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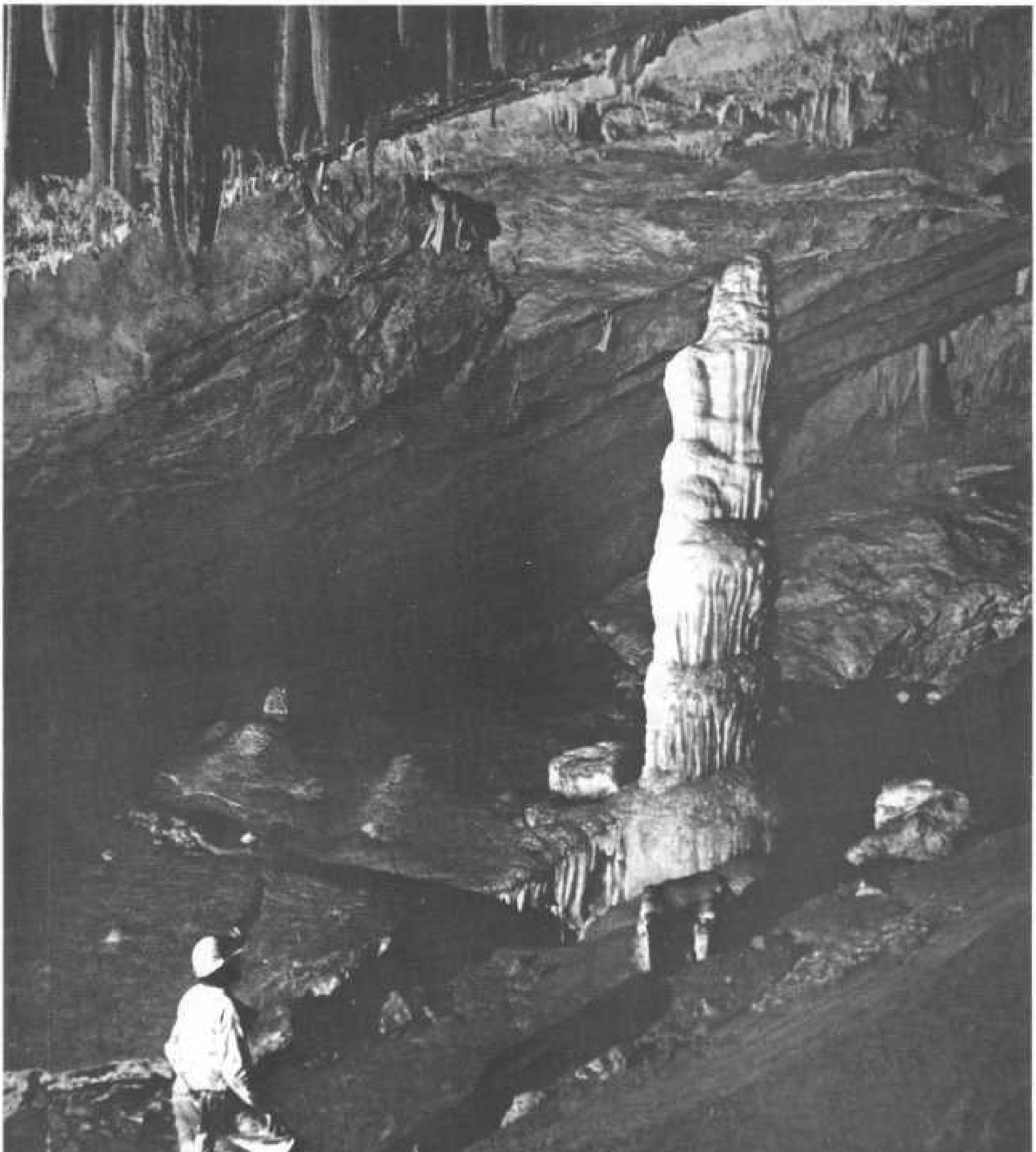
Helictite

JOURNAL OF AUSTRALASIAN CAVE RESEARCH



Lot's Wife, the largest stalagmite in Main Cliefden Cave.
Photo by Andrew Pavey.

HELICTITE

Helictite was founded by Edward A. Lane and Aola M. Richards in 1962.

This Journal was (and is) intended to be wide ranging in scope from the scientific study of caves and their contents, to the history of caves and cave areas and the technical aspects of cave study and exploration. The territory covered is Australasia in the truest sense – Australia, New Zealand, the near Pacific Islands, New Guinea and surrounding areas, Indonesia and Borneo.

In 1974 the Speleological Research Council Limited agreed to support the Journal with financial assistance and in 1976 took over full responsibility for its production.

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To explore and chart and organize and promote the exploration and charting of caves and cave systems.

To promote, support and assist in the scientific evaluation and investigation of caves and to foster speleology as a science and a sport.

To promote and to assist in the promotion of speleology and speleological Societies and to assist such Societies with grants of money and otherwise.

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J.R. Dunkley 1972. - a detailed history and description.

CAVES THROUGH THE AGES. G. Hangay, J.M. James & M. Dorrell 1974.
- a colouring book for children.

PAPUA NEW GUINEA SPELEOLOGICAL EXPEDITION NSRE 1973. J.M. James 1974.
- the report of the 1973 Niugini Speleological Research Expedition to the Muller Range.

A BIBLIOGRAPHY OF THE JENOLAN CAVES. PART ONE: SPELEOLOGICAL LITERATURE.
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REVIEW

THE SCIENCE OF SPELEOLOGY, edited by T.D. Ford and C.H. Cullingford. Academic Press, London, New York and San Francisco, 1976. pp xii + 593; 15 x 22.5 cm. Price in UK £14.00 stg. Review copy supplied by the authors.

The Science of Speleology has developed from the well-loved British Caving and consists of 14 chapters by no less than 22 authors, edited by Trevor Ford (editor of BCRA Transactions) and Cecil Cullingford (editor of the original British Caving). The list of chapters gives some idea of the scope of the book: Cave Surveys; Geology of Caves; Geomorphology and Caves; Caves in Rocks of Volcanic Origin; Erosion of Limestones; Hydrology of Limestone Terrains; Chemistry of Cave Waters; Cave Minerals and Speleothems; Physics of Caves; Cave Faunas; Cave Flora; Bats in Caves; Cave Palaeontology and Archaeology; The Computer in Speleology. This book is much more international in outlook than was British Caving; not all the authors are British (they include one Australian living in England and two Englishmen living in Australia as well as various North Americans) and most of the chapters are free of geographical bias, though the biological and archaeological chapters include specifically British sections.

Not surprisingly, individual chapters differ in standard and level, and in some cases the choice of topics seems to have been influenced by the people available to write them rather than vice-versa. The chapter on cave surveying is short and very rudimentary, aimed at the user of surveys rather than the surveyor. Trevor Ford's Geology of Caves is much more satisfying, indeed one of the best sections of the book, presenting virtually all the geology a speleologist needs to know in a very readable fashion. Gordon Warwick's following chapter on Geomorphology and Caves, though comprehensive, is rather pedestrian. However, the rather specialised chapters on limestone erosion, karst hydrology and cave-water chemistry also came within the general realm of cave geomorphology, and the four chapters together provide a more comprehensive source than is likely to be found anywhere else.

The three biological chapters provide a sound introduction to the field and an excellent guide to the literature. Archaeology, with only one chapter to cover a huge field, is inevitably only an outline, though more comprehensive on British material. Any more, though, would have detracted from the main aim of the book.

The remaining chapters are rather less easily categorised. Cave Minerals and Speleothems is superb, though quite heavy going. C. Wood's chapter on volcanic caves seems thorough enough to this reviewer, who has never set foot in such a cave. Cave Physics is no such thing - it is really two quite separate chapters, one on cave meteorology ond one on remote detèction of caves. Each is good, and they would have been better as separate chapters. The remaining chapter, The Computer in Speleology, seems, to be honest, to be of very dubious relevance. Whatever its merits, it is surely ridiculous to devote 28 pages to this subject and only 10 to cave surveying.

Overall, the book simply has no competition. In spite of its high price, it must find a place on every scientific caver's bookshelf, whether he be an amateur or a professional. The most telling proof must be the number of chapters from it cited as references - look for yourself in this issue of Helictite !

Guy Cox

STRUCTURE, SEDIMENTS AND SPELEOGENESIS AT CLIEFDEN CAVES, NEW SOUTH WALES

R. Armstrong L. Osborne

Abstract

The Cliefden Caves have developed in the Late Ordovician Cliefden Caves Limestone mainly by solution in the phreatic zone. Speleogenisis has been inhibited in steeply dipping thinly bedded limestone and shows a high degree of structural control. Collapse has been significant in late stage development of the caves. Much sediment has been deposited in the four caves studied in detail - Main Cliefden, Murder, Boonderoo and Transmission.

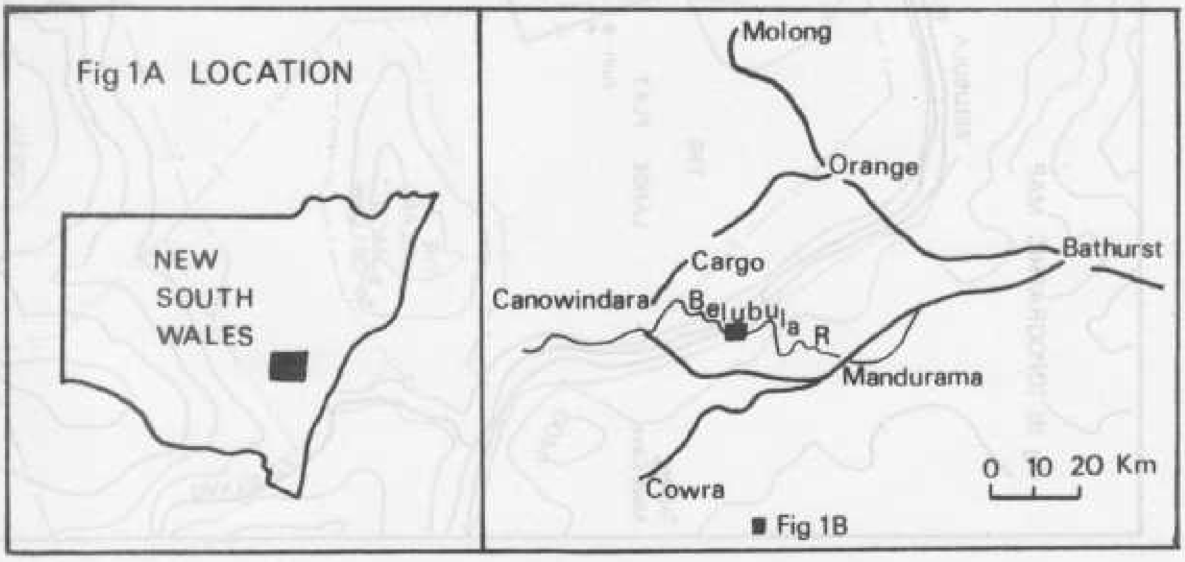
Formed in the phreatic zone, layered clay fill is the earliest sediment deposited and occurs in all but Transmission Cave. The phosphate mineral heterosite is found in these sediments. Subaqueous precipitation deposits deposited in the phreas or vadose pools are distinguished from speleothems by their texture. Aragonite is inferred to have been deposited in these sediments and to have since inverted to calcite. Friable loam and porous cavity fill are the most common vadose deposits in the caves. Vadose cementation has converted friable loam to porous cavity fill. Speleothem deposits are prolific in Main Cliefden, Murder and Boonderoo Caves. Helictites are related to porous wall surfaces, spar crystals result from flooding of caves in the vadose zone and blue stalactites are composed of aragonite. Cliefden Caves belong to that class proposed by Frank (1972) in which deposition has been more important than downcutting late in their developmental history.

INTRODUCTION

The Cliefden Caves are located in the valley of the Belubula River in central western New South Wales, approximately 30 km north east of Cowra and 50 km south of Orange. (Figure 1)

The Cliefden Caves Limestone in which the caves are developed was the first body of limestone to be discovered in inland Australia (Evans, 1915; Oxley, 1820). Caves were first reported in Department of Lands N.S.W. Plan No. B45691 of 1832 and first documented in some detail by Trickett (1908).

Anderson (1924) described Main Cliefden and related some of the history of the caves area. In 1932 and 1934 the Australian Museum collected specimens of speleothems from the caves many of which are now incorporated in the "Limestone Cave" exhibit at the Museum (Hodge-Smith, 1936).



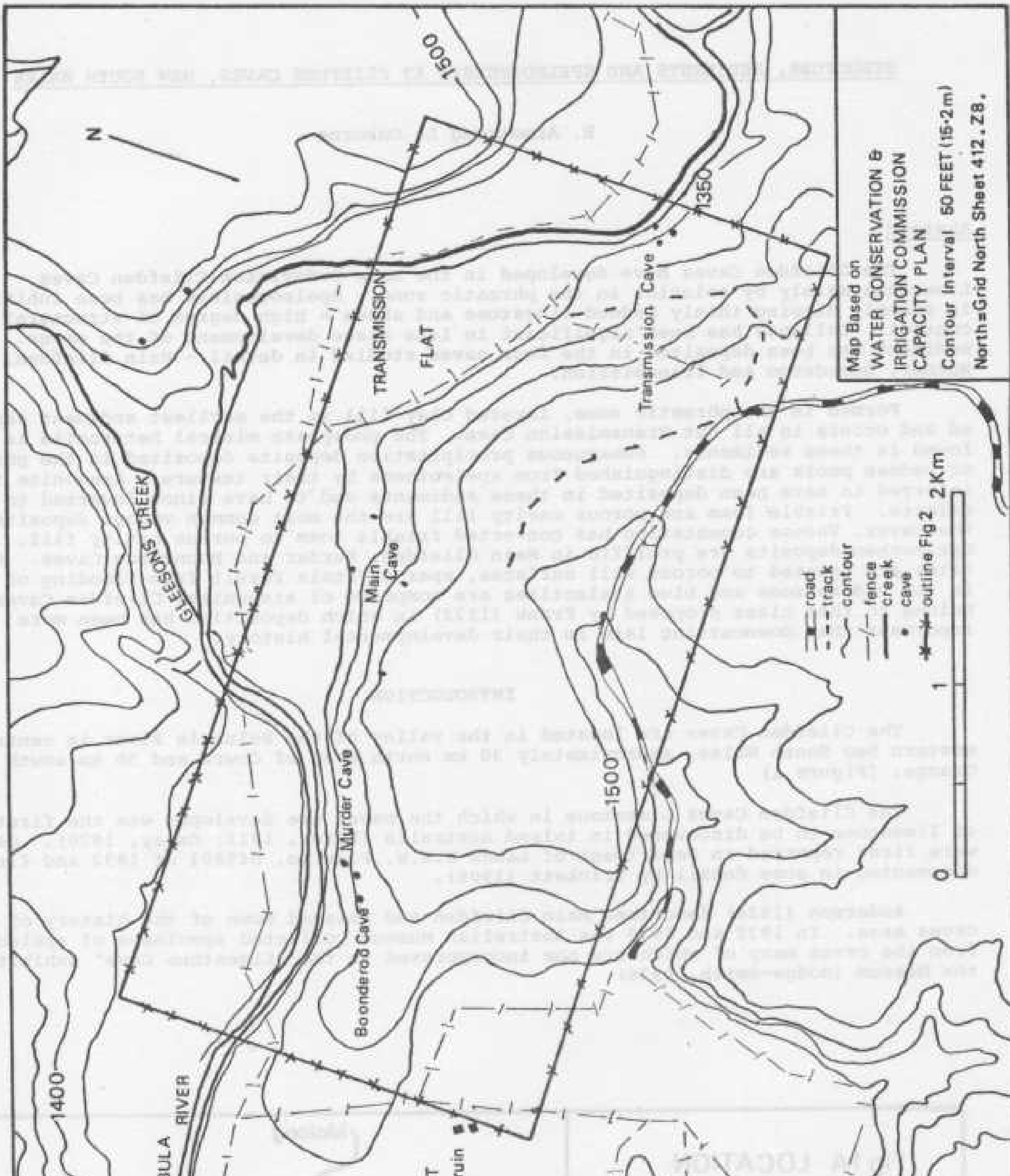


Fig 1B TOPOGRAPHIC MAP

In recent times much work has been carried out on the caves by speleological societies, particularly Orange Speleological Society and The University of New South Wales Speleological Society. This has resulted in the discovery of many additional caves to those earlier reported and the exploration and detailed surveying of most of the caves. In this paper the influence of structure and lithology on the development of five selected caves has been studied, together with the various associated cave sediments. The lettters U.S.G.D. followed by a five digit number refer to specimens housed in the petrology collection of the Department of Geology and Geophysics; University of Sydney while specimen numbers prefixed with "D" refer to specimens in the mineralogy collection of the Australian Musum, Sydney.

Petrographic descriptions of limestone follow the classification of Dunham (1962) while descriptions of pressure solution features and crystal aggregates follow Logan and Semeniuk (1976).

GEOLOGY

Cliefden Caves is located in the Molong High (Packham 1969), an area of andesitic volcanism and shallow water marine deposition during the early Paleozoic.

The basal formation in the Cliefden Caves area is the Walli Andesite (Stevens, 1952), consisting of altered basalts, andesites and breccias. These appear to have been deposited in a possibly sloping submarine environment (Smith, 1967), and have since been subject to burial metamorphism of the phrenite-pumpellyite facies, (Smith, 1968). The real nature of its boundary with the overlying Late Ordovician Cliefden Caves Limestone in the caves area is not apparent. In the Licking Hole Creek (Walli Caves) area this boundary is faulted (Percival, 1976).

The Cliefden Caves Limestone

Stevens (1952) described the Cliefden Caves Limestone as massive and shaly limestone and attributed a "Middle" Ordovician age to this formation. Webby (1974) concluded that the Cliefden Caves Limestone ranged in age from Gisbornian to Lower Eastonian (late Ordovician).

A three-fold subdivision of the limestone was introduced by Stevens (1952). The upper and lower members of this system were further subdivided into informal mapping units by Webby (1969). In this paper the subdivision of the limestone is expanded with the recognition of two major and four minor mappable units in the 130 metre thick middle member. The subdivisions used in this paper are based entirely on field relations and lithological considerations. Their use in this paper should in no way be considered to be a formalization of the subdivisions of the Cliefden Caves Limestone. The Fossil Hill Limestone Member is equivalent to the Lower Member of Stevens (1952) and is divided into seven units which are the informal units of Webby (1969).

The Boonderoo Limestone Member is equivalent to the Middle Member of Stevens (1952) and Webby (1969) and consists of a massive lower unit and an upper unit divisible into four subunits. The Upper Member of Stevens (1952) and Webby (1969) is here termed the Large Flat Limestone Member.

Fossil Hill Limestone Member

The Fossil Hill Limestone Member is exposed along the ridge leading to Main Cliefden and as an anticline on the southern side of the hill east of the Large Flat. Six of the seven units of Webby (1969) are recognisable in the cave area. (Figure 2)

This member consists alternately of massive and thinly bedded units. As no caves have developed in this formation, it will not be dealt with in detail here. The Fossil Hill Limestone Member is an important structural indicator with its easily recognised subdivisions exhibiting features not easily recognised in the overlying massive limestones.

Boonderoo Limestone Member

Lower Massive Unit

Though not exposed in its entirety in the caves area due to faulting and erosion by the river, the Lower Massive Unit conformably overlies the Fossil Hill Limestone Member. The boundary is marked by the easily recognised "lithic" unit of the Fossil Hill Limestone Member.

This Lower Massive Unit has a highly variable petrography ranging from wackestone to pelletal grainstone. Skeletal material is rare in this member, large quantities occurring only in restricted pods. Specimen U.S.G.D. 54300 consists of large brachiopod shells (? *Eodinobolus*), part of a pod towards the top of the unit. Scarce brachiopod and bryozoan fragments are the only other skeletal material, the main components being pellets and algal fragments.

Neomorphic features are common throughout this member. Specimen U.S.G.D. 54301 exhibits stylolites, sparry veins and zones where micrite cement has recrystallised to spar. Iron stylocumulate marks the stylolites and calcite reactate has formed between them. Cavity filling has occurred in two planes along the largest stylolites with microspar and fine equant calcite being deposited. Sparry veins run transverse to the stylolites and predate them.

The evidence of this specimen and the occurrence of sparry veins and stylobeds in outcrop indicate a complex post depositional history for this limestone.

Silica nodules in apparently continuous bands approximately one metre apart occur in the upper part of this unit. These are resistant to surface weathering but in the caves disintegrate to clay and their partially weathered remains are common in clastic cave deposits.

Upper Variable Unit

The 34 m thick Upper Member crops out in complete section near Murder Cave. This member is composed of well-defined alternating thinly and massively bedded subunits. (Figure 3). The lowest subunit is named after Murder Cave in which its boundary with the Lower is exposed. The unit consists of thinly-bedded, spar-cemented pelletal packstone (U.S.G.D. 54302) with sparse brachiopod and bryozoan fragments. The brachiopod fragments are recrystallised and surrounded by micrite envelopes. Large areas of spar indicate neomorphic alteration.

The Murder Subunit is overlain by a thin massive subunit with prominent outcrop, here named the Bold Subunit which is composed of pelletal packstone greatly affected by neomorphism. (U.S.G.D. 54303) Micrite matrix has been progressively recrystallised to spar. At least three generations of sparry veins and multiple stylolites indicate a major phase of pressure solution. The thinly bedded second highest unit of the Upper Member is named after Childrens Cave, near which it crops out. This a pelletal wackestone with a few brachiopod fragments, (U.S.G.D. 54304). Dark micrite has been recrystallised to spar producing dark and light patches in thin section.

A massive limestone with a bold outcrop pattern forms the uppermost subunit of the Boonderoo Limestone. Texturally this is a pelletal packstone with zones of micrite recrystallised to spar (U.S.G.D. 5405). Diagenetic texture in sample U.S.G.D. 54306 is lime mudstone with occasional groups of pellets eroded and the space filled first with spar and then with wackestone which has a much darker coloured micrite than that of the lime mudstone.

