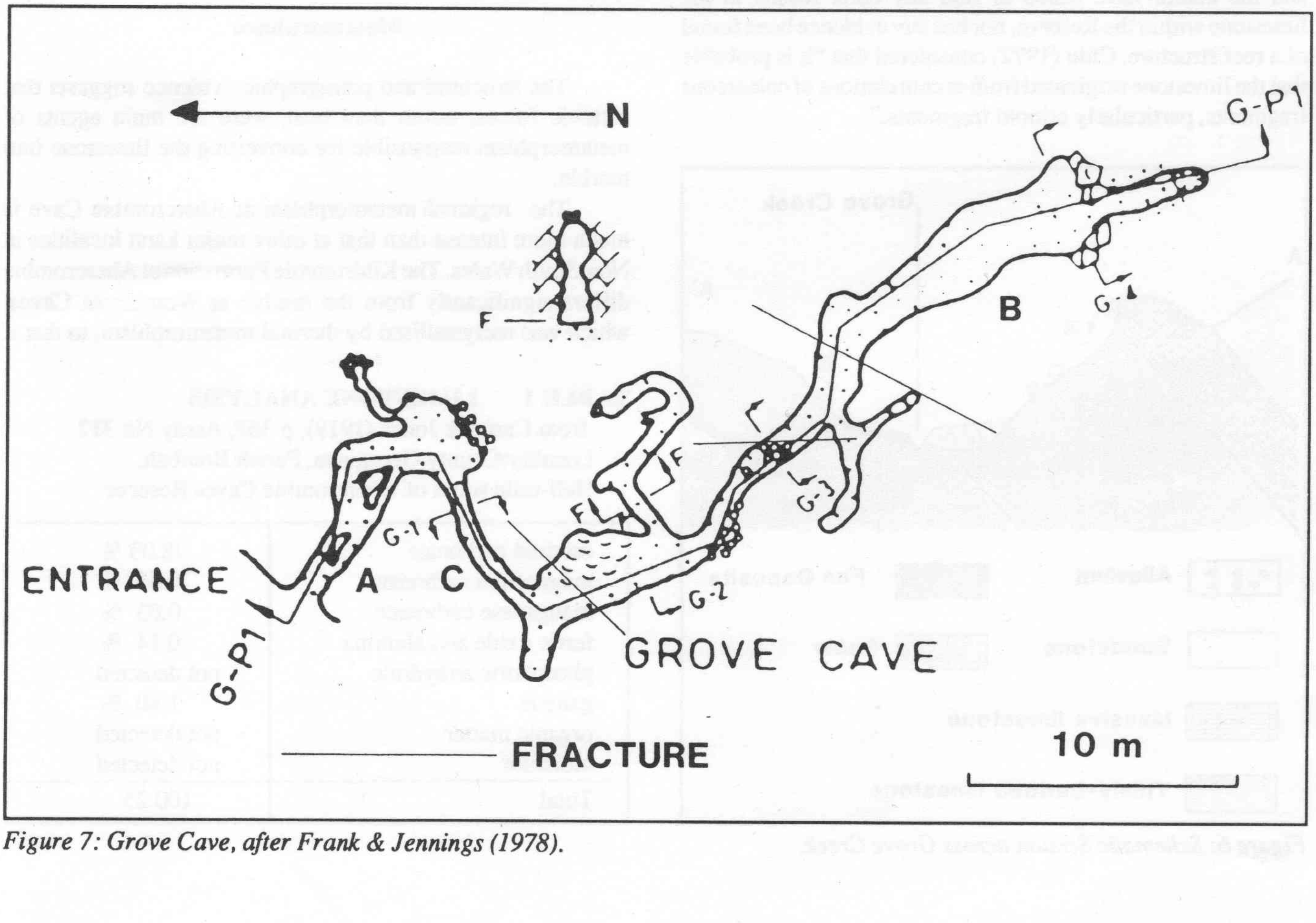

Figure 7: Grove Cave, after Frank & Jennings (1978).

associated volcaniclastics. It is most likely that the zircons and sapphires are derived from the basalts upstream of the Caves.

SURFICIAL GEOLOGY

Ancient Alluvium

Ancient alluvial deposits were first recognised in the Abercrombie Caves area by Wilkinson (1879) who assumed that they had a Pliocene age. Morrissey and Green (n.d.) showed two large "Ancient Alluvium" deposits on their map.

The alluvium consists primarily of quartz pebbles and cobbles up to 180 mm in diameter showing varying degrees of rounding in a matrix of either red soil or fine quartz sand. Small amounts of ferricrete and white sandy clay soil, indicative of deep weathering, are also associated with these deposits. The quartz is derived from quartz veins which are common in the area, angular fragments of vein quartz being found over much of the land surface of the Reserve.

Basalt

Basalt flows occur north and south of the Reserve (Figure 2). The flow to the north was dated at 17 million years by Wellman & Mc Dougall (1974).

The flow to the south of the reserve is adjacent to the incised valley of Grove Creek and, although not dated, may have a similar age. It is one of a series of flow remnants (Figure 2) that may represent the ancient course of the Abercrombie River.

Fan Deposits

The gently sloping land on which the eastern camping area has been developed ("A" in Figure 5) is an alluvial fan whose surface and strata dip to the west at approximately 6 °. The fan is composed of slate chips, slabs of slate and fragments of vein quartz derived from the strata underlying the limestone. The slate is decomposing to form a clay soil. The stream which deposited the fan has now incised a trench, up to 5 m deep, through it.

A similar deposit has been formed by the creek flowing from the east into the doline above the Arch.

Alluvial Terraces

Alluvial terraces, composed of sand, gravel and boulders from Grove Creek have formed on either side of the creek downstream of the Arch.

The largest of these terraces is the site for the current caravan and picnic area. This appears to be a composite terrace consisting of a true alluvial terrace overlain on its western side by scree and alluvial fan deposits derived from the steep slopes to the west.

Limestone Weathering

Rillenkarren and other forms of minor solution sculpture are poorly developed on the limestone. Prominent outcrops of massive limestone are frequently blanketed by angular blocks, approximately 150 mm across, apparently resulting from *in situ* shattering, possibly by frost wedging, of the parent rock.

In many places the limestone supports growth of moss, algae and lichen. This is probably a consequence of the coarse crystalline marble structure giving it a high surface porosity.

Scree

Small scree slopes are common landscape features on the sides of the high bluffs on the western side of Grove Creek to the south of the Arch. These are formed by movement under gravity of the angular limestone blocks described above.

Similar landforms, on a larger scale, adjacent to the Arch ("B" in Figure 5), were formed from rock waste produced during construction of the access road.

Erosion

The immediate environs of the caves contain steep slopes often with little binding vegetation. Much of the bedrock in the area, particularly the slates to the east of Grove Creek, is weak and easily eroded, weathering to clay chips which are readily transported, and weak and plastic when wet.

Disturbance of the slopes by grazing animals and engineering works, has, in places, resulted in a significant erosion. This is most serious in the case of the Mt Gray Fire Trail to the east of the Arch ("C" in Figure 5). Remedial action has recently been carried out in this area.

Slope Stability

On the eastern bank of Grove Creek (Figure 6) both hill slopes, and the bedding/cleavage in the bedrock dip steeply towards the creek. This provides a high potential for mass movement of material towards the creek.

There is also potential for mass movement of limestone towards Grove Creek, either by sliding on its boundary with the underlying slates, or by slippage down the bedding/cleavage. It is possible that mass movement of this type is involved in the fractures in Grove Cave (see below).

Although the slopes on the western bank of Grove Creek should be more stable than those on the east, as the bedding/ cleavage dips into the hill, cliffs formed on the limestone have a potential for rockfall. The cliffs are formed from massive beds towards the top of the limestone and have become undercut as less massive, underlying beds down slope have been more easily eroded (Figure 6).

Failure of overhanging limestone across bedding planes has resulted in large boulders of massive limestone rolling down slope, often reaching the creek bed. The greatest potential for further failure of this type this to occur is in the high cliffs west of the second toilet block ("D" in Figure 5).

GEOLOGICAL CONTROL ON CAVE DEVELOPMENT

There has been a significant degree of structural control over the development of the Abercrombie Caves. The principal factor controlling cave development has been the prominent westerly dip of the bedding/cleavage. Other significant factors are jointing and the presence of thinly bedded units and shale partings in the limestone.

The Arch

Development of the Arch and its associated branches has been controlled by the bedding/cleavage and prominent joints. Although striking generally north-south the bedding/cleavage has quite a variable strike in the Arch area. This variation in strike has had a significant influence on cave development and is reflected in the curvature of the western wall of the Arch.

The bedding/cleavage has a footwall / hanging wall relationship in much of the Arch. This is particularly the case at the southern end ("3" and "5" in Figure 4) where the western wall is the hanging wall and the eastern wall the footwall. Bedding/cleavage in this area dips to the west at 61°.

Easterly dipping conjugate joints have combined with the bedding/cleavage to control both breakdown and solution in the Arch forming "A tent" roofs in various parts of the Arch. Westerly dipping bedding/cleavage and easterly dipping joints have also produced "A tent" roofs in Bushranger Cave (e.g. at "18" in Figure 4).

Sub-horizontal jointing is visible at the entrance to Bushranger Cave and at various places (e.g. above "5" in Figure 4) in the Arch. This appears to have controlled breakdown at the northern end of the Arch.

Prominent joints have also had a major control over lateral cave development. This is best illustrated by the development of Bushranger Cave along an east-west striking (northerly dipping) joint, and the joint/bedding plane controlled development of the Long Tunnel (see Figure 4)

Thinly-bedded units within the marble crop out in King Solomons and Bushranger Caves where they seem to have encouraged cave development. King Solomons Temple ("23" in Figure 4) is a bedding-controlled rift developed by preferential erosion of thinly-bedded limestone, as is the western chamber of Bushranger Cave ("17", "18", "19" in Figure 4).

This is an unusual situation as thinly-bedded units usually inhibit rather than promote cave development. Two factors may be responsible for this; firstly the presence of chlorite which weathers by oxidation and is mechanically quite weak, and secondly the presence of pyrite which can weather to produce sulfuric acid, promoting solution of limestone.

Grove Cave

The westerly dipping bedding/cleavage has exercised considerable control over the development of Grove Cave. Both the entrance passage (Figure 7, "A") and the main chamber (Figure 7, "B") are developed along bedding. The passage connecting them (Figure 7, "C") is a dip tube.

Significant open fractures occur in Grove Cave (Figure 7) oblique to the axis of the cave passage. These fractures have opened both in bedrock and flowstone indicating that they are relatively new features of the cave. Microscope slide strain gauges placed across these fractures in 1968 (A. Lawrence pers. comm.) are still intact.

These fractures may be related to a deep open slot in the limestone bluff above Grove Cave ("E" in Figure 5) which seems to have resulted from mass movement of the limestone towards Grove Creek.

CAVE SEDIMENTS

Clastic Cave Deposits

Frank & Jennings (1978) described a number of clastic deposits in Abercrombie Caves which have considerable potential for further study.

Large deposits of actively-moving sediment occur in the southern end of the Arch and represent the bed load of Grove Creek. Silty sediment, possibly aeolian in origin, forms the floor of the Hall of Terpischore approximately 10 m above present creek level.