Large Flat Limestone Member

Island Unit

The Island Unit (Webby, 1969) which overlies the Boonderoo Limestone Member forms the central part of the Island, crops out in the Murder Cave section and on the hill east of the Large Flat. This unit consists of 20 m of light brown flaggy bedded limestone with bed thicknesses ranging from 20-50 mm. Percival (1976) described the texture as ranging from lime mudstone through to pelletal grainstone with pisolithic and skeletal packstones being the main constituents. Specimen U.S.G.D. 54307 from the Murder Cave section is a pelletal packstone rich in algal, bryozoan and brachiopod skeletal fragments. Stylolites have removed portions of the fossils and postdate replacement of the skeletal material by blocky spar.

Grey Unit

The Grey Unit is the uppermost 30 m of the Cliefden Caves Limestone and is overlaid by the Malongulli Formation. This massive limestone with a bold outcrop pattern crops out on the eastern end of the Island, on the hill east of the Large Flat and in the Murder Cave section.

Percival (1976) found the dominant texture to be wackestone and noted the lack of siliceous nodules in this limestone. U.S.G.D. 54308 from the Murder Cave section has an interesting assemblage of neomorphic features. At least three generations of sparry veins are recognised and these are postdated by stylolites. Fine reactate has been deposited between adjacent stylolites while other stylolites have been replaced by spar.

Malongulli Formation

The Malongulli Formation (Stevens, 1952) conformably overlies the Cliefden Caves Limestone at Trilobite Hill. Here it consists of spiculites, limestone breccias and finely laminated graptolitic shales. The lower units, shales and siltstones, contain an abundant Late Eastonian fauna of sponge spicules, graptolites, trilobites and brachiopods. (Webby, 1974).

Structure

The major structural feature of the Cliefden Caves area is a north easterly plunging anticline, the nose of which is represented by the limestone in the caves area (Figure 2). This structure is disrupted just east of Main Cliefden by a major fault which has considerably displaced the eastern limb of the anticline. The outcrop of Fossil Hill Limestone Member in the crest of the anticline to the southern side of

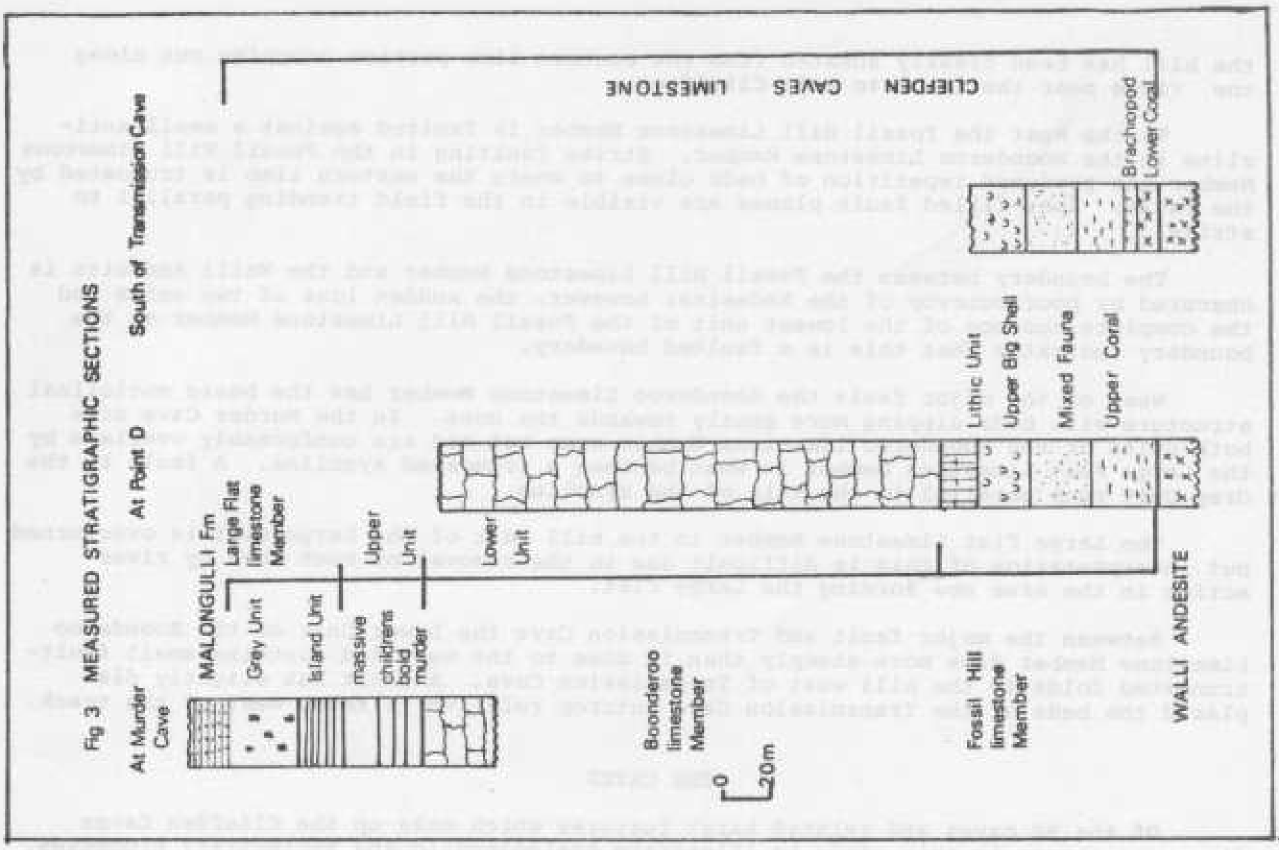


Fig 3 MEASURED STRATIGRAPHIC SECTIONS
At Murder Cave
At Point D
South of Transmission Cave
MALONGULLI Fm
Grey Unit
Island Unit
Large Flat limestone Member
Upper Unit
Lower Unit
Boonderoo limestone Member
Fossil Hill limestone Member
Lithic Unit
Upper Big Shell
Mixed Fauna
Upper Coral
Brachiopod
Lower Coral
WALLI ANDESITE
CLIEFDEN CAVES LIMESTONE
0
20m

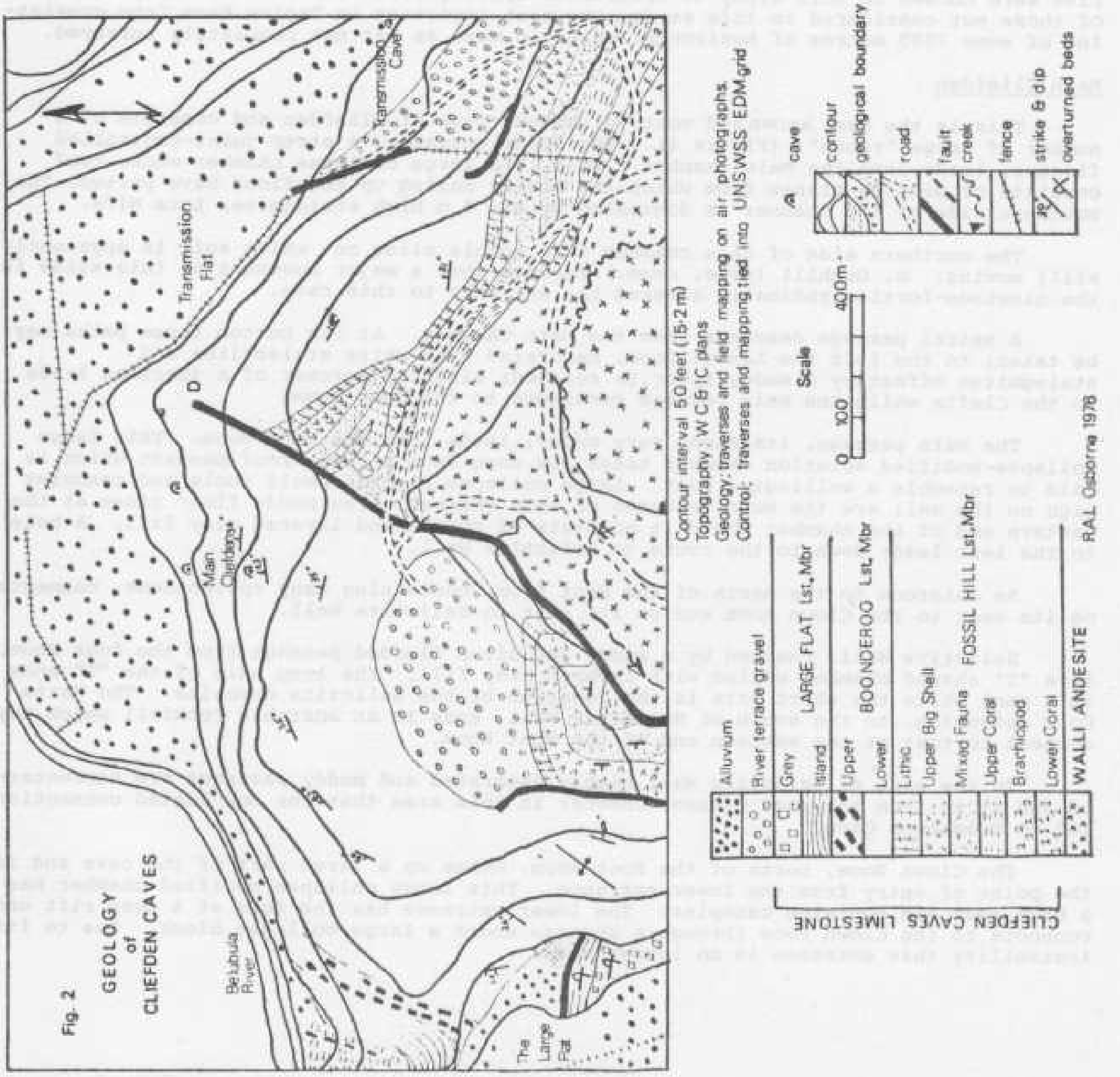


Fig. 2
GEOLOGY of CLIEFDEN CAVES
Belubula River
The Large Flat
Main Cliefden Cave
D
Transmission Flat
Transmission Cave
Contour interval 50 feet (15·2 m)
Topography W.C.&I.C. plans
Geology traverses and field mapping on air photographs
Control: traverses and mapping tied into UNSWSS EDM grid
Scale
0 100 400m
RAL Osborne 1978
Alluvium
River terrace gravel
Grey
Island
LARGE FLAT Lst. Mbr
Upper
Lower
BOONDEROO Lst. Mbr
Lithic
Upper Big Shell
Mixed Fauna
Upper Coral
Brachiopod
Lower Coral
FOSSIL HILL Lst. Mbr
WALLI ANDESITE
CLIEFDEN CAVES LIMESTONE
cave
contour
geological boundary
road
fault
creek
fence
strike & dip
overturned beds

the hill has been clearly sheared from the eastern limb portion cropping out along the ridge near the track to Main Cliefden.

To the West the Fossil Hill Limestone Member is faulted against a small anticline in the Boonderoo Limestone Member. Strike faulting in the Fossil Hill Limestone Member has produced repetition of beds close to where the eastern limb is truncated by the fault. Spar-filled fault planes are visible in the field trending parallel to strike.

The boundary between the Fossil Hill Limestone Member and the Walli Andesite is obscured by poor outcrop of the Andesite; however, the sudden loss of two units and the complete absence of the lowest unit of the Fossil Hill Limestone Member at the boundary indicates that this is a faulted boundary.

West of the major fault the Boonderoo Limestone Member has the basic anticlinal structure with beds dipping more gently towards the nose. In the Murder Cave area both units of the Boonderoo limestone Member crop out and are conformably overlain by the Large Flat Limestone Member in what becomes a truncated syncline. A fault in the Grey Unit runs parallel to the axis of the syncline.

The Large Flat Limestone Member in the hill east of the Large Flat is overturned but interpretation of this is difficult due to the removal of much rock by river action in the area now forming the Large Flat.

Between the major fault and Transmission Cave the Lower Unit of the Boonderoo Limestone Member dips more steeply than it does to the west and contains small fault-truncated folds in the hill west of Transmission Cave. A fault has slightly displaced the beds of the Transmission Cave outcrop relative to those west of the track.

THE CAVES

Of the 90 caves and related karst features which make up the Cliefden Caves five were chosen in this study to illustrate speleogenetic and sedimentary processes. Of those not considered in this study, the most important is Taplow Maze Cave consisting of some 7000 metres of horizontal phreatic maze as yet not completely surveyed.

Main Cliefden

This is the best known and most voluminous cave at Cliefden and consists of a number of large "rooms". (Figure 4). The Upper entrance, a steep joint-controlled fissure, leads into the Main Chamber. This is a large collapse chamber whose roof consists of bedding planes from which the blocks making up the floor have parted. The southern side of the chamber is dominated by the 5 m high stalagmite, Lots Wife.

The northern side of this chamber is a rubble slide on which soil is apparently still moving. B. Dunhill (pers. comm.) reports that a major movement of this slide in the nineteen-forties radically altered the entrance to this cave.

A spiral passage descends from the Main Chamber. At its bottom three paths may be taken; to the left the Laurel Room, decorated with white stalactites and stalagmites offset by a muddy floor,is reached; slightly further of a junction leads to the Clefts while the main passage continues to the Boot Room.

The main passage, its floor very muddy, leads into the Boot Room. This large collapse-modified solution chamber takes its name from a large roof pendant which is said to resemble a wellington boot. Large collapse blocks, small pools and canopies high on the wall are the main features of this chamber. The muddy floor rises at the eastern end of the chamber where it consists of rubble and layered clay fill. A hole to the left leads down to the route to Helictite Wall.

An anteroom to the north of the Boot Room, containing many speleothems, connects on its west to the Clown Room and on its east to Helictite Wall.

Helictite Wall, reached by a muddy and often flooded passage from the Boot Room, is a "T" shaped chamber walled with layered clay fill. The long axis of the "T" ends in a pool while the short axis is the location of the helictite deposits. The Matts Hole extension, to the south of Helictite Wall, ends in an unstable rockfall which may connect to that at the eastern end of the Boot Room.

To the east of Helictite Wall highly decorated and muddy passages are encountered and it is from the most distant chamber in this area that the now sealed connection led to Noonamena Cave.

The Clown Room, north of the Boot Room, makes up a large part of the cave and is the point of entry from the lower entrance. This large collapse modified chamber has a high roof and contains canopies. The lower entrance has the form of a deep rift and connects to the Clown Room through a squeeze under a large collapse block. Due to its instability this entrance is no longer used.

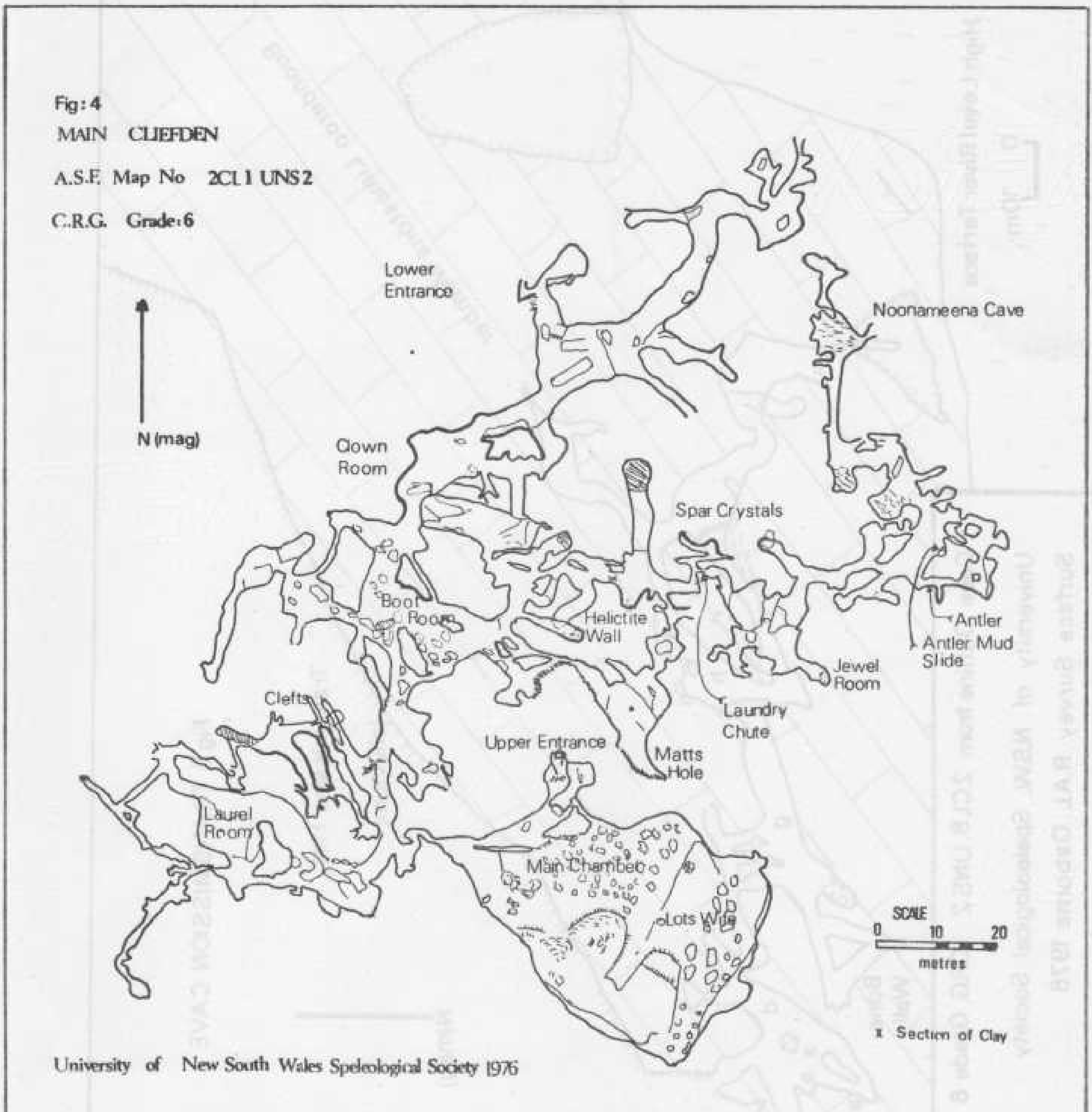


Fig: 4
MAIN CLIEFDEN
A.S.F. Map No 2CL1 UNS2
C.R.G. Grade: 6
N (mag)
Lower Entrance
Clown Room
Boot Room
Clefts
Laurel Room
Upper Entrance
Main Chamber
Lots Wide
Helictite Wall
Matts Hole
Spar Crystals
Laundry Chute
Jewel Room
Noonameena Cave
Antler
Antler Mud Slide
SCALE
0 10 20
metres
x Section of Clay
University of New South Wales Speleological Society 1976

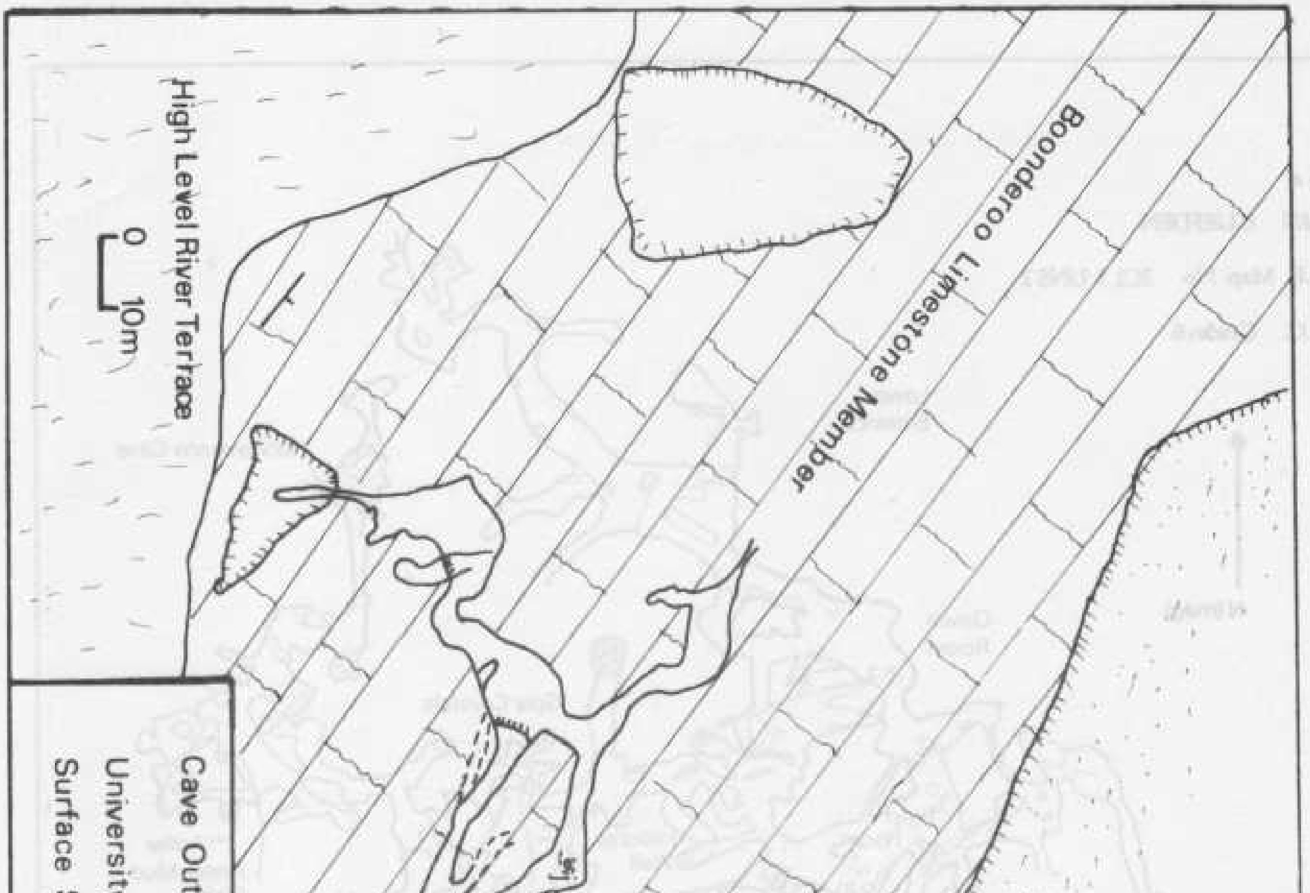


Fig 5 TRANSMISSION CAVE
Transmission Flat
(alluvium)
N(mag)
Boonderoo Limestone Member
High Level River Terrace
0 10m
Bone Wall
Cave Outline from 2CL8, UNS 2 C.R.G. Grade 6
University of N.S.W. Speleological Society
Surface Survey R.A.L. Osborne 1976

Murder Cave and Childrens Cave

These two caves open off a large double collapse doline and are genetically part of the one cave. Childrens Cave opens from the western opening of the doline, its floor being continuous with that of the doline. The cave has developed along strike and has prominent rock pendants and ceiling pockets. The cave floor is mostly dry soil with a few patches of dry flowstone. Many dry speleothems, particularly stalagmites, occur in the main chamber of the cave and a few of these show signs of rejuvenation. An impenetrable daylight hole extends from the end of the cave.