A deposit consisting of breakdown and alluvium is located at the northwest end of the Arch ("13" in Figure 4).

The floor of Bushranger Cave consists of cave earth of unknown depth. There is evidence that some coring of the cave floor has been carried out, but the results of this are not known, and poorly-identified samples have been left in the cave.

Careful examination of the walls of the inner parts of the Cave (particularly near "20" in Figure 3) has revealed the presence of sediment remnants and traces of a phosphatic reaction rim. A rift in the cave roof ("19" in Figure 4) remains filled with these sediments. The remnants, reaction rim, and filled rift indicate that Bushranger Cave was once almost completely filled with phosphate-bearing sediment, much of which has since been removed.

Frank & Jennings (1978) obtained carbon 14 dates for two samples from Bushranger Cave. One of 19,400 for charcoal from alluvial sediments "south of the large room" and another of 33,600 for charcoal from alluvial silt in spongework at 008050 in Figure 4. The stratigraphic relations of these particular samples remain unclear.

Frank & Jennings (1978) reported a pond deposit about 5 m thick in the King Solomon's Area ("24" in Figure 4). This deposit consisting of partly cemented laminated clay with manganiferous dendrites, may well date from a time when phreatic conditions existed in the Arch. This deposit warrants further study in view of the greater age suggested below for the Arch.

Frank & Jennings (1978) identified two entrance facies deposits in Cathedral Cave which they considered to be ancient. A previously unreported cemented bone breccia in Cathedral Cave ("25" in Figure 4) appears to be older than adjacent red entrance facies deposits.

Deposits of fluvial sediment, some consisting of interbedded sand and charcoal, occur in Long Tunnel. Frank & Jennings (1978) reported sulfate cementation in Long Tunnel sediments. From a pit in the cave floor (at 039009 in Figure 4) they reported carbon dates of 1,530 years at 40 cm and 4,710 years at 90 cm.

Speleothems

A variety of types of speleothem occur in the Abercrombie Caves. Apart from the craybacks described below; stalagmites, stalactites, flowstone and cave coral are found in both the Arch and Grove Cave.

Stalagmites, particularly those in Cathedral Cave and the Hall of Terpischore, have a stepped profile reflecting changes in drip rate. Some speleothems, particularly those in Cathedral Cave, have natural dust coatings.

Cave Coral is particularly well developed in King Solomons and on the western wall of the Arch ("11" in Figure 4).

Craybacks

Stalagmites with an elongate cross-section, and a hump-backed profile similar to those described as "Craybacks" and "Lobsters" (see Cox *et al.*, 1989) are abundant in the Abercrombie Arch. The best examples are found in the Hall of Terpischore (e.g. the "Eagles Wing", "Tombstone", "Plum Pudding" & "Icebergs") and on the western ledge at the northern end of the Arch, however they are by no means restricted to these localities. Elongate wet patches on the cave floor, known as "Footprints", representing the traces of drips from which craybacks form, are found in a number of places (e.g. "2" in Figure 4).

In general the long axes of the craybacks are orientated north-south, i.e. parallel to the long axis of the Arch. The craybacks in the Hall of Terpischore tend to have a distinct "tail" facing north while those at the northern end of the Arch (e.g. at "6" in Figure 4) are more symmetrical in outline.

A fragment of crayback, collected from the bed of Grove Creek downstream of the Arch (P.A. Willis pers comm), has been examined in thin-section and by X ray diffraction. This fragment shows the typical features of "Stromatolitic Crayfish-Like Stalagmites" as described by Cox *et al.*, (1989). It consists of alternating coralloid and laminated layers and incorporates detrital grains. X ray diffraction showed the principal mineral component to be calcite.

THE AGE OF THE CAVES

The first estimation of the age of the Abercrombie Caves was given by Wilkinson (1879) who considered that "these caves were formed subsequently to the Pliocene period, and towards the close of the Pleistocene period".

Wilkinson's dating was based on the assumption, often made prior to radiometric dating, that the basalt upstream of the caves, (Figure 2) and the gravels capping the hills to the west of the caves (Figure 3) were Pliocene (2-5 million years ago) in age. Radiometric Dating by Wellman and Mc Dougall (1974), however, has shown the basalt to be 17 million years old (Miocene).

Frank & Jennings (1978) did not consider the implication of the basalt for the age of the caves, but used carbon 14 dating of sediments to provide a chronology for Abercrombie Caves. They suggested that the Arch had been driven through the limestone by about 15,000 years ago. Frank & Jennings' date for the formation of the Arch was based on the assumption that the sediments which they had dated were the products of an initial phase of sedimentation. This very young age for cave formation would imply that Grove Creek was incised at a rate of thousands of metres per million years. This is at odds with recent studies of landscape development in eastern Australia (e.g. Bishop, 1985) which have shown incision rates to range between 2 and 8 metres per million years. Given that incision in the upper and middle tracts of Grove Creek has been retarded by the resistant volcanics forming Grove Creek Falls one might expect the incision rate at, and adjacent to, Abercrombie Caves to be somewhat lower than elsewhere.

Studies of basalt/ streambed relationships in the upper Lachlan River (Bishop, 1985) have indicated that the incision rate there for the last 20 million years was 8 metres per million years. Applying this rate to Abercrombie would suggest that Grove Creek was captured by the Arch (40 metres incision from the east saddle to the present creek level) approximately 5 million years ago.

Since the basalt upstream of the caves has been dated at 17 million years it is possible to calculate directly an incision rate for Grove Creek. At present this can only be an estimate, as it is not based on detailed mapping or accurate levelling. Grove Creek is incised approximately 160 m below the top of the basalt giving an incision rate of 9.4 metres per million years.

A similar rate of incision for Grove Creek above Grove Creek Falls is suggested by its relationship to the adjacent (undated, but probably of similar age) basalt.

An incision rate of 9.4 metres per million years suggests that the Arch captured Grove Creek a little more than 4 million years ago.

Present evidence therefore suggests that the Abercrombie Arch, as a through-cave, is somewhere between 4 and 5 million years old.

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Address for correspondence:
R.A.L. Osborne, Institute of Education, A22,
University of Sydney, N.S.W. 2006.

THE SULFATE SPELEOTHEMS OF THAMPANNA CAVE, NULLARBOR PLAIN, AUSTRALIA

Julia M. James

Abstract

Examination of the sulfate speleothems and chemical analysis of the cave drip waters of Thampanna Cave confirm that the major source of the sulfate is from seawater transported by rain.

INTRODUCTION

Thampanna Cave is located on the Hampton Tableland, part of a large karst plateau generally known as the Nullarbor Plain. The cave lies within the boundaries of Mundrabilla Station, Western Australia (Figure 1). The Nullarbor Plain is a semi-arid to arid karst (Jennings, 1983); the surface above Thampanna Cave has a ridge and corridor topography with relief of 5 - 10 m. Vegetation is eucalypt and acacia scrub on the rocky ridges and shrubby steppe foliage consisting of halophytic plants and grasses on the clay floors of the corridors. On the Hampton Tableland the climate is harsh with a temperature range from 5° C (winter night) to 50°C (summer day). The average annual temperature is 19°C and the average annual rainfall for the area is 238 mm (data for Mundrabilla Station and road-house, 1901-90). Precipitation occurs throughout the year with the winter months bringing the most rain.

Thampanna Cave drains a large corridor/blind valley at its lowest point. The blow hole entrance is at the centre of a rocky pavement 50 m in diameter and is an intermittently active inflow. An 11 m shaft leads to a series of intermittently active passages and collapse chambers. Perched debris indicate that some of the passages flood to the roof after intense rainfall. A number of perched pools are left in the cave after the flood waters recede. Two main series of passages lead south from the entrance chambers. The first contains "The Tube", a passage that resembles a phreatic tube, however, its origin is not clear as it has been considerably modified by vadose action and crystal wedging. Four weeks after a flood in 1982 the Tube was observed 2 m underwater with evidence of even higher standing water levels (G. Pilkington, *pers. comm.*). Beyond The Tube is a series of well decorated collapsed chambers. The highest chamber (The Glass Slipper Chamber) was first entered at Christmas 1990. The Glass Slipper Chamber has been invaded by tree roots indicating that it lies close to the surface.

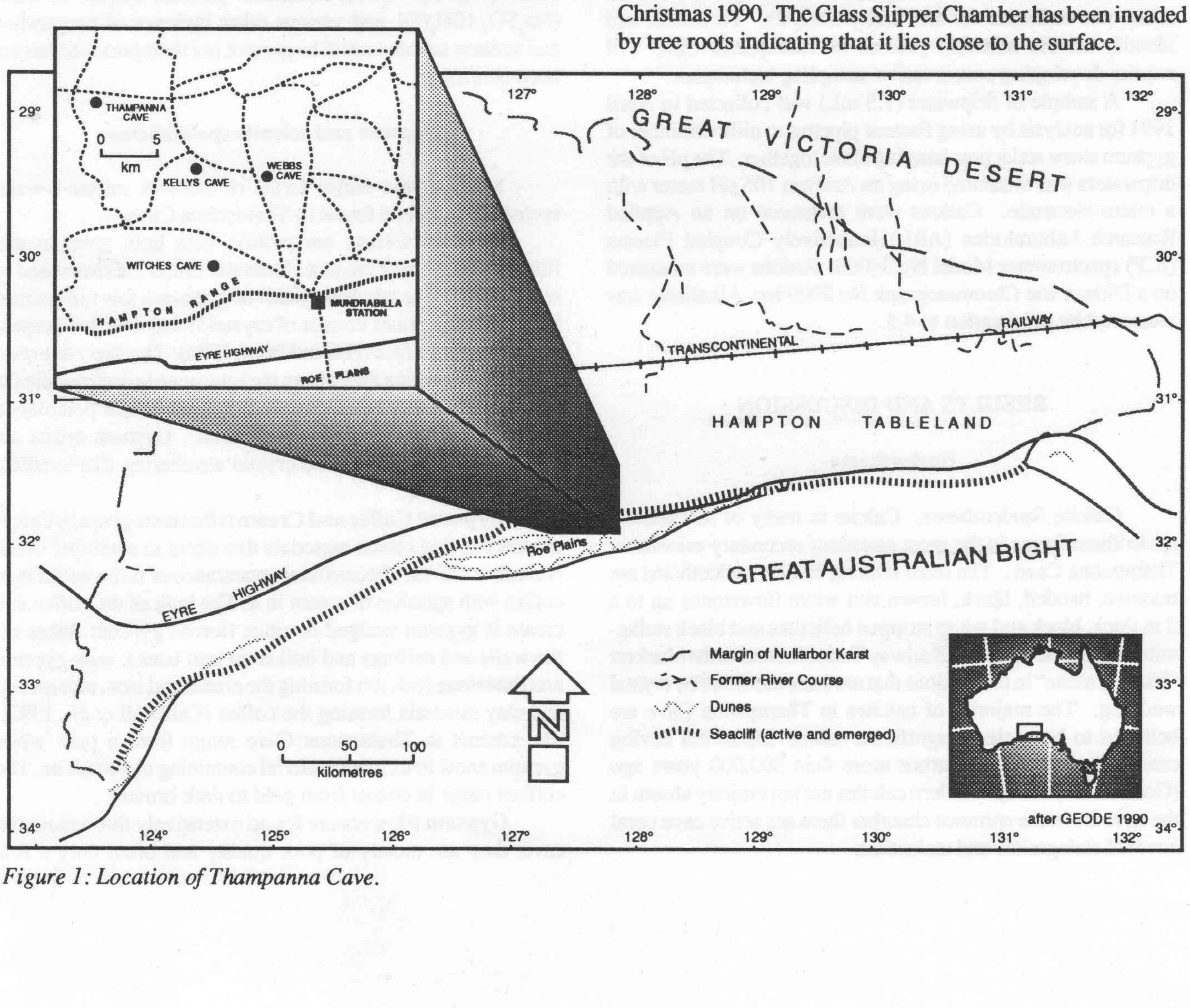

Figure 1: Location of Thampanna Cave.