The entrance to Murder Cave, located under a rockfall below the eastern opening of the doline, drops into the top of a high collapse modified chamber. A rockfall leads to the floor of this chamber; at its base a short level passage leads into the main chamber.

The main chamber is a rectangular room with its long axis developed along strike. The chamber contains a few orange flowstones and stalactites most of which are dry and inactive. *Deckenkarren* and clay-filled tubes occur in the ceiling.

A narrow sinuous passage at the southern end of the main chamber comes to a dead end while the remainder of the cave is reached through a rift in the ceiling. The floor of the passage reached from the rift slopes to the east and is split in places into parallel passages by rubble on the western side while the eastern side has the form of a rubble filled rift except where side passages lead out.

The passage opens out into a large sloping floored chamber with an eastwards dipping joint controlled roof. The western wall of the chamber consists of rubble and soil.

From here the cave splits into the Left Hand Branch and the Right Hand Branch which unlike the rest of the cave are quite moist. The Left Hand Branch extends to the east of the line of the cave and consists of high roofed passages with many active speleothems. The Right Hand Branch extends up to the west and its final wide passage, which contains a blue stalactite, terminates in a wall of clay.

Boonderoo Cave

Boonderoo Cave is entered through a vertical shaft which drops 2 m into a narrow tube leading into a wide low-roofed chamber. This is really the upper level of a large rectangular chamber divided up by rockfalls. Once the bottom of the chamber is reached it can be seen to have a high rift-like roof and almost perpendicular walls. This chamber is very wet and highly decorated. Another large chamber occurs parallel to the first chamber to the west at a higher level and its wall is controlled by a lithological boundary. This chamber contains canopy and stalactite deposits. At the southern end of this chamber a small muddy tube leads to the remainder of the cave. The chamber containing the blue stalactite branches off to the west and has also developed along a lithological boundary.

From the east of this tube the more remote sections of the cave are reached. These are wet and muddy with almost vertical bedding planes forming the walls and contain mudslides and false floors. Towards the southern end of the cave the roof of a collapse chamber has many tubular stalactites ("straws") and is known as the Milk Bar.

Transmission Cave

This cave can be best described in three sections, a dusty outer chamber, a main axis of cave development and a complex spongework. The outer chamber, entered by a half tube, has developed along strike and features roof pendants and sharp blades projecting from the wall. Its eastern end is in a bedding plane and is connected to the surface by joints while a series of dusty tubes lead from the western end to the remainder of the cave.

The main axis of cave development is dominated by a high chamber with bell holes in its roof. Under a flowstone to the east of this chamber is the collapse chamber which ends in Bone Wall.

From the western end of the large chamber the cave extends as a complex three-dimensional spongework of rock bridges, blades and spiral tunnels to which maps of the cave, not surprisingly, fail to do justice.

Cliff Cave

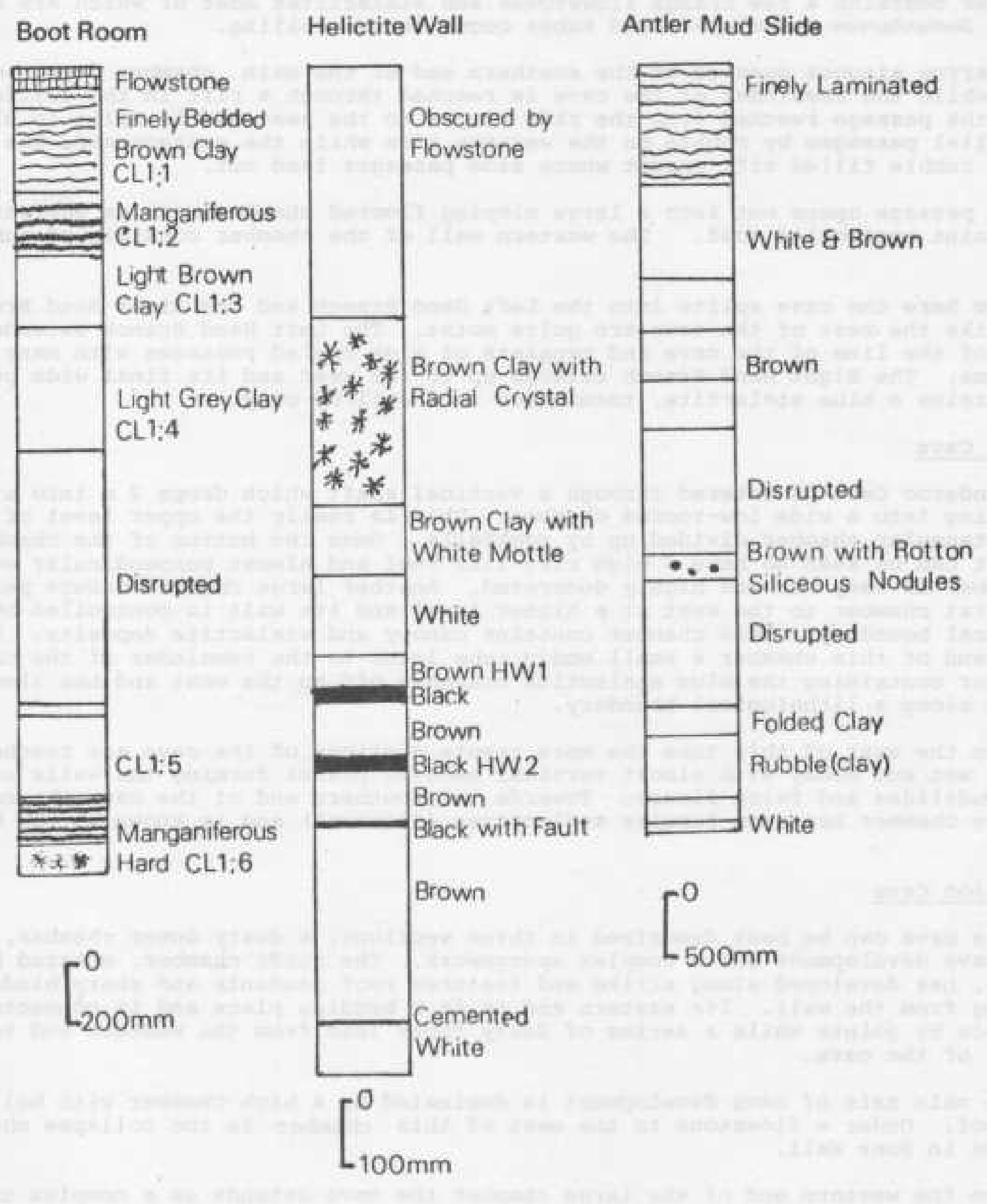
Located high on the eastern face of the Island outcrop Cliff Cave is entered by a broad low entrance through cemented fill. Just inside the entrance the floor falls away in a boulder pile which drops to a sloping soil floor. This part of the cave is a high rift-like chamber apparently developed along a joint. The western end of this chamber is partially blocked by a deposit of crystalline fill.

SEDIMENTS

Layered Clay Fill

Layered clay fill is the most important sediment in Main Cliefden Cave and also

Fig 6 LAYERED CLAY FILL DEPOSITS, MAIN CLIEFDEN



in both Boonderoo and Murder Caves. Typical deposits consist of water-saturated heavy clay with a variety of black, brown and white laminations approximately 10 mm thick with beds of cemented material and radial crystal growths in some localities.

In both Main Cliefden and Boonderoo Caves remnants of layered clay fill occur adhering to walls and ceilings. The extent of these deposits in Main Cliefden and the inclusion of this material in pockets high in the Boot Room and as false floors suggest that this sediment may have once filled Main Cliefden almost completely. In areas north of the Laundry Chute the floor and walls of passages frequently consist entirely of layered clay fill.

Active erosion of this material is continuing in all three caves today and can be observed in Main Cliefden where small tunnels are being emptied of fill.

Detailed study of this deposit was restricted to Main Cliefden where samples were examined from sections near Boot Room, at Helictite Wall and from the Antler Mud Slide (Figure 6).

Towards the top of the deposits a marker horizon of well laminated clay with alternating black and brown layers is recognisable at approximately the same level throughout much of Main Cliefden. Radial fibrous crystals of calcite occur in these horizons.

Chemical tests of the dark laminations showed that they contained maganese and phosphate. X-ray powder diffraction indicated that this manganese and phosphate was in the phase heterosite, $(Fe^{3+}, Mn^{3+})PO_4$.

Deposition of finely laminated clays requires a low energy subaqueous environment. The high position of fill remnants in the caves indicate that at the time of deposition much of the caves were filled with water. Some of the strata contain significant sand fractions, Appendix 1A, but on examination these are found to consist of sparry and cryptocrystalline calcite probably derived from within the cave.

Thin sections of clays from Main Cliefden, Specimens U.S.G.D. 54309 and 54310, contain much fine calcite. This calcite was determined by digestion, (Appendix 1B). This indicates that carbonate deposition was occurring contemporaneously with clay deposition.

The lowest stratum of the section near Boot Room consists of radiating crystals and clay. These crystals have a peculiar "weathered" appearance which is discussed at a later stage. At Helictite Wall the clay section is disrupted by a small fault.

These clay deposits could either be the result of late phreatic processes (Bretz, 1942) or of deep phreatic deposition (Thrailkill, 1968). Both these theoretical situations would provide the environment in which finely laminated clays and calcite could be deposited together. The presence of silica nodules derived from the limestone and sand-sized crystal indicates that some of the material may be autochthonous but it is likely, as suggested by Bretz (1942), Bogli (1961) and Jennings (1971), that most of the clay material was derived from the surface. High level river terraces and clay soils from the Walli Andesite appea to be the most likely sources for this material.

Porous Cavity Fill

Porous cavity fill occurs in the entrances to many caves, along solution enlarged joints and between rocks in talus slopes. These sediments occur in the entrances to Main Cliefden and Cliff Cave.

In hand specimen, porous cavity fill has a light orange colour and consists of an amorphous matrix, often with small cavities in it, containing a few clasts of variable size, rounding and petrography.

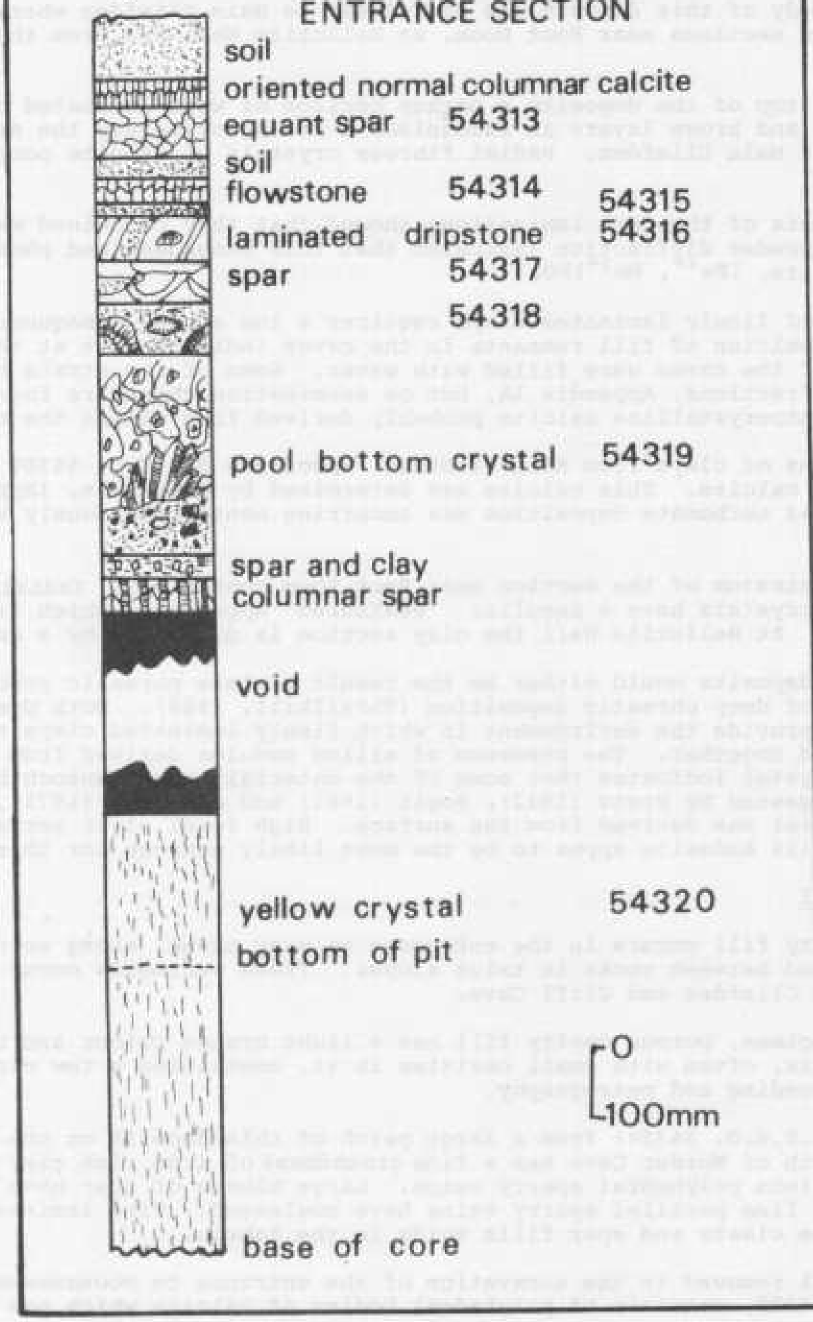
A sample (U.S.G.D. 54324) from a large patch of this deposit on the western side of the doline south of Murder Cave has a fine groundmass of iron rich clay and calcite which is divided into polyhedral sparry veins. Large blocks of spar have formed where a series of fine parallel sparry veins have coalesced. Fine laminae of spar surround limestone clasts and spar fills voids in the fabric.

The material removed in the excavation of the entrance to Noonameena Cave, sample U.S.G.D. 54325, consists of polyhedral bodies of calcite which has invaded and surrounded the clay.

Sample U.S.G.D. 54328 from the entrance to Carripan Cave consists of clay, calcite and spar lined voids and here again the spar has invaded and surrounded the clay. This texture is best developed in sample U.S.G.D. 54328 taken from the entrance to Cliff Cave. Rounded masses of clay surrounded by calcite are the main components of this material.

Brain (1958) proposed that such sediments were formed by precipitation of calcite from water percolating through fill material. It is possible to recognise at Cliefden a genetic sequence for this process. The parent material, dry friable loam, has been altered by percolation of saturated water resulting in a reduction in voids and an increase in the ratio of calcite to clay.

Fig 7 TRANSMISSION CAVE ENTRANCE SECTION



Sample U.S.G.D. 54329, has 15% voids and 29% calcite (a calcite/clay ratio of 0.5). Further movement of saturated water will result in a further reduction in voids as in specimen U.S.G.D. 54328 with only 5% voids. The final result of this process is seen in specimen U.S.G.D. 54325 from Noonameena Cave which has a calcite/clay ratio of 1:1.

Similar origin to porous cavity fill is the calcite-cemented bone breccia which occurs in Transmission Cave. This deposit consists of a mingling of clay, pebbles and bone fragments cemented by invading veins of calcite. The clastic components of this deposit presumably accumulated in a surface depression connecting to the interior of the cave. The pebbles are well rounded and volcanic, probably derived from the Walli Andesite, with the rounding being the result of river action on the terrace above the cave which this deposit postdates.

Cementation was produced in a similar way to that of the porous cavity fill but has resulted in large veins of spar rather than the small zones of the porous cavity fill.

Deposits similar to porous cavity fill occur among rocks on talus slopes and in solution enlarged joints. Lattman and Sinonberg (1971) report that the surface of colluvial mantles in a carbonate terrain may become cemented within two years of being exposed to the atmosphere in road cuttings. They concluded that infiltration from rainfall was the major cause of this process.

Although this is a similar process to that producing porous cavity fill, the rates of cementation may differ considerably due to the likely high saturation of vadose seepage and the usually dry state of cave loam.

Subaqueous Precipitation Deposits

Deposition of carbonates from bodies of saturated water produces sediments of the type herein classified as subaqueous precipitation deposits. Such deposits are briefly described by Kukla and Lizek (1958) as "sinter beds" while Frank (1972) describes "flow calcite" which would be classified as a member of this group. White (1976) describes "sub-aqueous carbonate deposits" which include some, but not all, of the sediments here classified as subaqueous precipitation deposits.

Excavation of the entrance to Transmission Cave revealed a complex sequence of these sediments, Figure 7, with other important occurrences being in Cliff Cave, at the base of clay sequences in Main Cliefden and in the Murder Cave doline.

Pool bottom crystals are common subaqueous deposits which may be precipitated either in small isolated perched bodies of water or at the base of a major phreatic body.

Pool bottom crystals are in habit not unlike flowstone since both consist of oriented normal columnar calcite which may or may not be graded.

In thin section, pool bottom crystals are often slightly radiated and develop on their upper surfaces individual spar crystals which in specimen U.S.G.D. 54312, from the entrance to Transmission Cave, have clay and fine precipitates filling in between them. Flowstone can be distinguished from pool bottom crystals in thin sections by lack of large individual crystal development on its upper surface due to the limiting effect of the depositing film. Flowstone tends to consist of more oriented crystals than do pool bottom deposits, though the latter tend to have the long axis perpendicular to the bottom and side.

Equant spar is an important component of subaqueous precipitation deposits. Crystals may range in size from less than 0.1 mm to 6 mm in size in sample U.S.G.D. 54313. Crystal sizes are generally fairly constant for any particular area of spar.

Equant spar can be shown to be the result of three processes: primary deposition, secondary deposition from percolating water and inversion of acicular fibrous carbonates.

Secondary deposition can be seen in specimen U.S.G.D. 54318 (Plate 1B) in which large equant spar has invaded fine spar forming lensoidal vugs. Inversion of acicular fibrous crystals to equant spar can be seen in specimens U.S.G.D. 54315 and 54312, both from the entrance to Transmission Cave. Fine equant spar, apparently of a primary origin, is often associated with clay (U.S.G.D. 54317) and this clay may provide points of nucleation on which primary equant spar forms.

The availability of many points of nucleation would control whether a body of saturated water would deposit either pool bottom crystals- nucleation on walls and floor - of equant spar - nucleation within the water itself.

Microspar is an important minor constituent of subaqueous precipitation deposits and occurs both in laminar and botryoidal forms, sample U.S.G.D. 54317, or as fine vein filling between clay patches. Although most of the microspar is a secondary vein deposit the laminated and botryoidal forms appear to be primary.

One stratum of a series of false floors in Transmission Cave consists of a

Fig 8 EDGEWISE CONGLOMERATE
TRANSMISSION CAVE

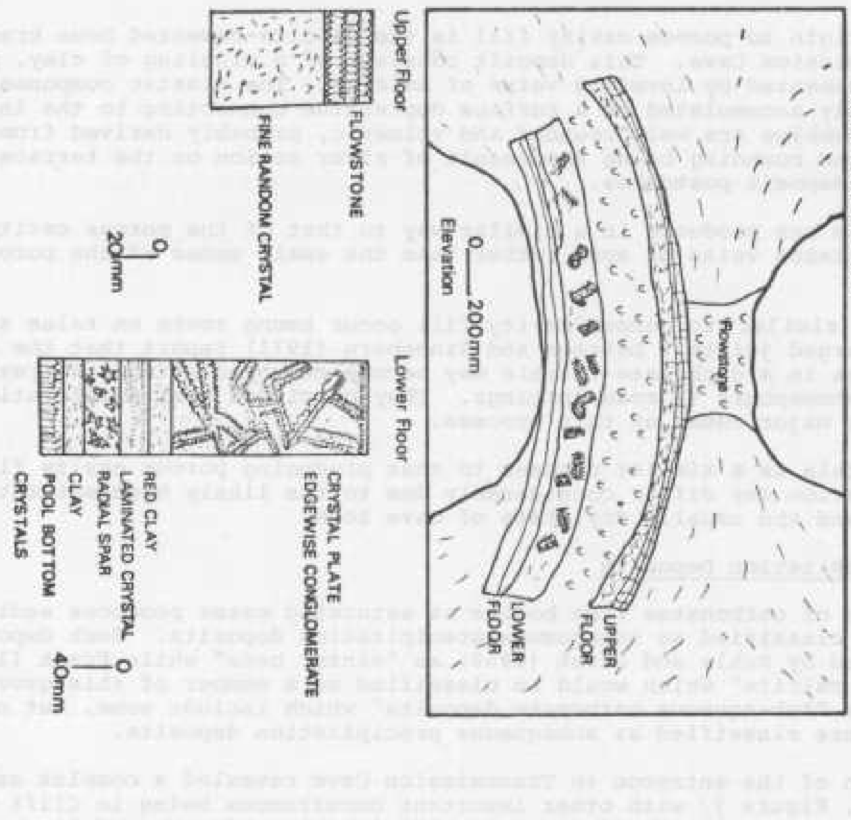
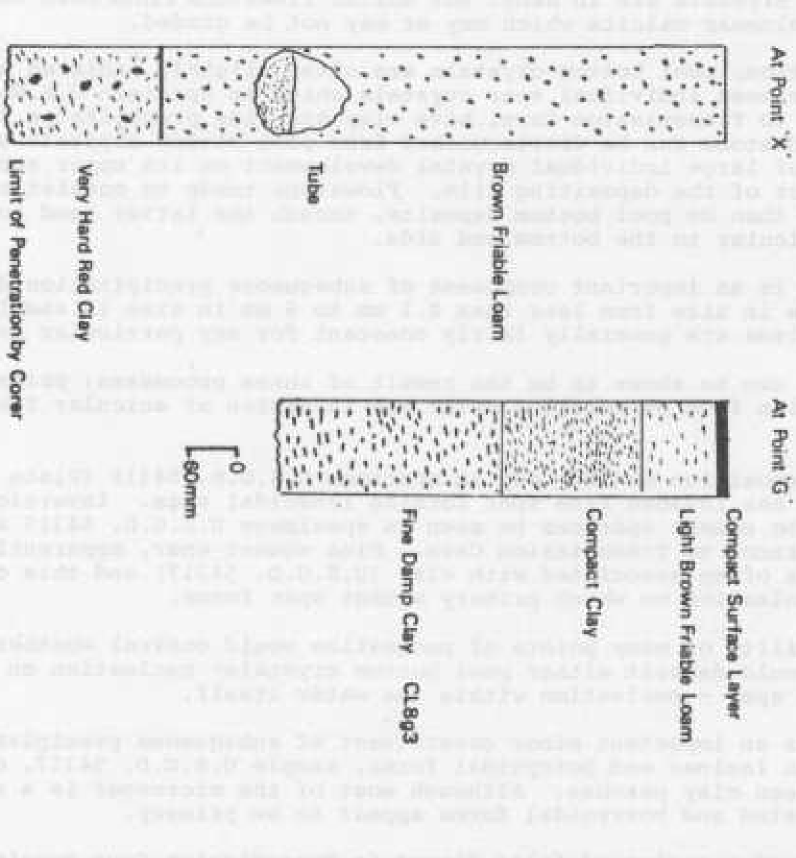


Fig 9 CAVE LOAM: TRANSMISSION CAVE



sediment best described as an edgewise crystal conglomerate. The features of this deposit and the section in which it occurs are shown in Figure 8. It consists of plates of oriented normal columnar crystals grown on either side of a thin layer of clay. The plates are arranged in a random fashion, Plate 1G, and are cemented together by crystals which have grown between them.