The largest chamber (Enigma Chamber) is floored with large collapsed slabs many of which have been modified by crystal wedging and deposition of secondary minerals. The second series of passages is entered through "The Drain", a maze of low crawls and flatteners which finally enlarges into "The Railway Tunnel". Where The Railway Tunnel has not been modified by collapse or crystal wedging it is undeniably of shallow phreatic origin. Towards the limits of its present exploration The Railway Tunnel becomes much larger and frequent boulder collapses divide it into a series of chambers. In total Thampanna Cave has some 3-4 km of passages and chambers and at present is neither fully explored nor surveyed.

Speleothems from Thampanna Cave have been previously studied by Goede *et al.*, 1990 and Caldwell *et al.*, 1982. This paper specifically discusses sulfate speleothems from Thampanna Cave but also includes an overview of speleothem deposition in the cave. In December 1990 the gypsum stalactites in Enigma and The Glass Slipper Chamber were dripping. A knowledge of the composition of these dripwaters is crucial to any discussion of the mode of formation of the stalactites and the source of sulfate in them. Thus a return visit to Thampanna Cave was made in April 1991.

METHODS OF ANALYSIS

Calcite, gypsum, and halite in the cave were identified from their crystal and speleothem morphologies. The white minerals were discretely given careful taste and scratch tests to assist their identification. Only one small sample of a broken straw was collected for laboratory analysis. To collect and identify all the minerals present in Thampanna Cave will require developing conservative sampling techniques.

A sample of dripwater (1.5 mL) was collected in April 1991 for analysis by using Pasteur pipettes to milk a number of gypsum straw stalactites hanging close together. The pH of the dripwaters was measured using an Activon 105 pH meter with a micro-electrode. Cations were measured on an Applied Research Laboratories (ARL) Inductively Coupled Plasma (ICP) spectrometer Model No 34000. Anions were measured on a Dionex Ion Chromatograph No 2000 isp. Alkalinity was measured by pH titration to 4.5.

RESULTS AND DISCUSSION

Speleothems

Calcite Speleothems. Calcite in many of its classical speleothem forms is the most abundant secondary mineral in Thampanna Cave . The most striking calcite speleothems are massive, banded, black, brown and white flowstones up to a 2 m thick, black and white stripped helictites and black stalagmites and stalactites. The Railway Tunnel contains the blackest "Black Calcite" in the sections that are least modified by crystal wedging. The majority of calcites in Thampanna Cave are believed to be ancient, significant calcite deposition having ceased beneath the Nullarbor more than 300,000 years ago (Goede *et al.*, 1990). Modern calcites are not entirely absent in the cave for in the entrance chamber there are active cave coral covered stalagmites and stalactites.

Evaporite minerals. Gypsum {calcium sulfate-2-water ($CaSO_4.2H_2O$)} is believed to be the second most abundant secondary mineral in the cave, however, the cave also contains halite {sodium chloride ($NaCl$)} speleothems as crusts and it is impossible to distinguish between gypsum and halite or composite gypsum/halite crust visually, therefore, the relative quantities of these minerals are difficult to establish. All three major secondary minerals occur in the same area of The Railway Tunnel with calcite speleothems being overlain with halite and gypsum.

The meteorology of Thampanna Cave is ideal for the deposition of evaporite minerals. Consistently strong winds blow in and out of the entrance shaft. The velocity of the wind flowing out of the entrance has been measured at 72 km per hour (N. Poulter, *pers. comm.*) and throughout the cave there are strong draughts which lift dust. The cave is a barometric breather, thus the direction of the air flow in the shaft and cave reverses diurnally in response to day - night pressure changes (Neville Michie, *pers. comm.*). The continuous reversal of air flow removes moisture from the cave and replaces it with desiccating desert air.

SULFATE MINERALS

Gypsum is the major sulfate mineral however its polymorph selenite is found in a number of places. The varying meteorological conditions in the cave could produce anhydrite {calcium sulfate ($CaSO_4$)}, epsomite {magnesium sulfate-7-water ($MgSO_4.7H_2O$)}, mirabilite {sodium sulfate-10-water ($Na_2SO_4.10H_2O$)} and various other hydrates of magnesium and sodium sulfates could be present but their presence has not been confirmed.

Gypsum and selenite speleothems

Many of the major forms of calcium sulfate-2-water speleothems can be found in Thampanna Cave.

Gypsum Crusts are prolific with both granular and fibrous crusts being present. Granular crusts are composed of equant, curved or tabular crystals of gypsum a few millimetres long. Fibrous crusts consist of crystal fibres oriented perpendicular to the surface (Hill and Forti, 1986). The sheet like crust deposits are peeling away from the limestone in areas where the rock is sufficiently friable to allow uniform water percolation and high surface area for evaporation. Gypsum crusts are responsible for much of the crystal weathering that is taking place in the cave.

Gypsum: Coffee and Cream is the name given by cavers to banks of fine clastic materials that occur in a number of the Nullarbor Caves. The surficial appearance of these banks is of coffee with splashes of cream in it. The bulk of the coffee and cream is gypsum wedged detritus; fibrous gypsum flakes off the walls and ceilings and builds up into banks, with gypsum and limestone (calcite) forming the cream and iron, manganese and clay minerals forming the coffee (Caldwell *et al.*, 1982). The creams in Thampanna Cave range from a pure white gypsum snow to a cream material containing more calcite. The coffees range in colour from gold to dark brown.

Gypsum Flowers are found extensively throughout the cave, they are mostly of poor quality and often only a few centimetres long. Gypsum flowers are composed of branching and curving bundles of acicular gypsum crystals loosely packed together in a polycrystalline matrix. The flower petal bundle is made up of nearly-straight fibres which are gradually tilted around the curvature of the petal (Hill and Forti, 1986).

Selenite Needles. Selenite needles are acicular, twinned macroscopic crystals of gypsum that resemble darning needles (Hill and Forti, 1986). They can be found on the silt\clay floors of The Drain in areas that flood and thus the needles may be ephemeral.

Gypsum Straws, Stalactites, Stalagmites and Columns

In Enigma Chamber are numerous gypsum straws and stalactites up to 0.5 m in length. The floor is strewn with speleothems that have fallen either because they have grown too heavy for their means of support; because the nature of the seepage waters has changed resulting in solution of their support; or because they have been severed by crystal wedging from the bedrock. The largest fallen gypsum stalactite yet found is in the Railway Tunnel and is almost a metre long and 0.5 metre in diameter.

In the Railway Tunnel where there is a noticeable draught the gypsum stalactites have characteristic claw or tree root shapes and are covered with brown windblown or flood debris. In contrast where the humidity in the cave is higher and there is no noticable air movement, for example, in Enigma Chamber (humidity 87% and temperature 18.5° C) and Glass Slipper Chamber (humidity 90% and temperature 19° C) (Neville Michie *pers. comm.*) the gypsum stalactites are massive (cover photo) many with butterfly wing shapes in a range of colours from opaque white clear through golden to red brown.

Gypsum stalagmites and columns are rarer than stalactites however there is a 1.8 m high stalagmite in this chamber on the surface of which there are swallow tail twinned crystal facets characteristic of gypsum. However it is highly likely that this stalactite is a composite of a number of evaporite minerals. In The Glass Slipper Chamber there is a 0.8 m sulfate mineral column that has not been identified.

Gypsum stalactite dripwater chemistry

The modern seepage waters still exploit the routes that solutions saturated with calcium carbonate have taken in the past. In many places the calcite speleothems are being destroyed by crystal wedging or overgrown by gypsum and halite. Often calcite speleothems hanging from the roof have been completely removed thus calcite stalactites are rare.

Table 1 represents the single analysis of a number of drips from the stalactites and straws close to the 1.8 m stalagmite in Enigma Chamber. It is expected that the composition of the dripwaters will vary spatially, seasonally and with the intensity of any rainfall event. An important part of our on going research on the Nullarbor water chemistry is to sample the dripwaters from these speleothems whenever possible in order to establish the variations.

The chemical analysis (ion balance 6.6%) in Table 1 allows preliminary calculations of saturation indices using the water speciation program WATEQ4F (Version by J. Ball, United States Geological Survey, 1988). The water dripping from the gypsum stalactites is a brine (TDS 231 g L^{-1}) and the system is unlikely to be at equilibrium thus the calculated equilibrium saturation indices (Table 2) must be used with caution and in this paper are only used to illustrate trends.

TABLE 1 COMPOSITION OF DRIPWATER FROM GYPSUM STALACTITES

CATIONS mg L^{-1}		**ANIONS** mg L^{-1}	
Ca^{2+}	1450	SO_4^{2-}	5978
Mg^{2+}	9419	Cl^-	135106
Na^+	77138	HCO_3^-	31
K^+	1088	F^-	363
B	70	NO_3^-	220
Si	8		
Sr^{2+}	51		

pH 6.80 **Temperature** 19°C

The saturation indices results in Table 2 show that the solution is undersaturated with respect to calcite and aragonite; this is confirmed by the field observation that drips falling from the gypsum stalactites have eroded calcite stalagmites and limestone bedrock where they impact. A striking example of this form of corrosion is The Mud Men found in The Glass Slipper Chamber. The equilibrium calculations show that as expected the solutions are saturated with respect to gypsum. The composition of this solution has important speleogenetic implications for it is such that it can dissolve limestone yet precipitate gypsum and it is possible for this to occur in either a closed or open system.

TABLE 2 SATURATION INDICES

Aragonite	$CaCO_3$	-0.661
Calcite	$CaCO_3$	-0.463
Anhydrite	$CaSO_4$	0.305
Gypsum	$CaSO_4.2H_20$	0.169
Halite	NaCl	-0.336
Epsomite	$MgSO_4.7H_2O$	-1.389
Mirabilite	$Na_2SO_4.10H_20$	-0.733

The solutions are undersaturated with respect to halite and this salt is expected to precipitate out later either in time or space. The undersaturation of this solution is modest and it is expected that a small amount halite will be co-crystallising with the gypsum. This has been found in the analysis of other specimens (Caldwell *et al.*, 1982). Any significant amounts of halite that form on the surface of the gypsum stalactites during drier periods are likely to be removed at times of higher rainfall by seepage waters undersaturated with respect to halite. In general, halite deposits are most extensive in the better ventilated sections of Thampanna Cave.