This sediment is separated from the underlying fine crystal deposit by an erosional boundary and so would appear to have been emplaced by the action of running water. It would appear that the crystal plates were formed by precipitation elsewhere in the cave and were transported to their present position by running water. Following their emplacement still water conditions allowed the precipitation of the crystal material which now cements the plates together.

Possible Subaqueous Deposition of Aragonite in Caves

Crystalline sediments consisting of fibrous acicular crystals often arranged in radial masses occur in the lower strata of layered clay fill deposits of Main Cliefden, in the entrance section at Transmission Cave, and compose the sediment filling the end of Cliff Cave.

This material from Cliff Cave consists of interlocking masses of radiating crystal in-filled with clay and sparry vugs. In thin section (U.S.G.D. 54323) the crystal masses appear as fine, yellow plumose crystal groups. The composite crystals have an acicular sub-radiating habit and extinguish parallel to the growth orientation. X-ray diffraction revealed these crystals to be calcite. Areas of equant spar appear to be growing at the expense of the acicular crystals.

The radial crystals from the layered clay deposits of Main Cliefden (U.S.G.D. 54326) consist of poorly defined acicular plumose crystal groups which have an unusual "weathered" appearance. Equant calcite occurs between these groups and does not exhibit this "weathered" appearance. The equant spar often extinguishes simultaneously with the surrounding acicular groups and in some places appears to be replacing them.

These two cases indicate that the acicular crystals are inverting to equant spar. Specimen U.S.G.D. 54315 from the entrance to Transmission Cave gives clear textural evidence for this. In thin section this specimen is seen to consist of plumose yellow crystal groups and clear equant spar. Some grains of spar contain yellow patches with some remnant acicular structure. These patches however, behave as part of the equant spar grain and go to extinction with the rest of the grain. This indicates a textural inversion of the yellow plumose crystals to the clear equant spar with the yellow colouring being a relic feature.

The habit of the yellow plumose crystals resembles that of aragonite and the inversion of the calcite pseudomorphs to clear equant spar would similarly suggest that the original deposit was unstable under existing conditions in the caves. This inversion is a two stage process, the first stage involving the loss of the aragonite structure as shown by X-ray diffraction indicating this material to be calcite. The second stage is a textural inversion to equant spar as is indicated by study of thin sections of this material. Textural inversion in samples U.S.G.D. 54315 and 54323 is related to sparry veins indicating that post-depositional seepage is a major factor in producing these inversions.

Precipitation of aragonite under the conditions found in caves (1 atm and 20^{o}C) can be achieved (Lippman, 1973) if a solution can be made saturated with respect to aragonite. This saturation can only be achieved if calcite is inhibited from precipitating. Certain ions, notably Mg^{2+}, have this ability (Lippman, 1973) and it is likely that such a mechanism was responsible for the original deposition of the aragonite. Vadose seepage water, responsible for forming the veins, would remove the ions stabilising the aragonite and so lead to its inversion. The influence of vadose water on the inversion of aragonite to calcite in recent reef limestones is well accepted (Bathurst, 1975) and I believe that this mechanism is responsible for the inversions described here.

Aragonite deposits similar to those just described have been reported in the form of algal tufa in the Dead Sea (Buchbinder et al.,1974) and as marine cavity fills in reef limestone, (Ginsberg and James, 1976).

Entrance Facies Deposits

Entrance facies deposits were studied in Childrens Cave, Transmission Cave and Cliff Cave. At each of these localities exploratory pits were dug in deposits of cave loam near the cave entrance. The sequences revealed at Transmission Cave and Cliff Cave were very uniform and friable, indicating deposition by gravitation with little water involved. A pipe formed at a depth of 560 mm in the Transmission Cave deposits appeared to form a sub-surface drainage system although at the time of excavation this was quite dry.

The excavation in Childrens Cave reached solid limestone at a depth of 1.4 metres and the sediments exposed reflect the history of this cave's entrance (Figure 10a; plate 2). At a depth of 0.2 m a major change in sediment type occurs. Above the boundary the sediment is friable, organic rich loam with a structure representing a filled surface water course. Below the boundary are 0.2 m of calcareous sand underlain by clay with large boulders of limestone.

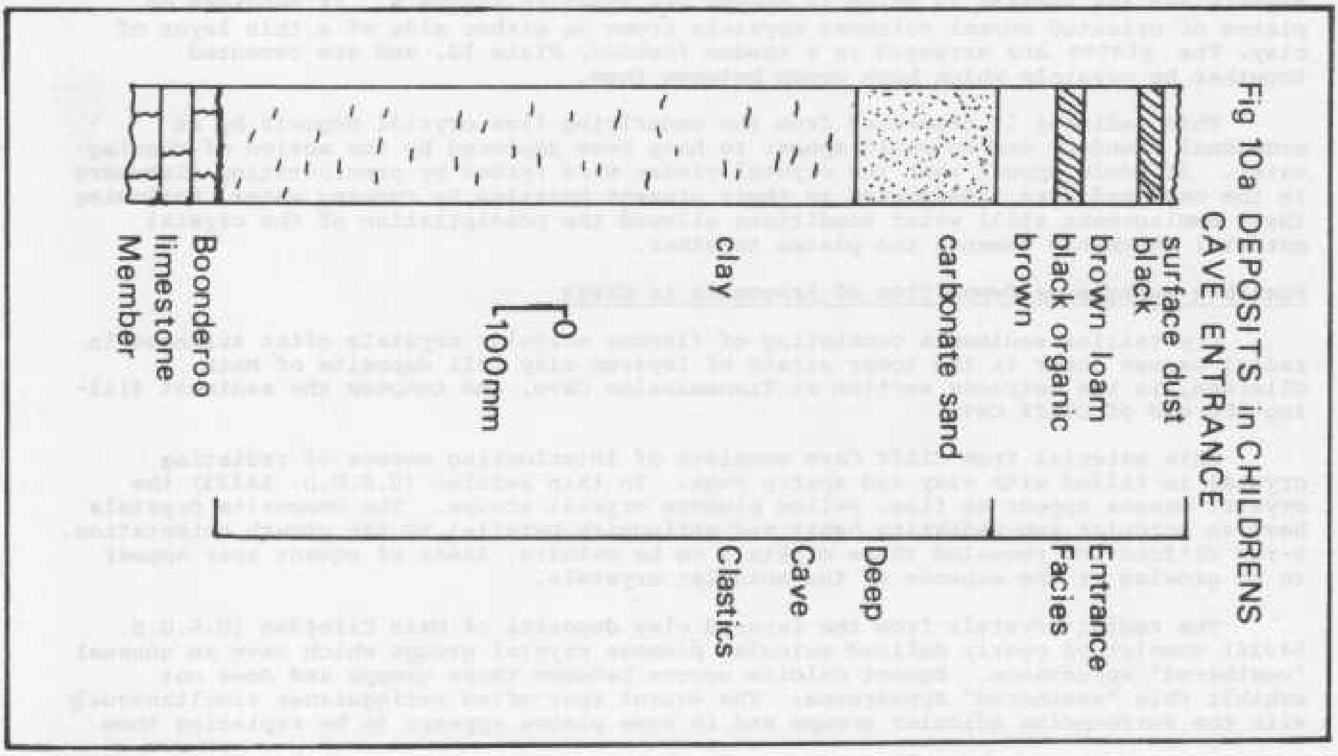


Fig 10a DEPOSITS in CHILDRENS CAVE ENTRANCE

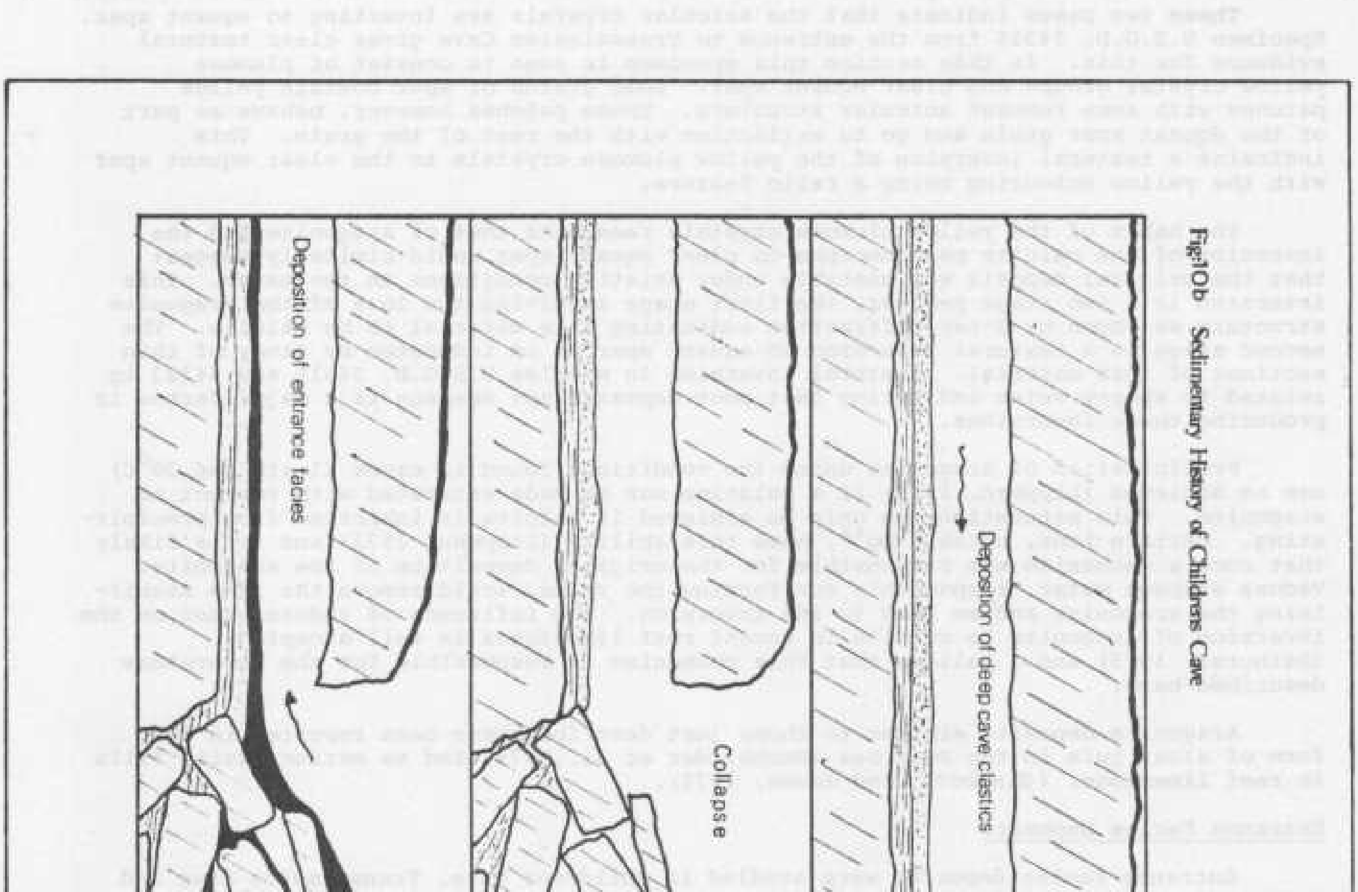
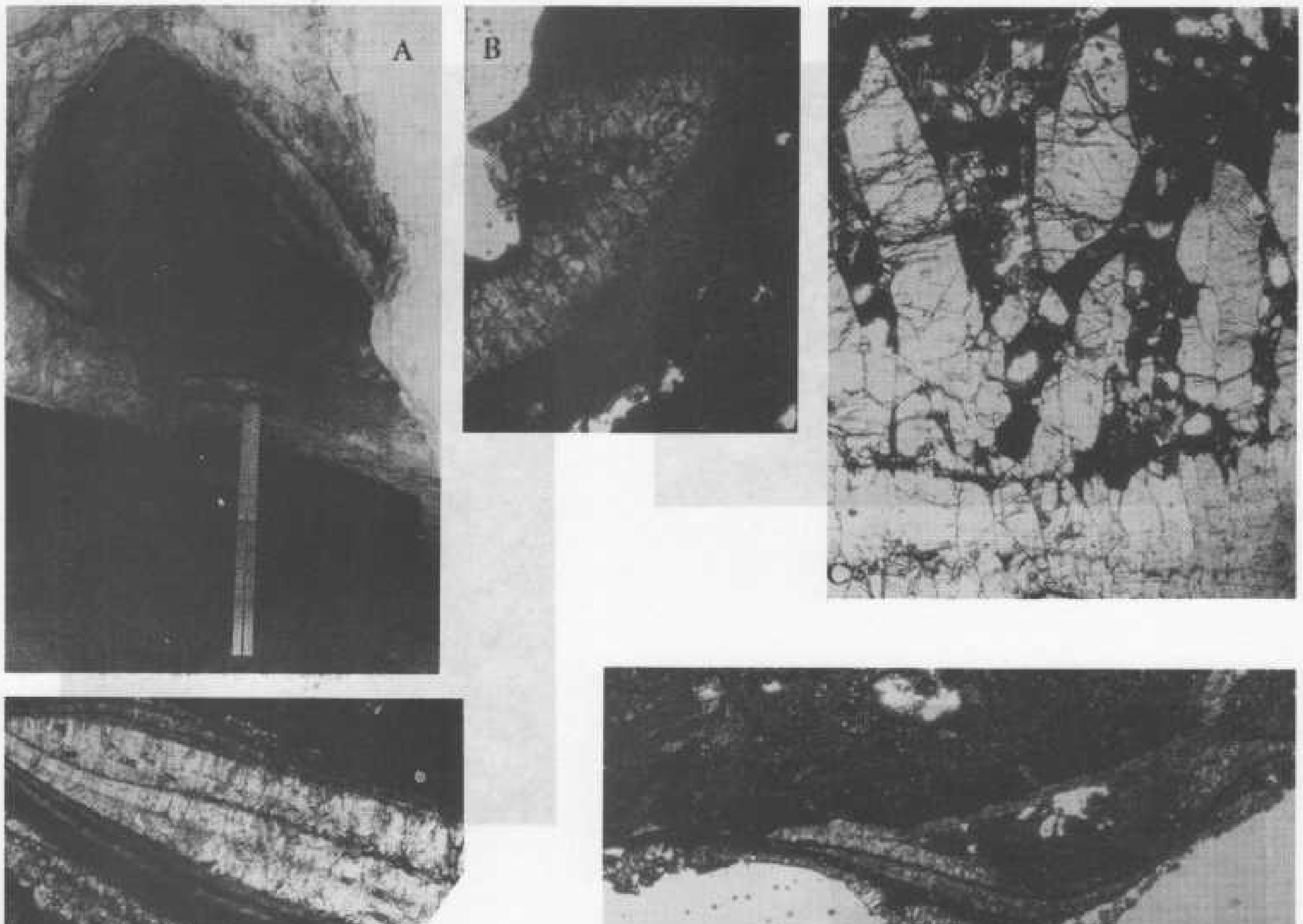


Fig 10b Sedimentary History of Childrens Cave

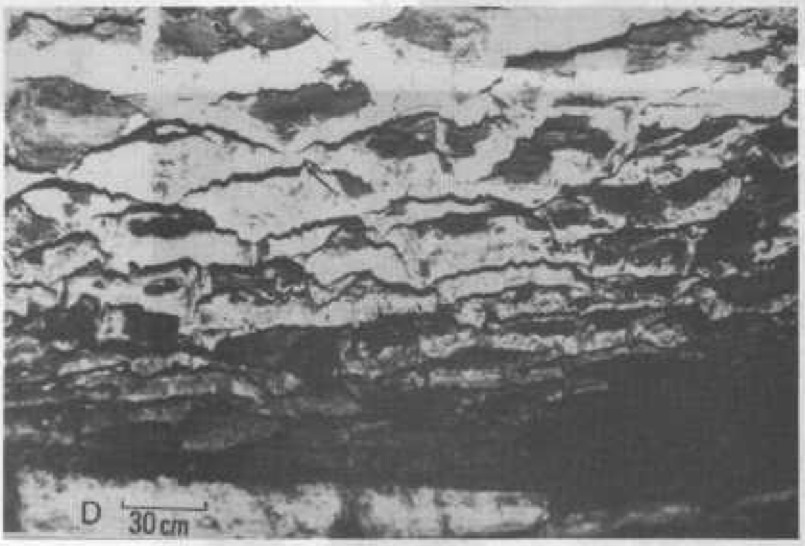


A: Entrance to Transmission Cave showing false floor.
B: Slide No. 54318 magnification approx. 2.5x, showing vugh of large spar developed in microspar groundmass.
C: Pool Bottom Crystals, Slide No. 54312 magnification approx. 3x, dark clay has filled in between large columnar spar.
D: Laminated Dripstone, Slide No. 54316 magnification approx. 4x.
E: Slide No. 54317 magnification approx. 3x.
F: Pool Bottom Crystals, Slide No. 54319 magnification approx. 2x.
G: Top false floor at point "k".

A

B

C



D

Plate 2. A: Layered Clay Fill in section near Helictite Wall. A small fault can be seen in the centre of the photograph.
B: Slide U.S.G.D. 54315, from the entrance to Transmission Cave, Plane Polarised Light, 2x. This shows inversion of fibrous calcite pseudomorphs after aragonite into equant spar. Relic texture is preserved in the centres of the two equant grains just right of mid-field.
C: Sampling pit dig in the centre
C: Sampling pit dug in the entrance of Childrens Cave. Layer of carbonate sand and halo around limestone block are clearly visible.
D: Underside of false flowstone floor in Clown Cave. Boxwork was produced by flowstone filling mudcracks in the clay then being removed.

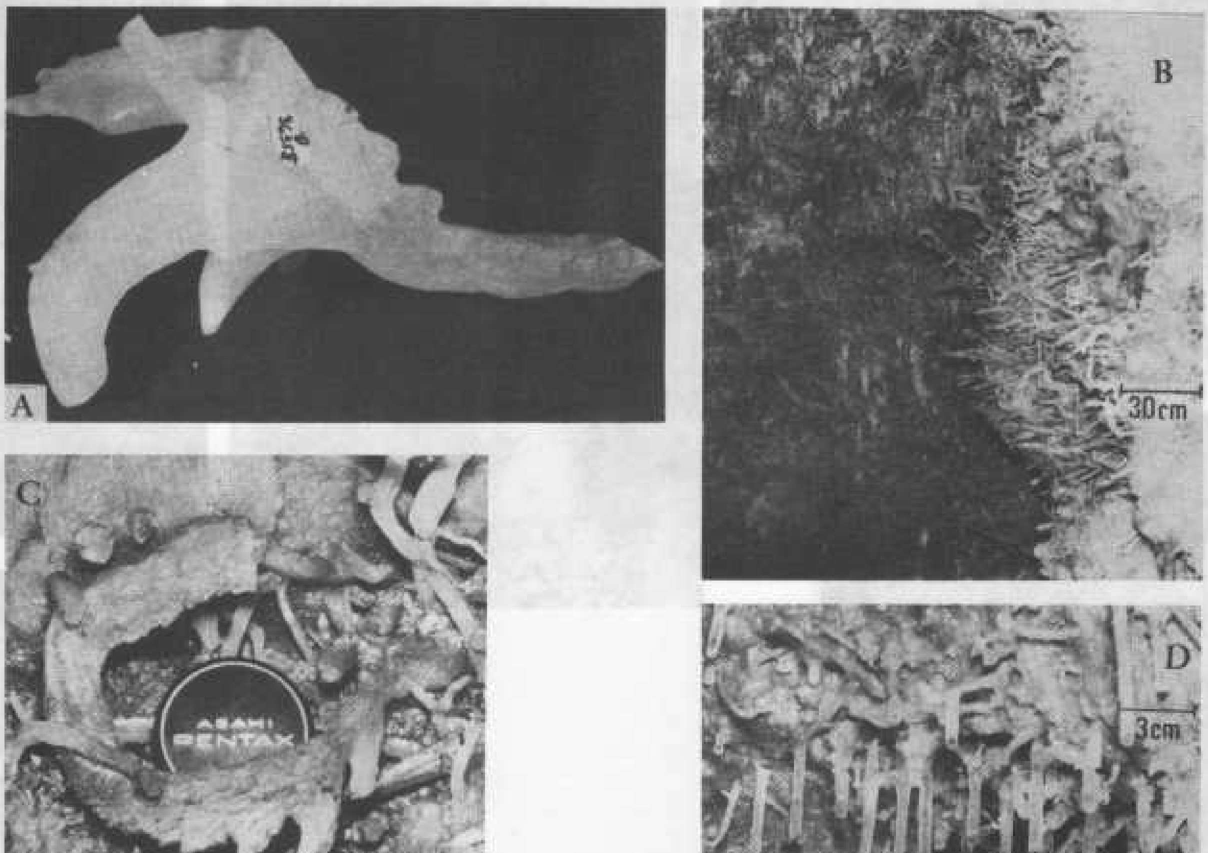


Plate 3. A: Museum specimen D 36358 illustrating the branching form of helictites. Label 10 mm long.
B: View of Helictite Wall illustrating the size of the deposit and the density with which the wall is covered by helictites.
C: Cleavage rhombs visible in helictite at Helictite Wall.
D: Monocrystaline tubular stalactites and helictites near Spar Crystals.
E: The Antler.
F: The Pretzel, a complex planospiral helictite.