The solution analysed was undersaturated with respect to mirabilite and epsomite however it is possible for these solutions to become sufficiently concentrated for them to crystallise by evaporation. In Thampanna Cave there are many stalactites which could be composed of either mirabilite or epsomite. They have compact clear and transparent forms with their sides undulating in the fashion of water icicles. Glassy clear straws and stalactites have grown on the tips of opaque gypsum stalactites. The first phase to be deposited from a mixed sulfate solution is gypsum. As water is lost the composition of the residual liquid becomes more and more enriched with magnesium or sodium sulfate until nearly pure epsomite or mirabilite crytallises (White, 1968).

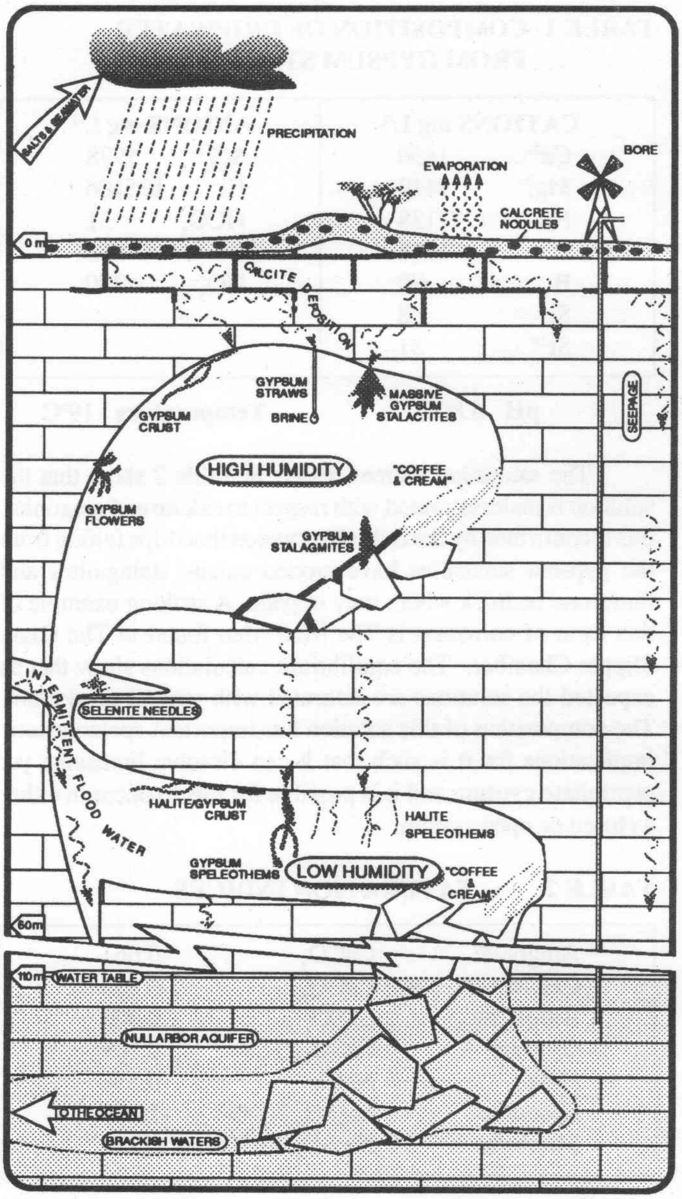

Figure 2: The Water Cycle.

The solutions are more saturated with respect to anhydrite than gypsum yet there is preferential deposition of gypsum. The formation of anhydrite in caves has been attributed to it precipitating from solutions that have a high halide content (Hill and Forti, 1986). Table 1 shows that the dripwaters have an exceptionally high halide concentration and a more detailed examination of the minerals in Thampanna Cave may find anhydrite.

The source of the sulfate

The major sources of sulfate ions in caves are usually either soluble sulfate mineral strata in the rock sequence above or oxidation of sulfides from minerals or hydrogen sulfide gas (Ford and Williams 1989; White 1988). Although there must be a contribution in Thampanna Cave from the latter source, the major source is cyclic salt from the ocean (the sulfate is associated with other ions from seawater). Figure 2 is a simplified diagram of the route that water takes from and to the ocean. The generation of sulfate speleothems depends upon the waters encountering ventilated cavities.

The salts from the seawater and salt pans are transported to above the cave by rain and wind. When rain falls it further increases its salt content by dissolving any soluble salts on the surface. The rain is undersaturated with respect to calcite (SIc = -1.6; James *et al.*, 1991 (in prep) and thus it will dissolve limestone or any secondary calcite on or near the surface. Such solutions evaporate if they remain close to the surface, concentrating and precipitating salts in them. The waters that disappear underground rapidly dissolve the soluble salts in the soil but are not concentrated by evaporation.

The rain waters containing the dissolved calcium carbonate are that are concentrated by evaporation in the soil and upper layers of the limestone reach saturation with respect to calcite and it precipitates as calcrete nodules and case hardens limestone. Goede *et al., 1990* has used uranium disequilibrium studies to date a gypsum stalactite and it was found to be very low in uranium. This is to be expected as any uranium present in the cyclic salt or mobilised by solution of limestone will be co-precipitated with calcite in calcretes on or near the Nullarbor surface.

As the seepage waters penetrate deeper they are now undersaturated with respect to calcite and more concentrated with respect to the soluble components of seawater. The majority of the seepage waters will descend through the limestone until they reach the watertable altering only slightly in their water chemistry. The largest variations will be in carbonate species and will be dependent upon the residence time of the waters in the vadose region of the limestone. A minority of the seepage waters enroute to the watertable will intersect caves or cavities. If the cavities they encounter are open but poorly ventilated and the humidity is reasonably high gypsum alone may crystallise. If they encounter well ventilated cavities of lower humidity both gypsum and halite will crystallise. In some areas of Thampanna Cave there are speleothems which are almost pure halite. Indicating that both the gypsum and

TABLE 3 **MAJOR ION MOLE RATIOS FOR SELECTED WATERS**

Data from James *et al.*, 1991 (in prep)

Mole Ratios	Sea-water	Rainwater	Thampanna	Mundrabilla Bore No 4	Mundrabilla Bore No 5
Ca/Cl	0.02	0.77	0.01	0.06	0.06
Mg/Cl	0.1	0.12	0.1	0.1	0.1
Na/Cl	0.83	1	0.91	0.83	0.77
SO_4/Cl	0.05	0.19	0.016	0.06	0.07
HCO_3/Cl	0.0042	1.56	0.0001	0.015	0.015

The rainwater results are for rain collected during a storm on the December 21st 1990 and analysis of the sample indicates that it contained soluble dust. This analysis should only be taken as representative of the rain falling during the summer months.

TABLE 4 **TOTAL DISSOLVED SOLIDS(TDS) AND NITRATE**

Data from James *et al.*, 1991 (in prep)

Parameter	Sea-water	Rainwater	Thampanna	Mundrabilla Bore No 4	Mundrabilla Bore No 5
TDS mg L^{-1}	32000	91	231000	11000	10000
NO_3^- mg L^{-1}	11	0.22	200	54	59

calcite have crystallised out of the seepage waters higher in the limestone. The seepage waters that encounter well ventilated cavities are evaporated by the caves' breathing and thus never reach the watertable.

The waters that do reach the Nullarbor Aquifer move slowly south and return to the ocean. Support for this water cycle as the major source of the sulfate is obtained from a number of observations and measurements.

The sequence of minerals crystallising from seepage waters in Thampanna Cave is similar to that obtained when seawater is evaporated. The order in which minerals precipitate out from seawater (Usiglo's experiment, Krauskopf, 1976) is as follows; calcite is expected to precipitate first, then gypsum, gypsum and halite followed by relatively pure halite finally epsomite will precipitate.

In most ground water systems chloride is a conserved ion and therefore it is common practice to compare ions that are likely to vary to it. The magnesium to chloride ratio is stable throughout the water cycle and the sodium to chloride shows only small variations indicating that magnesium and sodium as well as chloride are largely being conserved throughout the system. The changes in calcium to chloride and sulfate to chloride ratios in the Thampanna Cave dripwaters are a consequence of the removal of calcium as calcite and gypsum. The exceptionally low value of hydrogencarbonate to chloride in the dripwater illustrates the dramatic effect of removing the soluble carbon dioxide in the seepage water as calcite in the soil and top few metres of the limestone.

The data in Table 4 for total dissolved solids and nitrates provides further evidence for concentration steps by evaporation in the water cycle and a variety of routes for seepage waters to the watertable.

The rain analysed has a high TDS content. Despite this the seepage in the cave is some 2500 times as concentrated. The rain will have picked up soluble salts in the soil, and been concentrated further by evaporation both at the surface and in the cave. Bore waters drawn from the Nullarbor Aquifer have a lower value of dissolved solids than the dripwater in the cave indicating that it is sourced from more direct inputs and/or has seepage routes that do not lead to its concentration by evaporation underground.

All simple ionic nitrate compounds are soluble and the concentrations of nitrate can be followed through the proposed water cycle. They are very low in rain water and rise to a maximum in the waters dripping from the stalactites, again indicating that there has been considerable concentration by evaporation. The system is perturbed by vegetation adding nitrate to the seepage waters and concentration by evaporation can not be calculated from nitrate values.

It is intended to carry out sulfur stable isotope studies to further confirm cyclic salts in precipitation as the major source of the sulfate.

CONCLUSION

The sulfate speleothems of Thampanna Cave are abundant, varied and asethetically pleasing. The cave contains the only examples of the massive gypsum speleothems recorded in Australian Caves. Their value is not only in their beauty and rarity but in the information that they supply about speleogenetic processes beneath the Nullarbor Plain.

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Address for correspondence:
J. M. James, School of Chemistry, F11,
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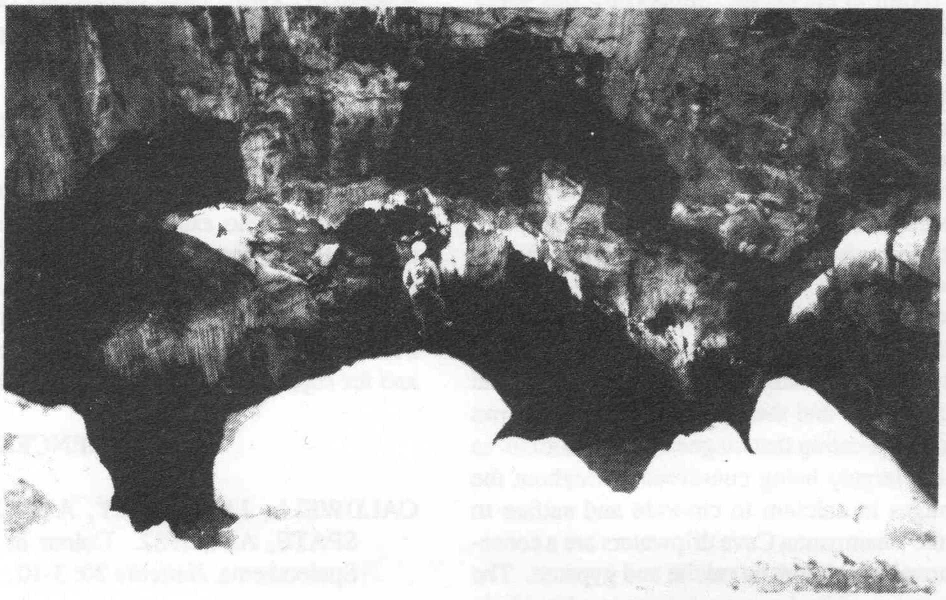

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