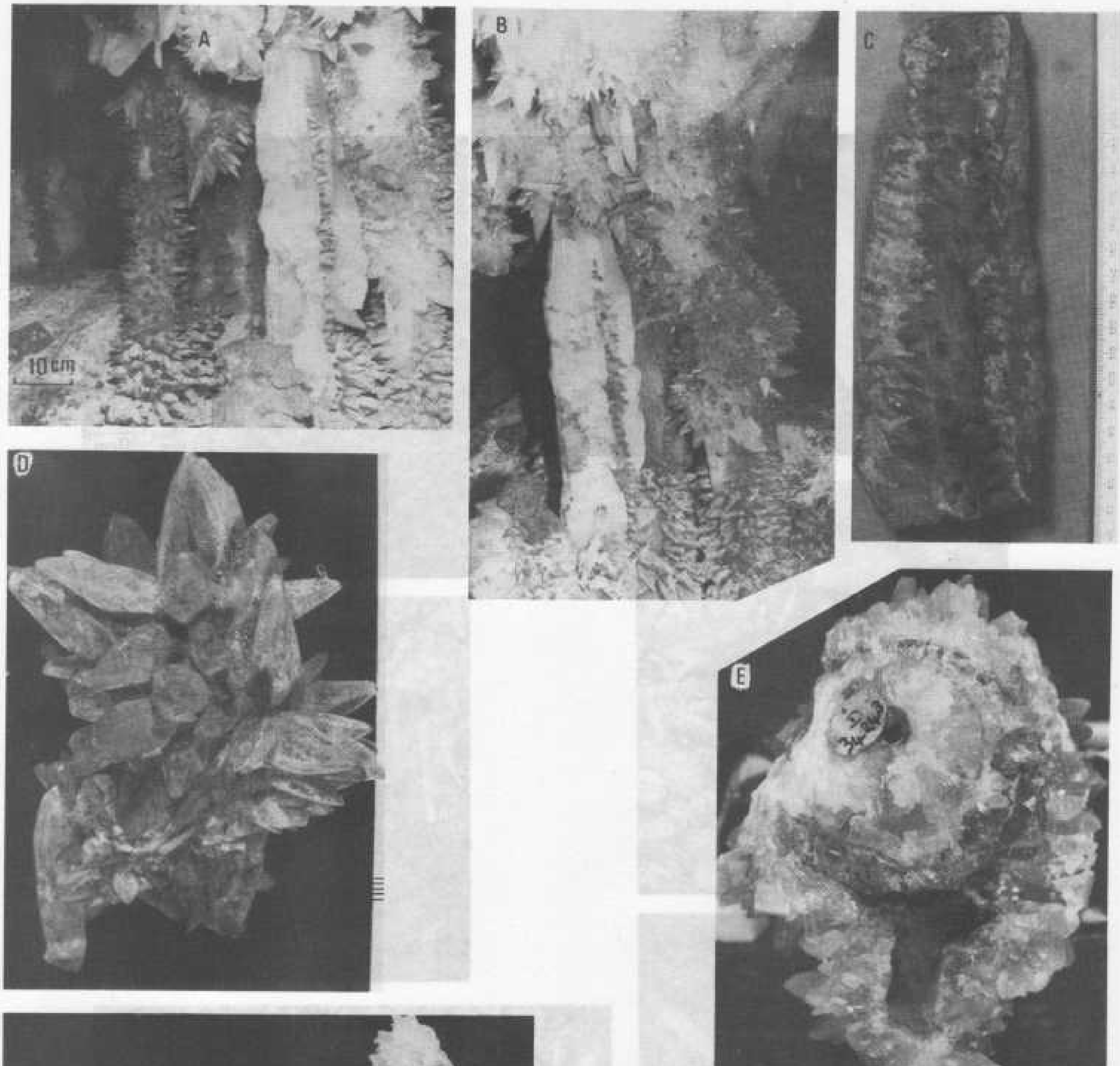


Plate 4. A: View of part of the Spar Crystals, note the two forms of column.
B: Close up showing both blade and radiating crystal columns.
C: Museum specimen D 36376 showing the unusual blade shape.
D: Start of a radiating crystal group, D 36372.
E: Cross section of D 34243 showing it to consist of a conical stalactite overgrown by spar, label 10 mm long.
F: Side view of sample D 34243. Scale 10 mm long.
G: View of ceiling at Spar Crystals showing encrustation.

This sand consists of blocks of carbonate and fine saccharoidal calcite crystals, some of which are cemented together to form aggregates. A grain mount (U.S.G.D. 54321) showed the blocks to consist of extremely fine laminated spar. Digestion determined this sediment to be 48% carbonate. The clay at the base of the sequence contains boulders of limestone whose surfaces have been weathered in situ. A halo of white friable material (92.7% carbonate) 20 mm thick encrusts them.

The sand and the clay deposits would have been deposited within the cave, the sand not having been transported far, while the organic rich loam is surface derived through the doline entrance. The boundary in this sequence probably represents the opening of the Murder-Childrens doline, Figure 10b.

Speleothems

In Main Cliefden canopies, often forming false floors, are fairly common. This is a result of deposition on layered clay fill since removed. One suspended false floor, Plate 2, in the Clown Room has its underside composed of boxwork formed by deposition in mud cracks in the clay substrate in a similar fashion to examples at Walli nearby (Frank, 1974).

An extensive deposit of helictites occurs at Helictite Wall in Main Cliefden. This deposit, Plate 3B, has grown from a wall of clay fill, thus supporting the view of Moore (1954) that a porous wall surface is required for the formation of helictites. Pavey (1971) examined helictites in the Jewel Room area and found that although they were all single crystals, not all contained a central canal. Sample D 36358, apparently from Helictite Wall, illustrates well the branching form and the difficulty in recognising the central canal in helictites.

As well as branching forms, complex curved helictites occur in Main Cliefden these include the Antler and the Pretzel illustrated in Plate 3 E & F. Rotation of the "c" axis in curved helictites as described by Moore (1954) can be seen in a helictite with well developed crystal faces due to immersion, Plate 3C. The abundance and complexity of helictites at Cliefden Caves makes this one of the most promising areas for the study of the formation of helictites.

The Spar Crystals are located in a small tunnel in Main Cliefden at the end of a muddy extension from Helictite Wall. The walls and ceiling of this tunnel are lined with large dogtooth spar crystals while stalactites and columns of radiating crystals and large blade-shaped crystalline columns add to the distinctiveness of this deposit.

Stalactites and columns from this deposit are well represented in the Australian Museum Collection. Specimen D 34243 consists of a conical stalactite overgrown by large radiating dogtooth spar crystals. Moore (1962) believes that the film depositing a stalactite restricts the full development of their component crystals and that when a stalactite is flooded by a saturated solution these can develop as in this specimen. Specimens D 34243 and D 34244 clearly show that this is the case and suggest that flooding by a saturated solution was the cause of this overgrowth (Plate 4).

Blade-shaped columns and the dogtooth spar on the tunnel walls would also have been produced by this saturated solution. Specimen D 36376 is a blade-shaped column which when examined in cross section can be seen to have grown on a tubular stalactite. This blade-shape then is an expression of the monocrystalline structure of the overgrown tubular stalactite. Andrieux (1962) described such forms as polyhedral stalactites and found that these were formed when monocrystalline stalactites were overgown by calcite in a flooded cave. As well as indicating that the cave was subject to some post-vadose flooding spin crystals give insight into the otherwise obscured crystallography of monocrystalline tubular stalactites (Plate 4).

Blue stalactites occur in Murder and Boonderoo Caves. The blue stalactite in Murder Cave is a small deposit formed on the roof of a high chamber. It has a striking azure colour and despite its small size, c. 200 mm long, is easily seen.

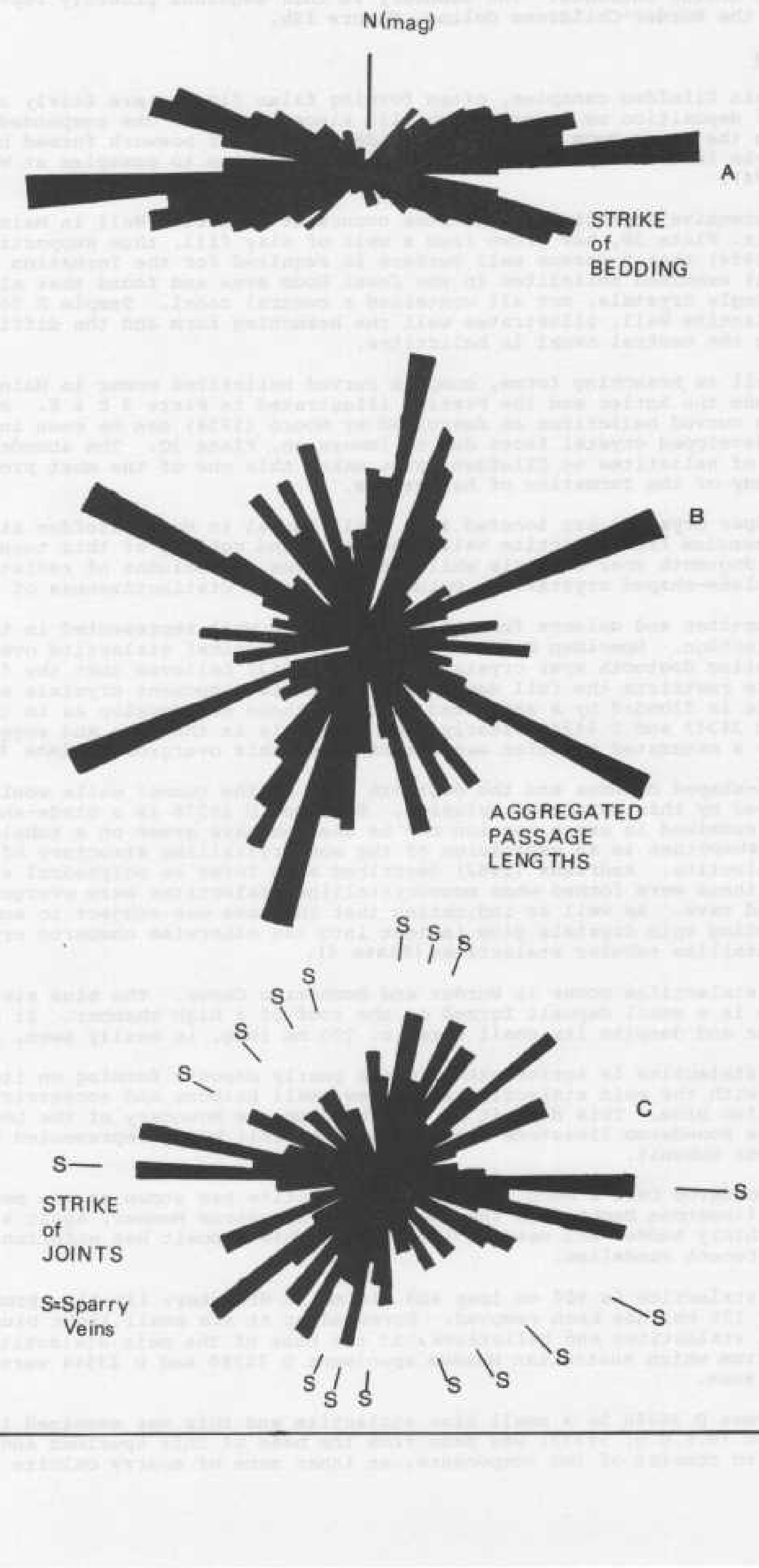
This stalactite is active with a white pearly deposit forming on its tip. Associated with the main stalactite are a few small bulbous and eccentric stalactites which are also blue. This deposit is growing from the boundary of the Lower and Upper Units of the Boonderoo limestone Member the Upper Unit being represented by the thinly-bedded Murder Subunit.

In Boonderoo Cave a much larger blue stalactite has grown at the boundary of the Boonderoo limestone Member and the Large Flat limestone Member, again a boundary between a thinly bedded and massive limestone. This deposit has unfortunately been the subject of recent vandalism.

This stalactite is 900 mm long and 110 mm in diameter; its tip, probably having a length of 150 mm, has been removed. Surrounding it are small light blue or pearly white small stalactites and helictites. At the base of the main stalactite the positions from which Australian Museum specimens D 36380 and D 23544 were removed can be clearly seen.

Specimen D 36380 is a small blue stalactite and this was examined in detail. A thin section (U.S.G.D. 54322) was made from the base of this specimen and showed the stalactite to consist of two components, an inner zone of sparry calcite and an outer

Fig 11 MAIN CLIEFDEN STRUCTURAL CONTROL



fine zone of radially orientated acicular crystals which gives the stalactite its blue colour. X-ray powder diffraction showed this outer material to be aragonite. This structure of a calcite core with an aragonite exterior is similar to that described by Siegel (1965).

Examination of the large blue stalactite across its broken tip showed it to have the same structure. The persistence of the blue colour in even small fragments of the aragonite layer indicates that the colour is due to some impurity in the aragonite and not to refractive effects.

SPELEOGENESIS

Structural and Lithological Control

Main Cliefden

Main Cliefden is developed in the Massive Unit of the Boonderoo Limestone Member. To study the possible effects of structural factors in the development of Main Cliefden detailed mapping of an area of 20,000 m^2 representing the surface extent of cave development was carried out. This resulted in extensive sampling and the measurement of 139 bedding plane orientations, 148 strikes of joints, 44 strikes of sparry veins and 5 strikes of fracture planes.

Lithological variation in this area was found to be considerable but could not be related in any way to cave development. The orientation of bedding is shown in the rose diagram Figure 11a and the orientation of the joints is shown in Figure 11c.

To allow comparison of this data with the development of the cave the methods of Deike (1969) and Williams (1974) were applied to cave survey data at a grade of CRG 6 supplied by Mr A.J. Pavey. The rose diagram produced from ths data, Figure 11b shows the extent of cave development in any direction, while a statistical analysis of the data is given in Table 1.

Comparison of this data with the strike of bedding in Figure 11a shows that this has had little effect on the development of the cave. This would result from the relatively low dip (20-30°) of the limestone in which the cave has developed. The spread of bedding strike in Figure 11a is due to proximity to the nose of the anticline.

The importance of joint directions in controlling cave development can be seen in Table 1. Compared to a random distribution three directions of passage development, 10-14°m 65-69° and 115-119° are highly significant (0.95 level), while one direction, 20-24° is significant (0.68 level). Of these directions 10-14° is a significant joint direction as is 65-69°. Interestingly two highly significant joint directions, 90-94° and 100-104° are not significant for passage development while one highly significant direction of passage development, 115-119° is not significant as far as joints are concerned.

Sparry veins are highly significant in the direction, 10-14° and significant for the direction 20-24°, where joints are not significant and so seem to have exercised some control over speleogenesis.

Transmission Cave

The lower unit of the Boonderoo Limestone Member at Transmission Cave is a highly jointed, stylobedded, dense algal micrite which would have had little primary porosity. Bedding observed in the cave walls varies from 50 mm to over one metre in thickness and webs of calcite strain lineations are developed.

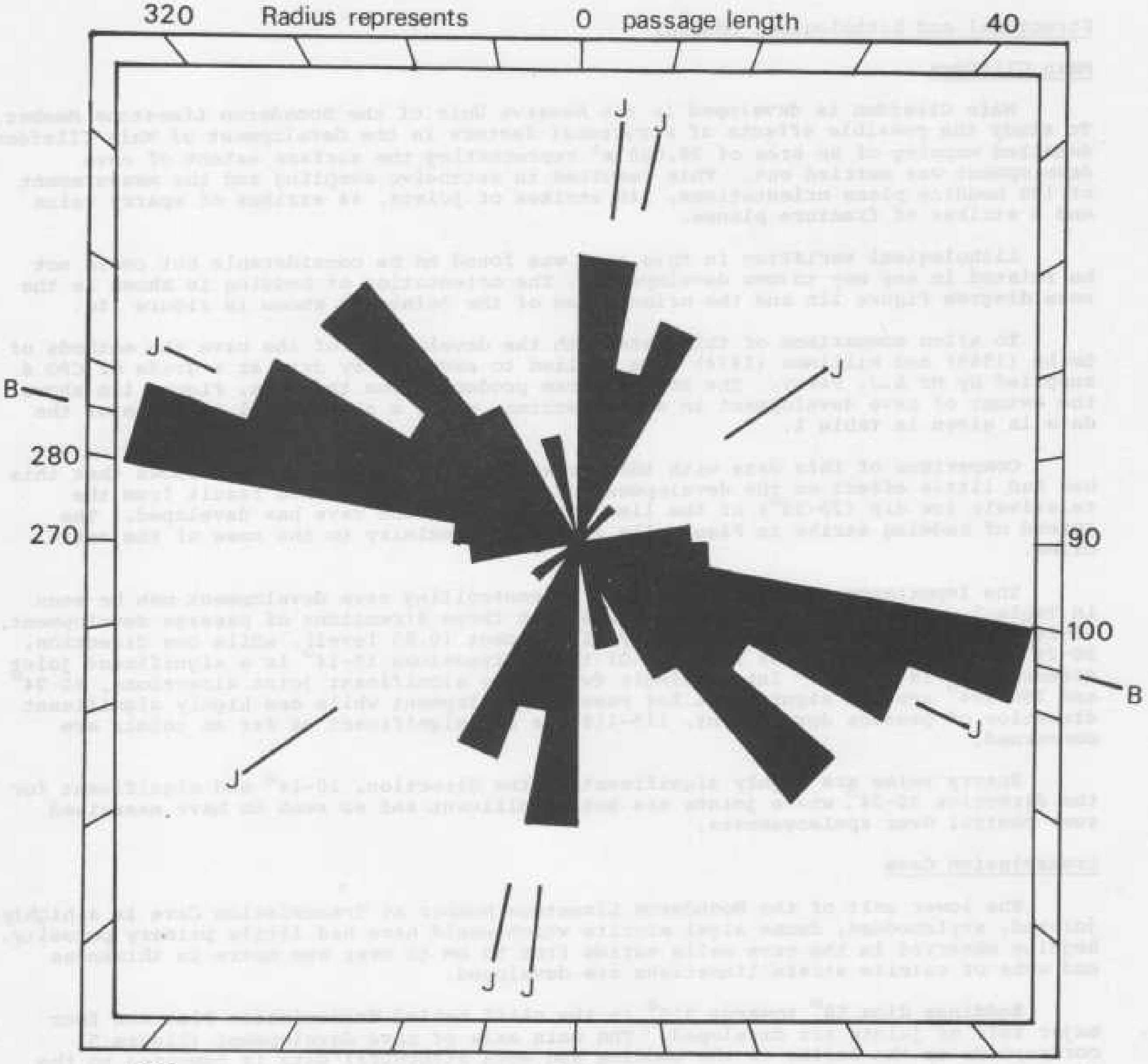
Beddings dips 58° towards 015° in the cliff behind Transmission Flat and four major sets of joints are developed. The main axis of cave development (Figure 5) corresponds to the strike to the bedding and when strucutral data is compared to the orientation of cave development in a rose diagram (Figure 12) it can be seen that the small passages at right angles to the main trend have been controlled by joints.

Murder and Boonderoo Caves

Murder, Childrens and Boonderoo Caves, along with a doline, have developed in the upper parts of the Boonderoo Limestone Member. As can be seen in Figure 13 these caves have been greatly influenced by bedding. Lithological boundaries have been important loci for cave development. The boundary between the lower unit and the Murder sub-unit has controlled the development of parts of the Right Hand Branch of Murder Cave while the boundary between the massive sub-unit and the Large Flat Limestone Member has been an important factor in the development of Boonderoo Cave.

On the other hand cave development has been inhibited by thinly bedded limestone. This is particularly the case with the Island member into which Boonderoo Cave has made little impression. The Childrens and Murder sub-units seem to have prevented the coalescence of Murder and Boonderoo Caves in their souther sections with only tangential passages extending into the thinly bedded limestone.

Fig 12 PASSAGE ORIENTATION TRANSMISSION CAVE



10 Degree groups
J = Joints
B = Bedding

TABLE 1 STATISTICAL ANALYSIS OF STRUCTURAL DATA, MAIN CLIEFDEN

Strike	Passage Length	Significance Passage Length	Significance Joints	Significance Sparry Veins
0 - 4	28.00			0.95
5 - 9	27.12			
10- 14	47.97	0.95	0.68	0.95
15- 19	2.67	(0.68)		
20- 24	36.02	0.68		0.68
25- 29	31.07		0.68	
30- 34	22.66			
35- 39	21.10			
40- 44	10.49			
45- 49	5.80			
50- 54	18.15		0.68	
55- 59	13.15			
60- 64	4.30			
65- 69	50.25	0.95	0.68	
70- 74	12.28			
75- 79	-	(0.68)		
80- 84	21.08			
85- 89	12.30			
90- 94	26.20		0.95	0.95
95- 99	- -	(0.68)		
100- 104	15.90		0.95	
105- 109	13.25			
110- 114	17.82			
115- 119	50.17	0.95		
120- 124	25.60			0.68
125- 129	12.60			
130- 134	13.82			
135- 139	- -	(0.68)		
140- 144	29.80			
145- 149	21.71			
150- 154	28.65			
155- 159	7.80			
160- 164	32.80			
165- 169	15.45			
170- 174	9.10			
175- 179	18.20			

Inhibition of embryonic cave development in thinly bedded limestones could be due to large amounts of insolubles blocking water movement but in this case the most impure limestone, Appendix 1B, has less than 7% insoluble matter by weight, probably not significant in preventing percolation of corrosive groundwater.

The thin bedding itself may explain the lack of cave development as this would prevent the concentration of phreatic solution in embryonic caves by allowing many routes for corrosive groundwater. This view is supported by Ford (1976) who considered beds less than 20-25 cm thick precluded cave development. The range of bedding suggested by Ford is the same as that developed in the Island unit. This inhibition of cave development in thinly bedded limestones may explain why no caves have yet been reported as forming in the Fossil Hill Limestone Member.

Solution

Solution in the phreatic zone has been the major factor in the formation of the caves described in this paper. The network pattern of Main Cliefden and the degree of structural control of the other cave as well as ample morphological evidence support this assertion. Smooth walls, rounded ceilings pockets and large remnants such as the Boot indicate solution in three dimensions. The maze which forms the most western section of Transmission Cave similarly indicates that sluggish solution of the nothephreatic type (Jennings, 1976) has been responsible for the excavation of these caves. The nothephreatic development of Main Cliefden and the Boonderoo, Murder Cave group is probably contemporaneous with the development of a river terrace which forms the top of the hill above Main Cliefden. Nothephreatic development in these caves was followed by deposition of layered clay fill and possibly in Main Cliefden with a period of vadose incision.

Transmission Cave appears to have been formed when the river flowed over a lower terrace (Figure 2), under which it is developed, and so would be the youngest of the caves described here. Main Cliefden, Bonderoo and Murder Caves are now undergoing a period of sediment removal in which the layered clay fill is being removed. This has revealed the presence of passages with typically vadose cross-section in the lower levels near the Boot Room which may have been formed at the beginning of the present phase of removal or prior to the deposition of the fill. A detailed examination of the relationships between the fill and these passages should reveal the detailed sequence of events in this stage of the history of Main Cliefden.

Collapse

Collapse has palyed an important role in the late stage development of Main Cliefden, Boonderoo and Murder caves. The main chambers in these caves are all modified by collapse to some extent, with considerable control over the nature of collapse being exercised by structure.

In Main Cliefden the Main Chamber is essentially a collapse chamber whose roof is controlled by bedding planes. Blocks of limestone bounded horizontally by bedding planes and vertically by tension cracks have fallen and occupy much of the floor of the chamber. Sililar collapse has occurred in the Boot and Clown Rooms. A similar form of collapse in Boonderoo Cave is likely to be controlled by horizontal joints with the nearly vertical bedding controlling the sides of collapse blocks.

These structural features make conditions ideal for collapse but minor seismic activity reported in the area (Osborne, 1976) may have served as a trigger for this process.

CONCLUSIONS

Speleogenesis at Cliefden Caves has been influenced to a large extent by structural factors.

Joints and bedding planes provide the main planes of discontinuity in the limestone along which solution has acted.

In steeply dipping limestones the bedding thickness has controlled the hydrology and thus the degree of cave development. The petrography of the limestones does not appear to exercise significant control over cave development in this area.

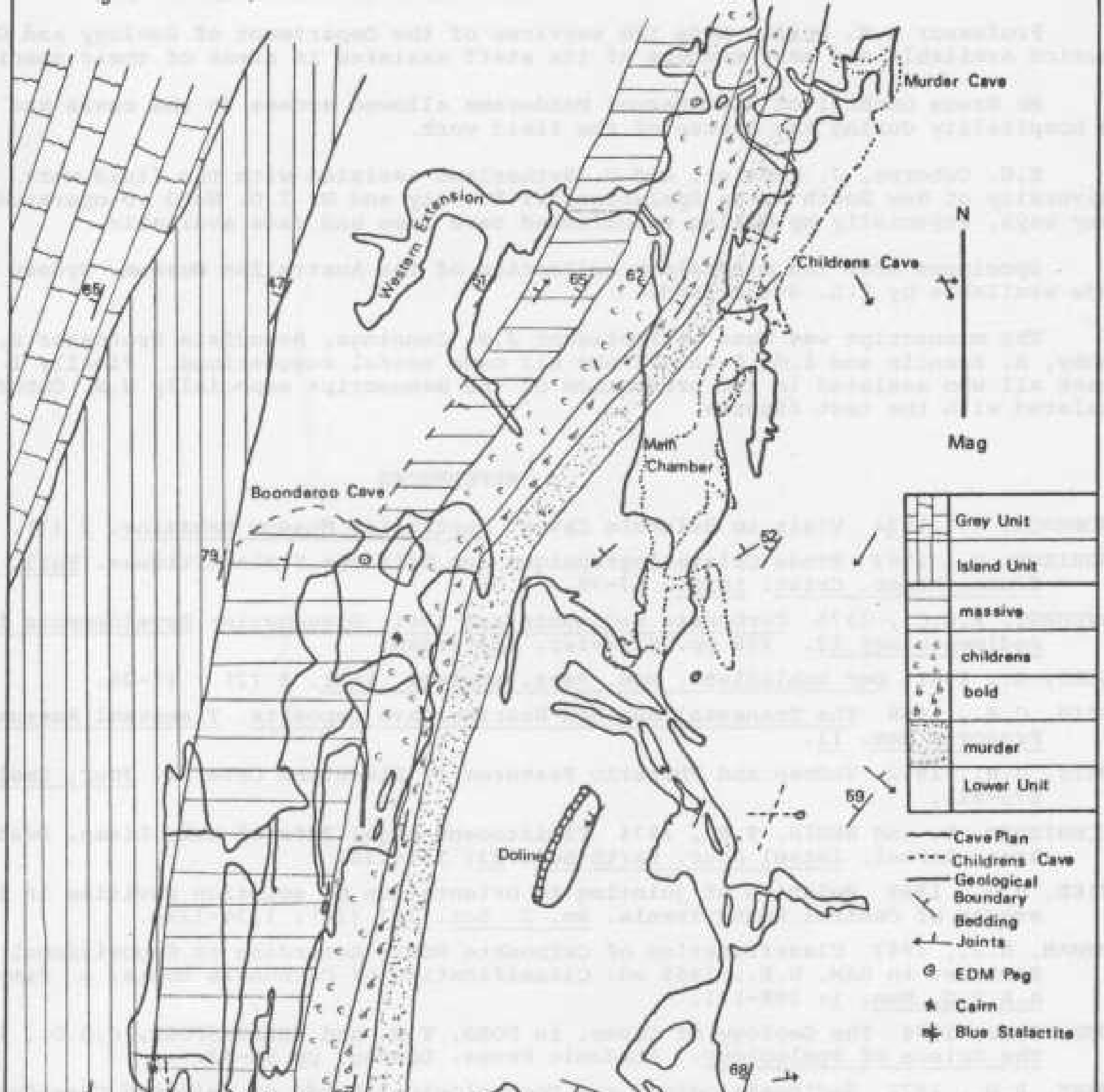
The horizontal development and prominent phreatic morphology of the caves suggest that they developed during two periods of stable hydrological conditions probably related to high level river terraces. Collapse modification may be related to regular minor seismic activity.

Extensive sedimentary deposits in all the caves studied indicate that deposition rather than downcutting has been the main process of later stage cave development at Cliefden. Frank (1972) recognised two distinct classes of cave system in New South Wales: the first class, represented by systems like Jenolan and Abercrombie, has extensive vadose development related to downcutting and little in the way of sediment except for gravel and speleothems; the second class is represented by systems such as Walli and Wellington where much sediment has been deposited, and completely sediment-filled caves, such as the Phosphate Mine at Wellington.

Cliefden Caves belong to this second class. These caves present real problems in the study of their developmental histories as they are less easily related to uplifts and geomorphic events than the first type of caves. A period of uplift affecting a cave of the first type would produce distinct vadose canyons which are easily recognised, while in a cave of the second type it is likely to result in the removal of sediments soon obscured by subsequent deposition.

In caves like those at Cliefden the persistence of tunnels through many stages of sedimentation makes it difficult to assign meaningful ages to periods of cave development. This handicap however, is compensated for by the presence of layered clay-fill, subaqueous precipitation depositis and porours cavity-fill deposits none of which are common in caves of Frank's first class.

Fig 13 MURDER, CHILDRENS & BOONDEROO CAVES



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APPENDIX I

TABLE A PARTICLE SIZE ANALYSIS RESULTS

Sample No	Sand	Silt	Clay
CL 1/1	0.5%	65%	34%
CL 1/3	0.8%	27%	74%
CL 1/4	3%	53%	44%
CL 1/5	2%	64%	34%
CL 55/H1	13.7%	50%	10%
CL 55/H3	12.6%	63%	13.3%
CL 55/H5	9.9%	60%	13.3%
CL 55/H6	17.7%	50%	10%
CL 55/H7	27.1%	47.6%	6.6%
CL 55/H7	12.3%	56.7%	26.7%
CL 55/H8	16.5%	36.7%	36.7%
CL 55/H9	41.8%	36.7%	3.3%
CL 8/g3	14%	80%	10%
HW (A)	0.1%	66.7%	23.3%
Ms 2	0.6%	73.7%	16.9%
Ms 3	0.1%	83.3%	10%
Ms 4	2.7%	40%	26.7%
Ms 5	0.2%	73.3%	16.7%

Analysis by pipette method, sand fraction removed with 63 micron sieve.

TABLE B CARBONATE DIGESTION OF SEDIMENTS

Ovendried samples digested in HCl. Residue filtered, washed and weighed after being oven dried.

Sample	% Insoluble	% Carbonate (by difference)
CL 12/1	40.0%	60.0%
CL 12/2	34.0%	66.0%
CL 12/3	38.8%	61.2%
CL 12/4	53.5%	46.5%
CL 12/5	30.0%	70.0%
CL 12/6	51.3%	48.7%
CL 12/7	81.8%	18.2%
HW (A)	79.8%	20.2%
CL 12 (white zone)	3.8%	96.2%
CL 1/3	85.3%	14.7%
CL 1/5	88.8%	11.2%
CL 1/6	46.5%	53.5%
Ms 2	88.8%	11.2%
Ms 4	87.5%	12.5%
Ms 5	91.0%	9.0%
Ms 6	86.0%	14.0%
Ms 7	89.6%	10.4%
Ms 8	87.8%	12.2%
CL 55/H1	85.3%	14.7%
CL 55/H3	84.5%	15.5%
No 54329	34.3%	65.7%
No 54328	41.0%	59.0%

TABLE C CARBONATE DIGESTION OF LIMESTONES

Strata	% Insolubles	% Carbonate
Boonderoo limestone Member:		
Lower Massive Unit	1.3%	98.7%
Upper Variable Unit		
Childrens Subunit	1.1%	98.8%
Massive Subunit	2.8%	97.2%
Massive Subunit	3.5%	96.5%
Large Flat limestone Member:		
Island Unit	6.9%	93.1%
Island Unit	2.8%	97.2%
Grey Unit	3.5%	96.5%

QUILL ANTHODITES IN WYANBENE CAVE, UPPER SHOALHAVEN DISTRICT, NEW SOUTH WALES

J.A. Webb and J.B. Brush

Summary

Anthodite fragments collected at Frustration Lake in Wyanbene Cave were examined by X-ray diffraction and scanning electron microscope, and found to be both calcite and aragonite. The aragonite quills are original; some of the calcite ones represent overgrowths of aragonite, but others may have formed as original calcite or by transformation of aragonite.

WYANBENE CAVE

The entrance to Wyanbene Cave (grid reference 424347 on 1:100,000 Araluen sheet) is on the western side of the Minuma Range in the Upper Shoalhaven karst region (Nicoll and Brush, 1976), between the Shoalhaven and Deua Rivers in southeastern New South Wales. The cave is developed in a lens of Upper Silurian limestone and is among the longest in the state, with more than 1830 m of known passage. It contains some large breakdown-floored chambers and a number of blind shafts connected by an active stream passage, at the southern end of which is Frustration Lake (Figure 1). On the eastern wall near the lake are a number of "aragonite flowers". They occur in several clusters, some located about 6 to 10 m above water level, and others in a row 1-2 m above the lake (Figure 2). The latter are mud-coated, indicating that at some time they have been submerged.

OCCURENCE AND COMPOSITION OF THE ANTHODITES

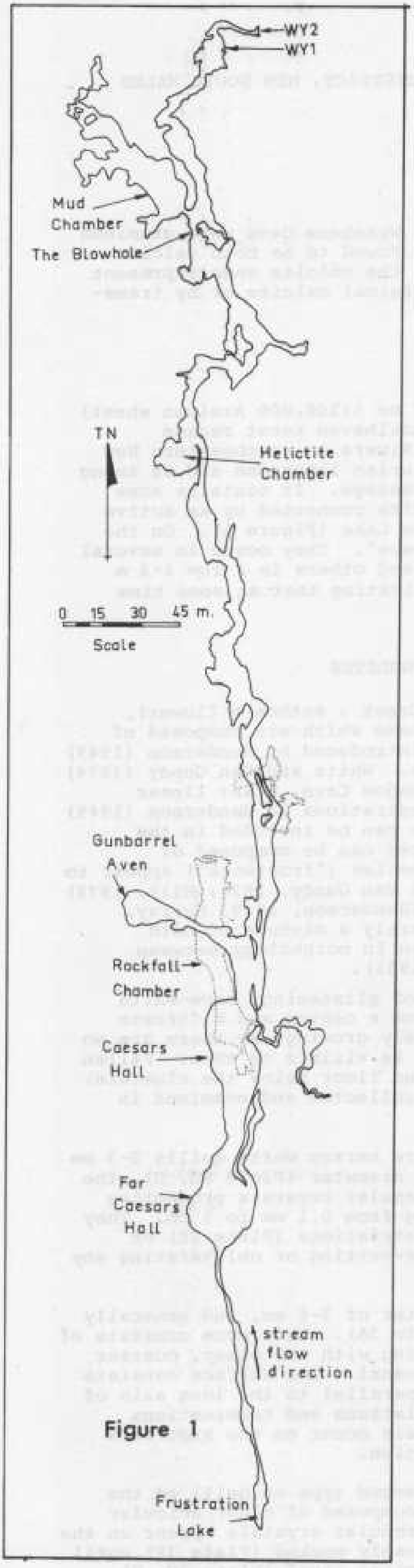
The "flowers" are best called anthodites (from the Greek : anthos = flower), following Hill (1976), who defined anthodites as "speleothems which are composed of clusters of needle or quill-like crystals" The term was introduced by Henderson (1949) being first coined by a guide at Skyline Caverns, Virginia. White and Van Gundy (1974) distinguished two froms of aragonite speleothems in Timpanogos Cave, Utah: linear helictites and radiating, acicular clusters; however, illustrations in Henderson (1949) and Hill's (1976) definition make it clear that both forms can be included in the general term anthodite. Disregarding alteration, anthodites can be composed of either calcite or aragonite. Those formed of radiating needles ("frostwork") appear to be exclusively aragonite (White and Deike, 1962; White and Van Gundy, 1974; Hill, 1976) whereas, although quill anthodites are usually aragonite (Henderson, 1949; Murray, 1951; White, 1976), they may be calcite (Hill, 1976) or rarely a mixture of both (White and Van Gundy, 1974). There is a complete gradation in morphology between frostwork and quill anthodites (Henderson, 1949; Murray, 1951).

The Wyanbene examples are made up of large numbers of glistening, snow-white branches up to 200 mm long, which more or less radiate from a centre and bifurcate antler-fashion (Plate 1). They do not appear to be actively growing, as there are no water drips in their immediate vicinity and no water film is visible on them. Fallen pieces, even whole branches, are scattered on the walls and floor below the clusters; small fragments from underneath B and C on Figure 2 were collected and examined in hand specimen and under the scanning electron microscope.

They fall into two obvious groups. Firstly there are narrow white quills 2-3 mm thick (Plate 2A, B), with a central canal approx. 1 mm in diameter (Plate 2C, D). The wall consists of randomly oriented, irregularly shaped granular crystals projecting internally and externally, with maximum dimensions ranging from 0.1 mm to 1 mm. They crystals may have sharp edges and well-developed surface striations (Plate 2E) or rounded, smoothed corners, and faces with etch pits cross-cutting or obliterating any striations (Plate 2F-H).

Branches of the second type are wider, with a diameter of 3-6 mm, and generally translucent, although some have an opaque white core (Plate 3A). This core consists of fibrous, finely crystalline material (Plate 3B), contrasting with the clear, coarser crystals surrounding it (Plate 3C). There is no central canal. The surface consists of acicular crystals several millimetres long aligned subparallel to the long axis of the quill (Plate 3D); these often show well-developed striations and terminations (Plate 3E). Occasionally small sheafs of radiating crystals occur on the side of a branch, probably representing points of incipient bifurcation.

One fragment shows a complete transition from the second type of quill to the first over a distance of about 15 mm. At the base it is composed of clear acicular crystals with a white fibrous core, but towards the tip granular crystals appear on the surface. These are scattered at first but become more closely packed (Plate 3F) until at the tip they form a continuous crust around a small central canal (Plate 3G, H), and the acicular crystals have entirely disappeared. The increase in diameter from 3



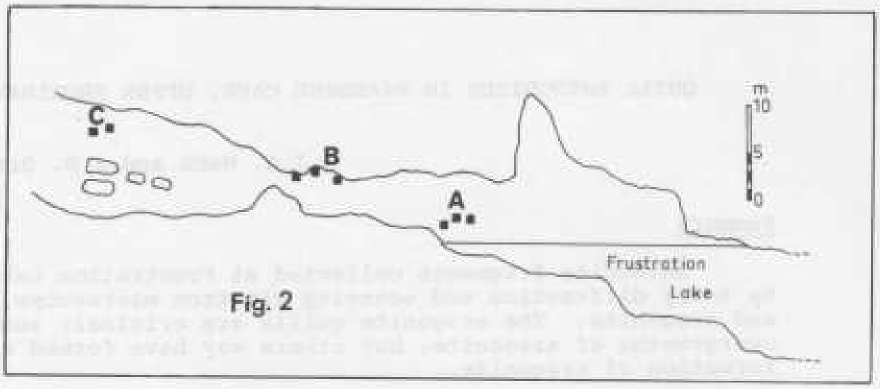


Figure 1. Outline plan of Wyanbene Cave, showing entrances and main passage features (dotted lines indicate separate levels). Adapted from Figures 22A, B in Nicholl.

Figure 2, North-south section of terminal portion of Wyanbene Cave, looking east and showing location of anthodites (marked by squares) - groups A - C are mentioned in the text. Adapted from figure in Bell (1970).

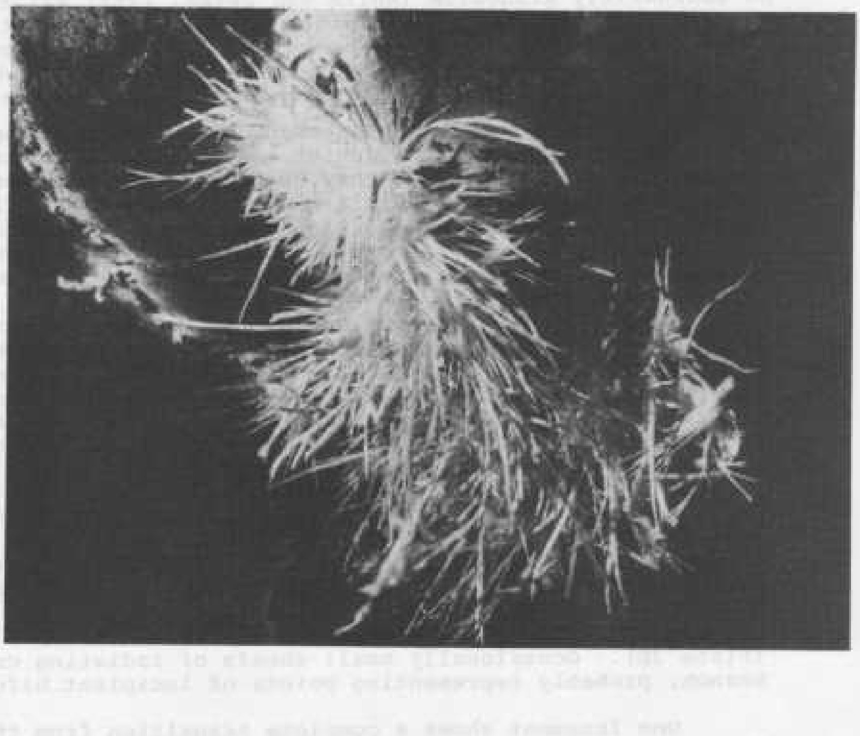


Plate 1. Anthodite in Wyanbene Cave (furthest to left in B in Fig. Fig. 2). Approx. x 0.2; branches are 15 -20 cm long.

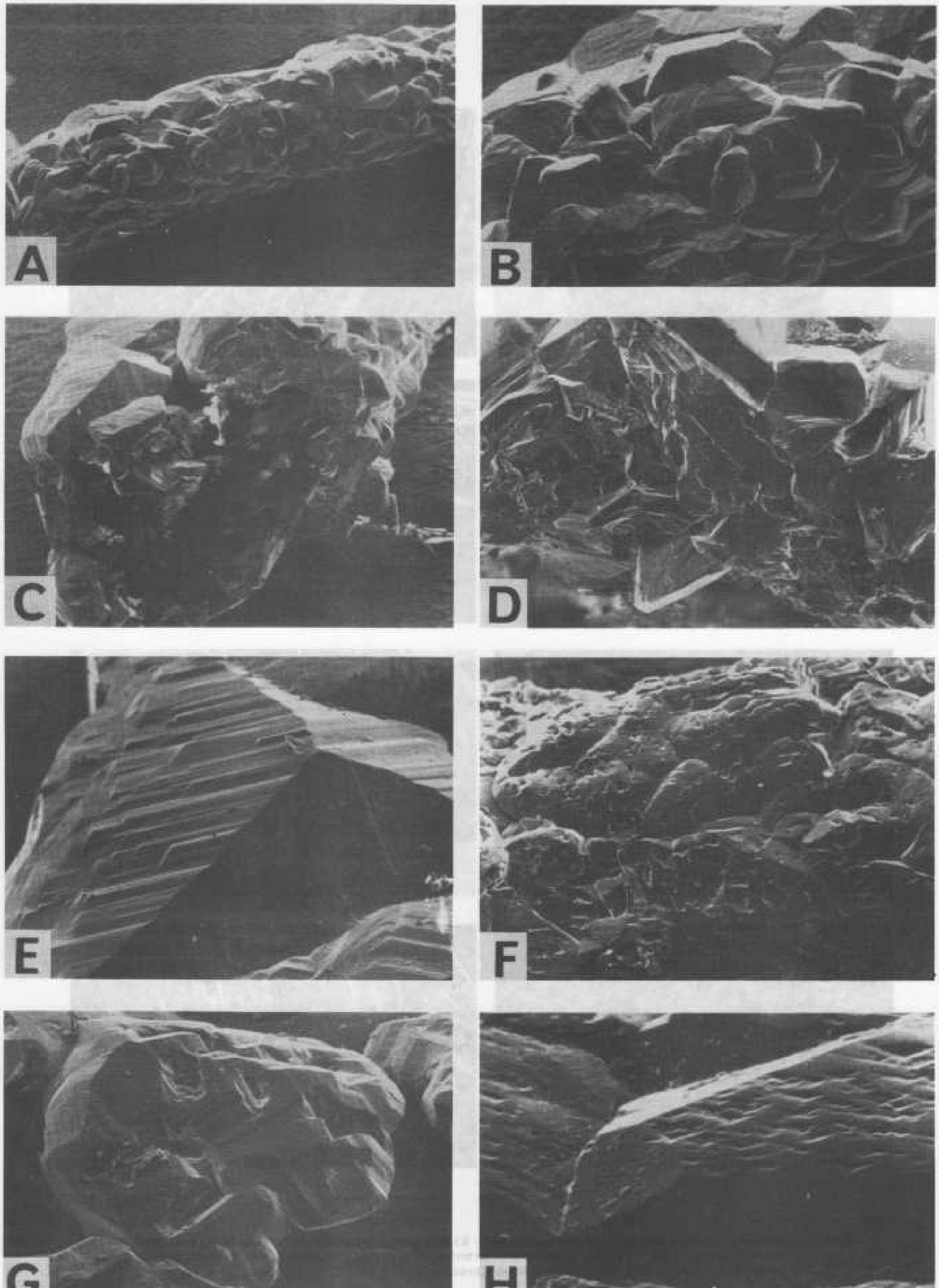


Plate 2. Scanning electron micrographs of two calcite quills (A- E, first specimen; F - H, second specimen, showing etching features). A, x 17; B, x 42; D, x 170; F, x 42; G, x 170; H, x 840.

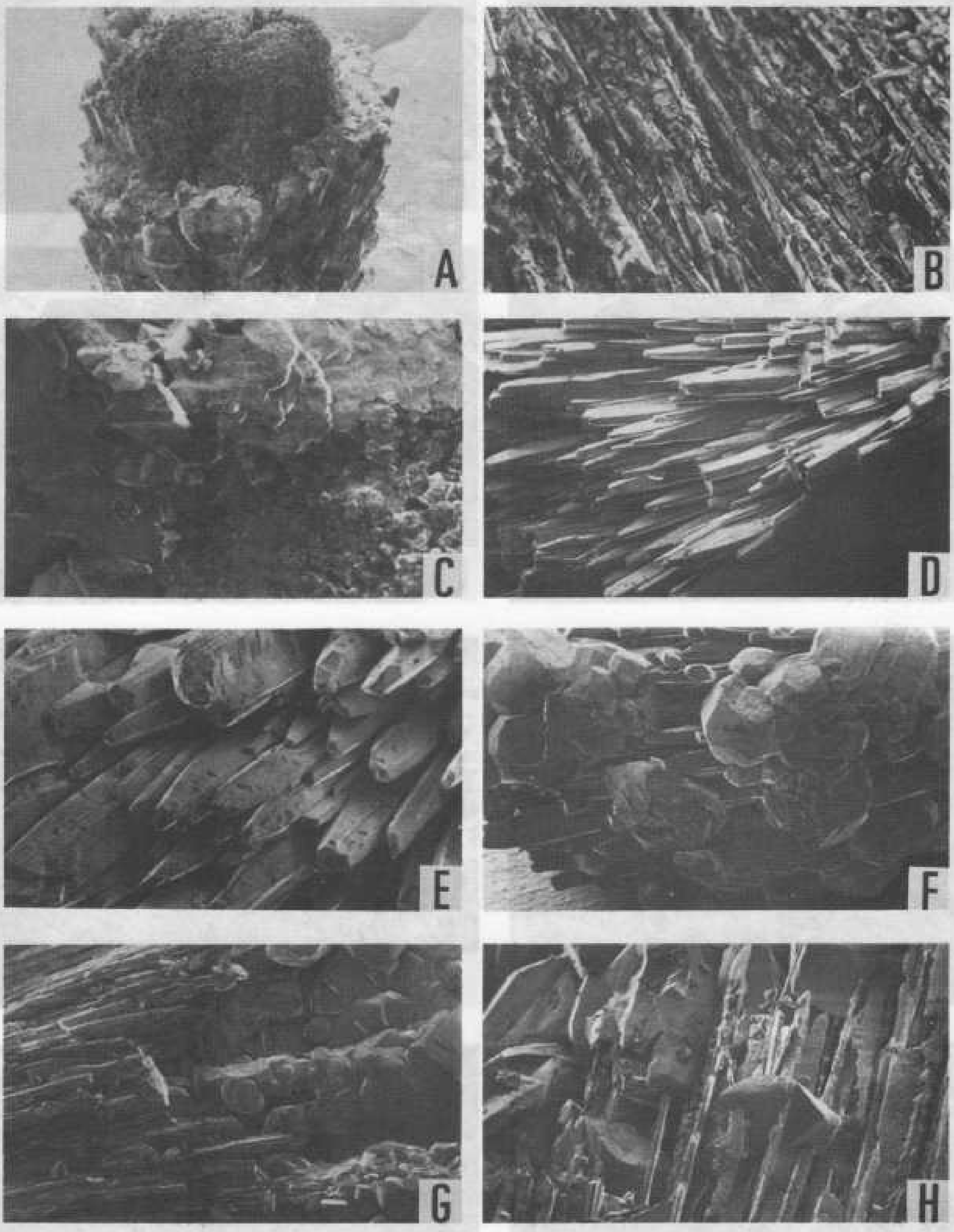


Plate 3. Scanning electron micrographs of aragonite (A - E) and calcite-aragonite (F - H) quills. A, x 17; B, x 90, fibrous core; C, x 90, transition from core to exterior (to left); D, x 16; E, x 42; F, x 18, calcite crystals on exterior of quill; G, x 18, transition from fibrous aragonite core to central canal; H, x 90.

to 6 mm reflects the overgrowth that has occurred, but contrasts with the typical 2-3 mm thickness of quills composed of granular crystals, as described above.

X-ray diffraction analyses of 5 samples showed the acicular and fibrous crystals to be aragonite and the granular ones to be calcite; the specimen illustrated in Plate 3F-H consists of both. One of the granular quills contained a small amount of aragonite according to the analysis, although none was visible under the scanning electron microscope. Since calcite can be partially converted to aragonite by grinding at room temperature (Lippman, 1973), it is possible that the aragonite in this quill was formed during sample preparation, which involves grinding the specimen to a powder. Although the identification of the minerals in the Wyanbene anthodites could have been guessed from their crystal morphology, X-ray diffraction is necessary for positive verification, as aragonite can revert to calcite while retaining the outward acicular form (Curl, 1962; Hill, 1976).

Both calcite and aragonite quills occur within the anthodites and among the broken fragments beneath; more than half the material appears to be calcite. Bell (1970), who previously examined the anthodites at Frustration Lake, recorded only aragonite, and these speleothems were always presumed to be entirely aragonite; hence their common name "aragonite flowers".

The Wyanbene anthodites closely resemble both calcite and aragonite examples in the literature (e.g. Hill, 1976; Henderson, 1949). White and Van Gundy (1974) noted that many of the aragonite anthodites in Timpanogos Cave exhibited the structure shown in Plate 3A-A; a fibrous core surrounded by acicular crystals. They also recorded overgrowths of calcite rhombs on the tips of some quills, although the anthodites always retained an aragonite core under the nodular calcite crust.

THE CALCITE-ARAGONITE PROBLEM

Before discussing the origin of the anthodites, it is necessary briefly to review the factors believed to be responsible for aragonite deposition in caves.

Aragonite and calcite are polymorphs of $CaCO_3$, aragonite being the high pressure form; pressures of over 3000 atmospheres are needed to synthesize it in the laboratory (Hill, 1976). Thus calcite is the stable polymorph at or near the earth's surface, and aragonite is metastable with respect to it. Furthermore, aragonite is more soluble than calcite at standard temperature and pressure (K_{sp} aragonite = $10^{-8.22}$, K_{sp} calcite = $10^{-8.35}$), so calcite should always be deposited before aragonite (Lippman, 1973). However, aragonite is actively forming in many caves and often occurs in close association with calcite. To explain this, a number of factors have been put forward that will either enhance the nucleation and growth of aragonite or inhibit that of calcite. These include supersaturation, foreign ions, temperature, acidity, microorganisms, and monohydrocalcite. Each will be considered in turn, although definite conclusions are difficult to reach because some of the evidence is conflicting.

If a $CaCO_3$ solution at 25°C is supersaturated by more than about 16%, either calcite or aragonite can precipitate as both their solubility products are exceeded. Such supersaturation can be caused by rapid CO_2 loss to the cave air (Holland, Kirsipu, Huebner and Oxburgh, 1964), rapid evaporation (Pobeguin, 1957), or by foreign ions which inhibit calcite precipitation (see below). Rates of diffusion of solutions can play a large part in determining CO_2 loss and evaporation (Pobeguin, 1957). Curl (1962) felt that while supersaturation was necessary for aragonite precipitation, it was not sufficient in itself because calcite formation mist be inhibited.

Three foreign ions, Sr^{2+}, SO_4^{2-}, and Mg^{2+}, may possibly affect aragonite formation. If the strontium concentration in a calcium carbonate solution is sufficient, $SrCO_3$, an isomorph of aragonite, can form and may act as a nucleus upon which aragonite can crystallize (Curl, 1962; Kitano, 1962). However, several workers, e.g. Goto (1961), Siegel (1965), Lippman (1973) and Murray (1975), could not confirm that the strontium concentration influenced aragonite precipitation. Bishoff and Fyfe (1969) found that SO_4^{-2} could inhibit the growth of calcite, although its effects were apparently not pronounced.

Magnesium is believed to promote the nucleation of aragonite by preventing calcite from forming (Curl, 1962). Folk (1974) proposed that Mg^{2+} poisons all crystal growth directions but that along the c-axis, thus favouring aragonite, which forms acicular crystals elongated in the c direction. A considerable amount of laboratory work (see Murray, 1954a; Lippman, 1973; Folk and Assereto, 1974) indicated that at 25°C a Mg concentration of greater than 50-180 ppm or a Mg/Ca ratio of about 2 or more caused $CaCO_3$ to precipitate mainly as aragonite. At higher temperatures less Mg was needed. However, Goto (1961) considered that Mg had no effect on aragonite formation, and Murray (1954b, 1975) found that the Mg content of the water associated with aragonite speleothems was quite low (19-27 ppm), the Ca concentration being slightly smaller (14-24 ppm). Water dripping from calcite speleothems in the same cave had very similar Ca and Mg contents. Holland et al. (1964) recorded in a different cave that the Mg/Ca ration of the water was highest where calcite deposition was predominant. Murray's (1975) results also indicated that Mg is less abundant in aragonite than calcite, being excluded more strongly by aragonite. White and Deike (1962) and White and Van Gundy (1974) found no obvious difference in Mg content between calcite and aragonite speleothems, and Siegel's (1965) work showed that the Mg content of calcite speleothems was in general very low, whereas mixed calcite/aragonite speleothems had higher amounts of Mg, although it was mostly in the calcite portion. Thus the significance of Mg in aragonite precipitation is open to question; however, many workers assign it a major role (e.g. Lippman, 1973; Folk, 1974).

Laboratory work by Kitano (1962) showed that aragonite forms at temperatures above 25°C, and only calcite precipitates below this temperature. Aragonite also has a higher crystallization rate than calcite, as indicated by the fact that at room temperature aragonite will crystallize from a $CaCO_3$ solution if it is seeded with aragonite (Murray, 1954a; Lippman, 1973). Siegel and Reams (1966) found that temperatures of 2-100°C had little effect on the $CaCO_3$ polymorph precipitated, and calcite alone should be deposited at temperatures of 21°C, the warmest recorded in North American caves. Since temperature fluctations in caves are usually minor, they are unlikely to affect aragonite precipitation (Thrailkill, 1971).

The formation of aragonite seems to be favoured by low acidity (Goto, 1961; Kitano, 1962), although Siegel (1965) recorded that in one cave the pH of speleothem drips was highest when they were actively depositing calcite. The effect of micro-organisms on $CaCO_3$ precipitation may be significant, but has not been sufficiently investigated (Siegel, 1965). Marschner (1969) discovered that monohydrocalcite is the main component of carbonate scales deposited from cold water in contact with air. It converts completely into aragonite in the presence of water, even at temperatures and with ions present that would normally favour calcite. Thus monohydrocalcite could be a factor in aragonite formation in low temperature caves (Hill, 1976).

It is not possible to say which of the above factors are most effective in promoting aragonite precipitation, although supersaturation and Mg concentration appear to be favourites. It is probable that several factors interact at any one time.

Calcite and aragonite frequently occur together in speleothems, as alternate layers, overgrowths, or patches of one in a speleothem composed largely of the other (Murray, 1951, 1975; Siegel, 1965). Such associations happen in two ways. Either changing conditions favour first the deposition of one polymorph, then the other, or original aragonite transforms to calcite. Factors affecting the first possibility have already been discussed. With regard to the second, although aragonite is metastable at ordinary temperatures and pressures, the solid state transition to calcite is extremely slow under these conditions (Curl, 1962). However, aragonite will revert quite readily if in contact with water, although small concentrations of Mg suppress the transformation (Lippman, 1973). Folk and Assereto (1976) reported speleothems with textures indicating such a reversion, which they believed could occur in two ways; ion transfer across a thin liquid film with no change in crystallographic orientation, or solution of the aragonite and later precipitation of calcite in the cavities, obliterating the original microfabric.

FORMATION OF THE WYANBENE ANTHODITES

The reasons for the occurence of aragonite in Wyanbene Cave are uncertain; however, the presence of Mg ions may have been important, since the limestone is overlain by volcanics which could supply Mg to the cave waters.

Needle anthodites are believed to originate under subaerial conditions by seeping or slowly moving films of water (Hill, 1976). There is some evidence that the best anthodite growth takes place in very humid caves, where there is sufficient water to maintain a moisture film over the entire speleothem (White, 1976). It is probable that quill anthodites form similarly.

The aragonite branches of the Wyanbene anthodites are presumed to be original, whereas at least some of the calcite ones are overgrowths on aragonite, as illustrated in Plate 3F-H. White and Van Gundy (1974) postulated that a similar occurrence of calcite overgrowths towards the tips of aragonite quills was due to loss of supersaturation as the CaCO solution progressed along the quills, assuming that the increasing Mg concentration of the solution caused by the carbonate precipitating would not inhibit calcite crystallization. Siegel's (1965) finding, mentioned earlier, that in mixed calcite aragonite speleothems most of the Mg is in the calcite, tends to support this mechanism, which may be applicable in the present situation. However, in Wyanbene the quills formed by overgrowth have a greater diameter than most of the calcite branches, as already noted. The narrower quills may have formed as original calcite (Hill (1976) recorded active calcite quill anthodites), or may have reverted from aragonite, losing all trace of the aragonite fabric in the process.

The significance of the central canal in the calcite quills is uncertain, but may reflect a greater water flow necessary for their growth relative to aragonite branches.

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CAVES AND KARST ON MISIMA ISLAND, PAPUA NEW GUINEA

C.F. Pain and C.D. Ollier

Abstract

27 caves were examined on Misima Island. Most are sea caves, but some have clear phreatic origins and some result from vadose solution along joints. One cave is formed by washing out of fragments in fault-shattered gneiss. Karst development in the raised coral appears to have been limited by the absence of streams flowing through the limestone. This results from the geomorphic development of the area, which has isolated the coral into discontinuous patches. Many caves have human burials, with associated pottery, and one cave contains at least 100 skulls.

INTRODUCTION

Misima Island is about 240 km east of mainland Papua New Guinea, in the Solomon Sea (Figure 1). This paper is based on fieldwork carried out in September 1977. Misima is mountainous, with a central sharp divide varying from 600 m to 900 m, the highest point being Mount Oiatau (1030 m). The island is 40 km long and 95 km across at its widest point. A high rainfall (3012 mm at Bwagaoia) supplies numerous streams that flow in steep sided, V-shaped valleys with numerous rapids and waterfalls.

GEOLOGICAL BACKGROUND

The geology of the island has been described by de Keyser (1961). The oldest rocks are metamorphics, unknown in age but thought to be equivalent to the Owen Stanley Metamorphics of mainland Papua New Guinea. These latter rocks are Palaeozoic and Mesozoic in age. On Misima there are two groups of metamorphics, a high grade group consisting of amphibolites and gneiss in the west and lower grade phyllites and schists in the east. Overlying the metamorphic rocks are a number of Tertiary beds including volcanics, limestone and clastic sediments. Raised coral reefs (presumed to be Quaternary in age) also occur, especially on the south coast. Faulting and folding are conspicuous in the metamorphic basement, while uneven elevations in the coral suggests variations in uplift rates during the Quaternary.

RAISED CORAL TERRACES

Raised Quaternary coral occurs in several locations on Misima (Figure 1), but is concentrated mainly along the south coast. It reaches its greatest elevation west of Eiaus, rising to about 450 m. Raised coral is largely absent on the north coast although east of Rokia Point raised coral lies behind the coast (Figure 1). Terraces are distinctive features of the raised coral. De Keyser (1961) notes that the maximum number of steps occurs at Ebora, in the west, where they rise to as high as 300 metres or more. At Bwagaoia, in the east, the coral is only 7 m above sea level. The coral terraces appear to be sharpest and best developed around Bwagabwaga and Patnai, on the south coast (Figure 1).

The terraces have their origin in the normal growth of coral at a level slightly below sea level. After their formation they are uplifted above sea level by tectonic processes. Steady uplift of the coast together with sea level fluctuations that are known to have occurred during the Quaternary act together to produce the terrace form. These processes and their resulting forms have been the subject of extensive work by Chappel (e.g. 1974) and will not be considered in any more detail here. Suffice it to note that the presence of terraces does not necessarily mean intermittent uplift.

Coral reefs consist of three zones. Actively growing coral forms the seaward edge of the reef, nearest the surface of the water. Breaking waves cause coral debris to fall down to seaward where it accumulates in a steep slope. Behind the growing reef limestone accumulates in the quiet conditions of the lagoon. This mode of reef growth produces three coral reef facies; the fore-reef which has steeply dipping bedded limestone, the reef facies which is generally unbedded with many pieces of coral in growth position, and the lagoon facies where the limestone is much finer and horizontally bedded (Ollier 1975).

It is rare for the fore-reef facies to be preserved, but we did find this in sea caves near Patnai. Most of the terraces consist of true reef facies with large corals still in position of growth, and rare occurrences of giant clam shells embedded in the coral. Small amounts of lagoon limestone are found on terrace treads.

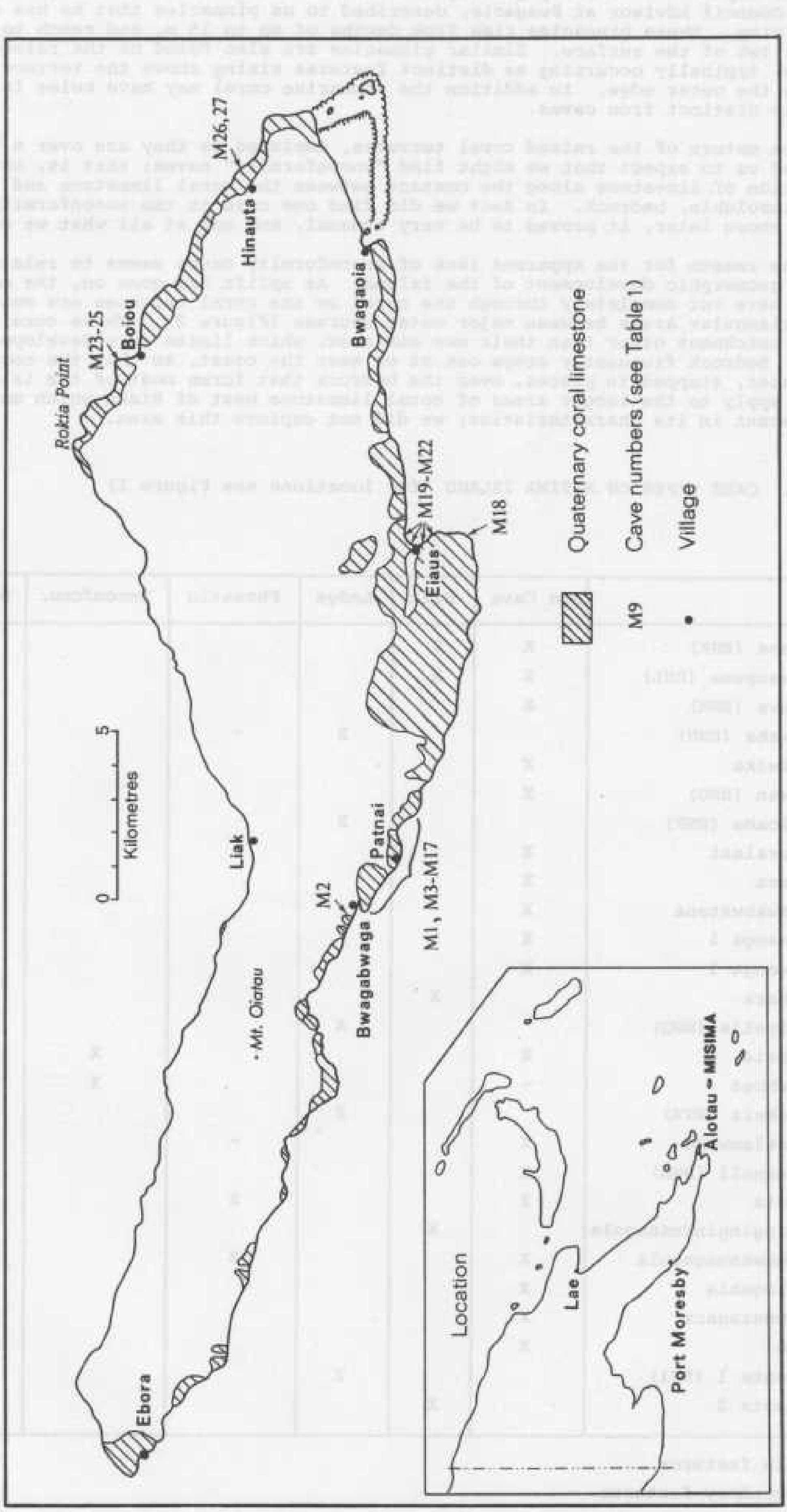

Figure 1. Misima Island, showing the areas of Quaternary coral limestone, cave locations, and locations of places mentioned in the text.

The top of the actively growing reef is not flat, but quite irregular. Mr Paul Bourne, Council Advisor at Bwagaoia, described to us pinnacles that he has seen while scuba diving. These pinnacles rise from depths of up to 15 m, and reach to within a metre or two of the surface. Similar pinnacles are also found on the raised coral terraces, typically occurring as distinct features rising above the terrace surface, often on the outer edge. In addition the submarine coral may have holes in it that are quite distinct from caves.

The nature of the raised coral terraces, emplaced as they are over a bedrock core, led us to expect that we might find "unconformity" caves; that is, caves formed by solution of limestone along the contact between the coral limestone and the underlying, insoluble, bedrock. In fact we did find one cave at the unconformity but, as will be shown later, it proved to be very unusual, and not at all what we expected.

The reason for the apparent lack of unconformity caves seems to relate to the general geomorphic development of the island. As uplift has gone on, the major streams have cut completely through the coral so the coral terraces are mostly preserved in triangular areas between major water courses (Figure 2). These coral remnants have no catchment other than their own surfaces, which limits cave development considerably. Bedrock frequently crops out at or near the coast, so that the coral is a mere veneer, stepped in places, over the bedrock that forms most of the island. This may not apply to the larger areas of coral limestone west of Eiaus which may be slightly different in its characteristics; we did not explore this area.

TABLE 1. CAVE TYPES ON MISIMA ISLAND (for locations see Figure 1)

	Sea Cave	Rift	Ledge	Phreatic	Unconform.	Bones/Pottery
1. Olbena (BNK)	X	X				X
2. Kaiwenpuna (BNL)	X	X				X
3. Bekuwa (BNM)	X					X
4. Weaweha (BNN)			X	-		X
5. Patiwaka	X					X
6. Unuwan (BNO)	X					X
7. Sailoama (BNP)			X			X
8. Tuburalasi	X					
9. Mumura	X					
10. Waubwabwatana	X					
11. Aiawanga 1	X					
12. Aiawanga 2	X					
13. Kunhara		X				
14. Wasiyelia (BNQ)			X			X
15. Bulesia	X				X	
16. Wagehoea	-				X	
17. Wanakela (BNR)			X			X
18. Tonaklamwana	X			-		
19. Pwanamali (BNH)	X					X
20. Aigola	X			X		
21. Masinginginananagola		X				
22. Boinuwanuanagola	X			X		
23. Analogabia	X					X
24. Boiugaragara	X					
25. Gino	X					
26. Hinauta 1 (BN1)			X			X
27. Hinauta 2		X				

X Main features

\- Secondary features

The three-letter codes after the names of caves with pots and bones are the site references in the PNG National File of Antiquities.

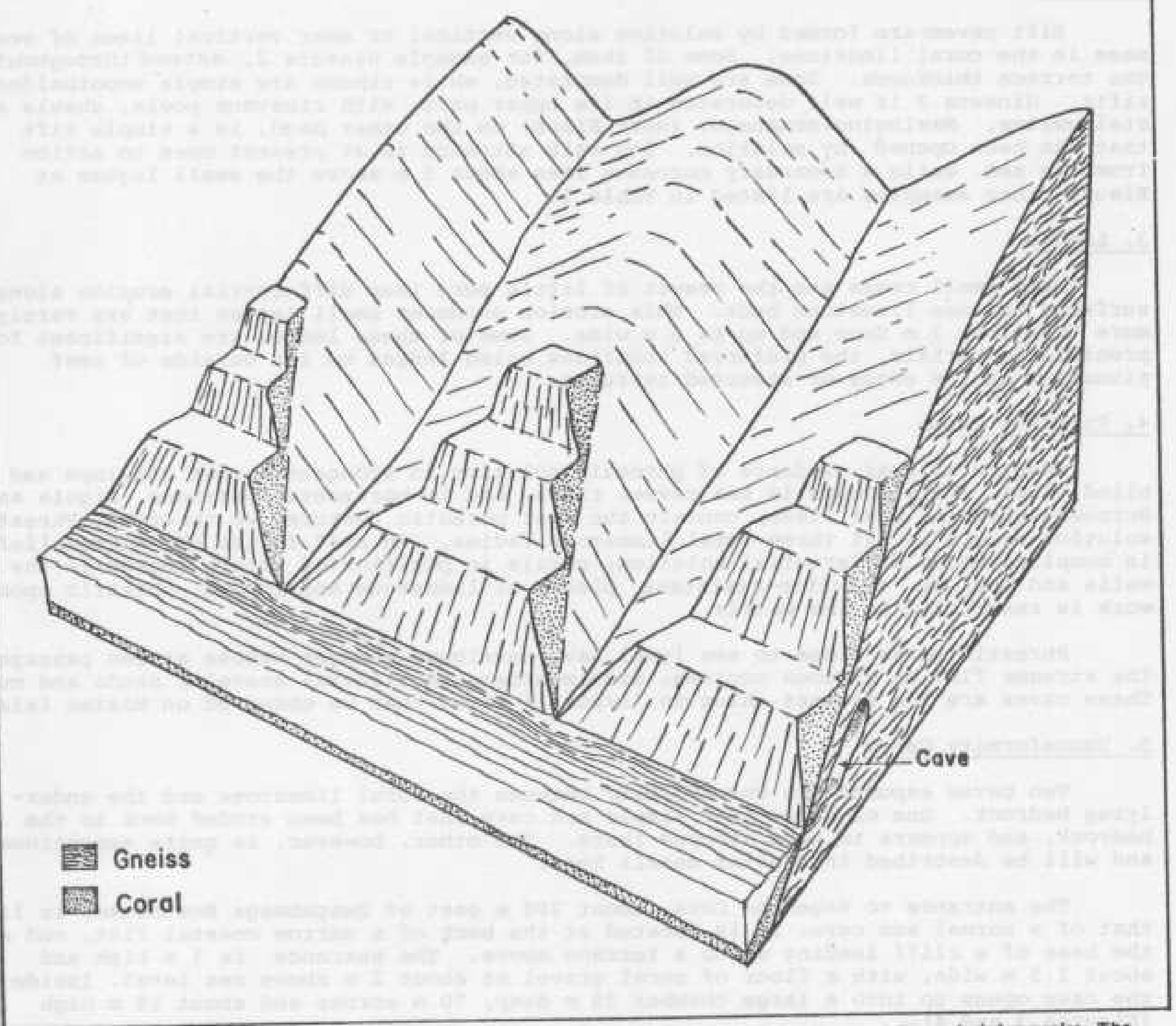

Figure 2. Block diagram illustrating the relationships between the coral limestone, terraces, and the underlying gneiss. The location of the gneiss cave is also shown.

KINDS OF CAVES

Table 1 lists the 27 caves we investigated on Misima. The caves are divided into types, and the presence or absence of archeological material noted.

1. Sea Caves

Almost everywhere where coral forms the coastline there is a wave-cut notch formed at and above the hightide level. The notch is typically located at the back of a platform or ramp cut into the coral, although in some places the back of the notch may in fact rise directly out of the sea. The coral cliff above the notch generally overhangs the back of the notch by as much as 4 or 5 metres.

Occasionally the notch enlarges into a sea cave. These sea caves are generally small, and are commonly formed along rifts or vertical cracks that have been enlarged by solution and/or marine erosion. They may go in for 10 - 15 m, and occasionally they lead along rifts through headlands. The floors are composed of rounded gravels and boulders of bedrock and coral fragments; all this material has been washed in by the sea, which apparently has the ability to throw material, including large boulders, into the backs of quite deep caves, as well as up to levels as much as 10 m above sea level. Some caves, especially on the north coast near Boiou, have calcite-cemented gravel ledges at levels about 2 - 3 m above hightide mark. These ledges presumably mark former cave floors.

Some older sea caves, now a few metres above sea level, have floors modified by collapsed blocks and flowstone. Some of these caves, now no more than 10 m deep, may have been much bigger before they were blocked by flowstone. Some sea caves (e.g. Tonaklamwana) west of Eiaus have been uplifted to considerable heights (20 - 25 m) above sea level. These uplifted sea caves are often well decorated, and have abundant flowstone in them.

Occasionally sea caves have very low (less than 1 m) entrances. Even these have floors covered with rounded pebbles that have been washed in by the sea; it seems that the sea is able to transport materials in and out of these sea caves with ease.

2. Rifts

Rift caves are formed by solution along vertical or near vertical lines of weakness in the coral limestone. Some of them, for example Hinauta 2, extend throughout the terrace thickness. Some are well decorated, while others are simple smoothsided rifts. Hinauta 2 is well decorated in its upper part, with rimstone pools, shawls and stalagmites. Masinginginananago, (near Eiaus) on the other hand, is a simple rift that has been opened by solution. Its main entrance is at present open to action from the sea, while a secondary entrance lies about 5 m above the small lagoon at Eiaus. Other examples are listed in Table 1.

3. Ledges

Many small caves are the result of little more than differential erosion along surfaces between limestone beds. This erosion produces small ledges that are rarely more than 1 or 2 m deep and up to 5 m wide. Some of these ledges are significant for prehistoric burials, the preferred locations being ledges on the outside of reef pinnacles on the edges of elevated terraces.

4. Phreatic Caves

Some caves bear evidence of phreatic solution in spongework roof scallops and blind tubes. This occurs in sea caves, rifts, and in horizontal passages. Aigola and Boinuwanuanagola, near Eiaus, contain the best phreatic features we observed. Phreatic solution occurs in all three coral limestone facies. In reef facies the microrelief is complicated by differential solution; corals in position of growth emerge in the walls and roof as solution-resistant pieces of limestone and typical phreatic spongework is restricted to the matrix.

Phreatic caves close to sea level have developed younger vadose stream passages The streams flow in sinuous courses, with meanders in alluvial gravels, sands and muds. These caves are the nearest thing to 'typical' karst that we observed on Misima Island.

5. Unconformity Caves

Two caves exposed the unconformity between the coral limestone and the underlying bedrock. One of these is a simple sea cave that has been eroded back to the bedrock, and appears to have stopped there. The other, however, is quite exceptional, and will be described in greater detail here.

The entrance to Wagehoea Cave, about 200 m east of Bwagabwaga Resthouse, is like that of a normal sea cave. It is located at the back of a narrow coastal flat, and at the base of a cliff leading up to a terrace above. The entrance is 1 m high and about 1.5 m wide, with a floor of coral gravel at about 2 m above sea level. Inside the cave opens up into a large chamber 35 m deep, 70 m across and about 10 m high (Figures 3 and 4).

The unconformity between Quaternary coral limestones and gneiss bedrock is exposed, but the cave is not formed at the unconformity. Instead, as can be seen in Figure 3, and in Plate 1, the area where the coral is exposed is only a small proportion of the total cave area, which is essentially escavated in gneiss (Figure 2). The gneiss is a migmatised feldspar-hornblende gneiss which is by no means soluble. This raises the problem of the origin of the cave; how was the large chamber formed?

The answer appears to lie in the presence of zones of extremely shattered gneiss. De Keyser (1961) maps a fault line which crosses the coast at about the location of Wagehoea cave, and indeed the most likely explanation of the shattering is movement along a fault. However, not all the shattered zones are vertical; some are at low angles, suggesting thrust faults. Since the overlying coral is not faulted, the faulting occurred before the coral was emplaced.

The roof of the cave is in places quite solid and unbrecciated. Projections extending into the cave are also generally of solid gneiss. It therefore seems that in some manner the more shattered gneiss has been removed leaving the cave bounded by more solid rock in most of the roof and some of the walls, with brecciated rock preserved in some places (Figure 3). This hypothesis cannot be tested because the postulated shattered rock has been removed. The cave appears to have been formed entirely in gneiss and the exposure of coral results from subsequent collapse. The collapsed blocks are still present and include two with the unconformity clearly exposed in the blocks. The whole intricate interface is preserved and there is no solution parting between coral and gneiss. This means that before the collapse of the blocks and exposure of the coral there must have been a cave wholly in gneiss, imploying the physical breakup of the gneiss and its transports out of the cave.

Transport of the fragments could have been by either marine or fluvial action. Breakdown of the gneiss probably took place by sapping, possibly aided by flow of water along particle interfaces. Water is certainly moving through the gneiss at present. Much of the cave is decorated by stalactites, helictites, and abundant shawls (Plate 1), showing that water saturated with calcium carbonate is moving through the gneiss. The density of decoration on the roof and walls of the cave is a measure of the stability of the gneiss; in places the roof and walls are bare of decoration and the floor underneath is composed of loose gneiss rubble. In a few places, particularly where the gneiss is intensely shattered, water emerges from between the gneiss particles, and the gneiss is unstable.

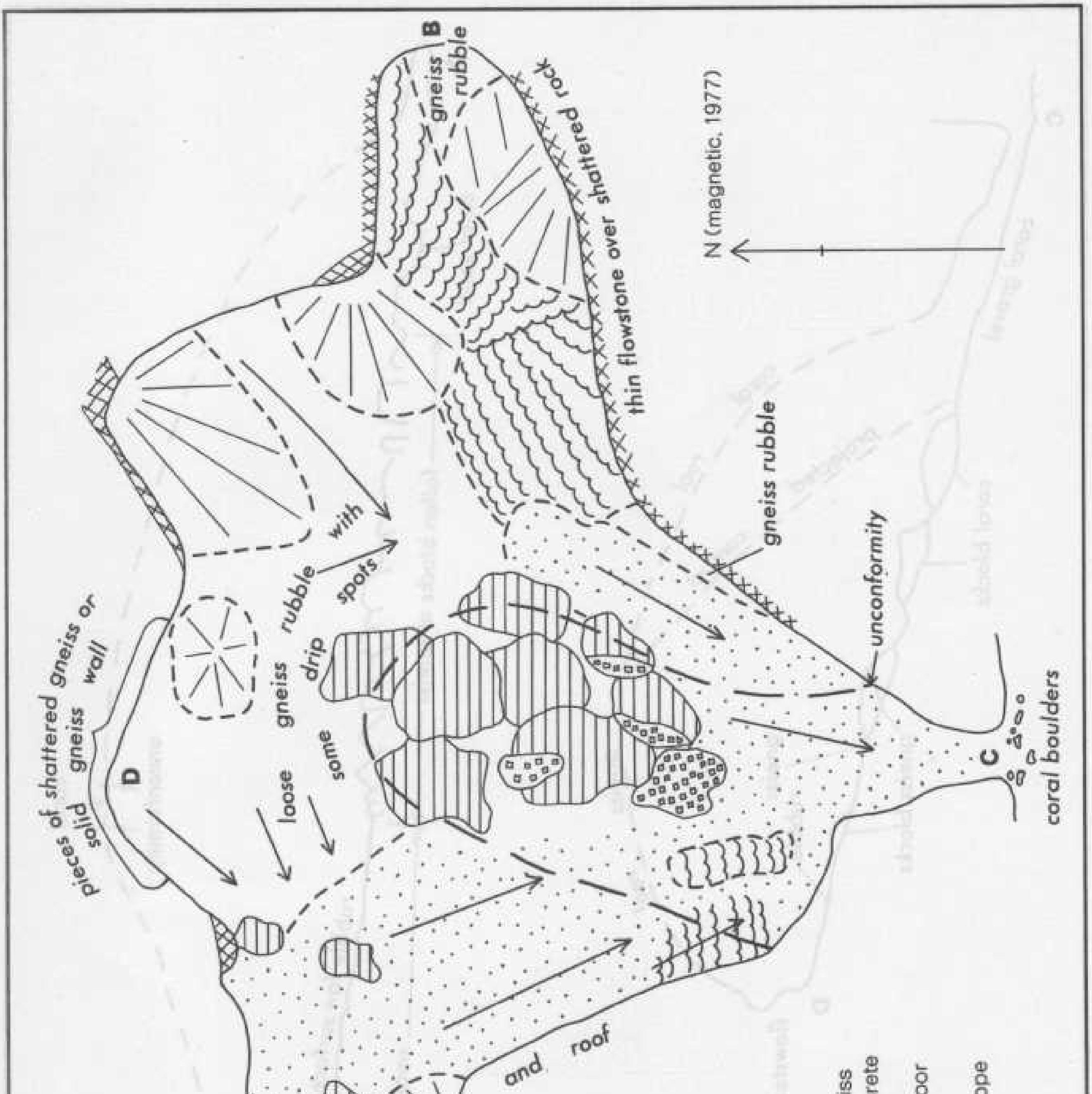

Figure 3. Wagehoea Cave (plan).

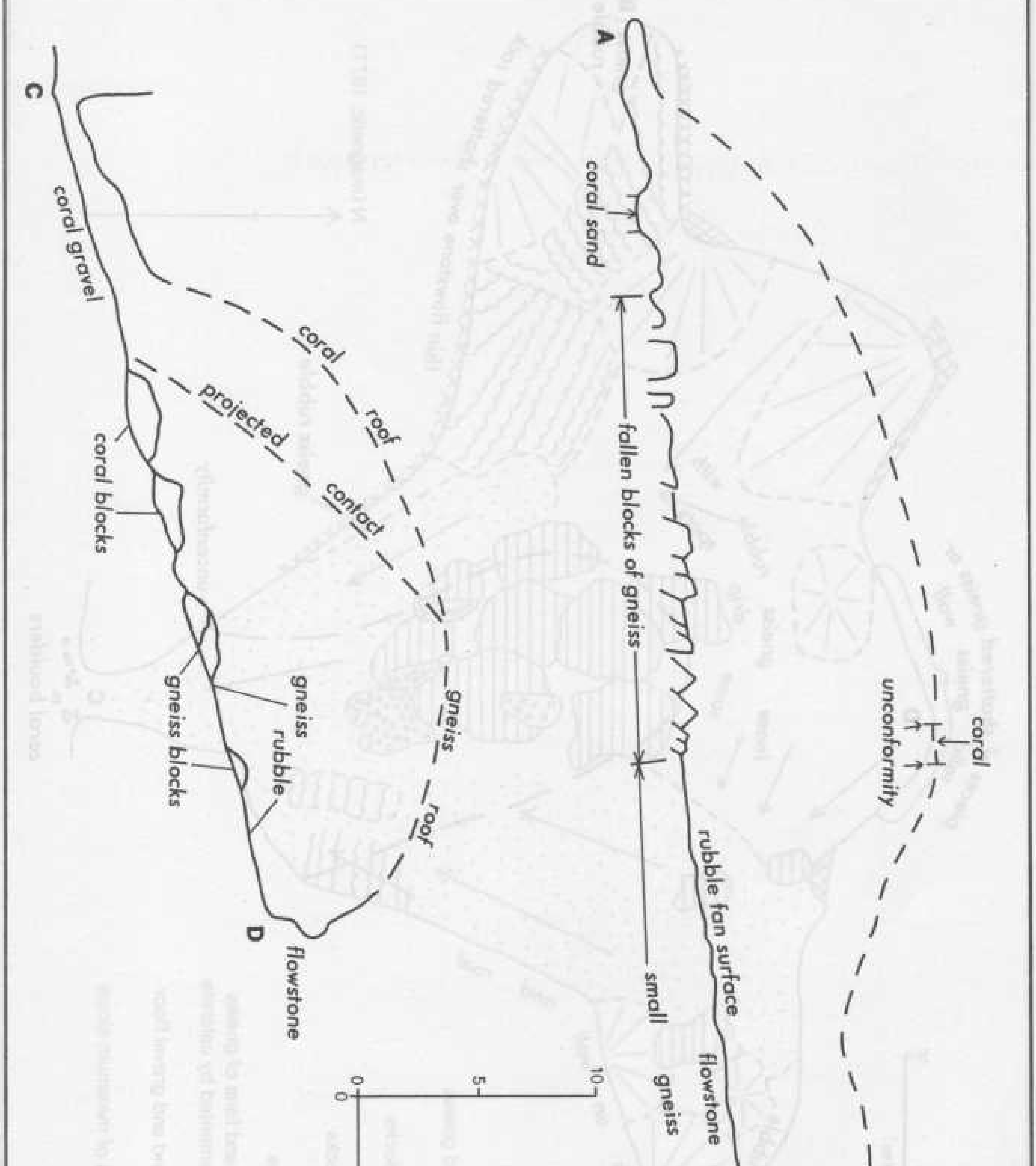

Figure 4. Wagehoea Cave (sections - for location see Figure 3).

In order to explain the origin of the cave, we can postulate a body of groundwater within the shattered gneiss with maximum flow along the water level within the gneiss rather than the coral. Groundwater movement leads to fretting of the gneiss and assists in the transport of the detached fragments out of the cave. Initially the cave would be entirely in gneiss except for a small area at the entrance; the unconformity has been exposed only by subsequent collapse. The coral, in fact, has had no part in the hydrological relationships that give rise to the cave. It does, however, have an important role structurally in providing support for the roof of the cave. A cave formed in the manner described above would probably collapse rapidly if the few metres of gneiss above the roof were exposed directly to the air.

We searched for a pattern in the brecciation of the gneiss, but did not find one. Low angle faulting is important. It provided a zone of shattered gneiss below a few metres of solid gneiss, creating suitable circumstances for this exceptional cave to form.

As noted above the cave is well decorated. In addition to the stalactites, helictites, and shawls, there are stalagmites, rimstone pools and flowstone. There is also a great deal of cemented gneiss debris, expecially around the walls (Figure 3). Elsewhere, where the fallen blocks do not occupy the floor, it is covered with coral debris that is identical with debris occurring in sea caves presently open to the sea; we assume that the coral debris in Wagahoea was also washed in by the sea.

The sequence of cave development is as follows:

a) The original formation of the cave by fretting of the gneiss walls and the accumulation of talus slopes at about 10^{o} slope angle around the edges.

b) Carbonate was then deposited on the purely gneiss debris and cemented it on the floor of the cave. During this phase large amounts of flowstone were deposited.

c) A period of erosion then cut through the flowstone and the underlying non-cemented debris leaving distinct ledges of calcite-cemented breccia. This may have been due to a change in the hydrologic regime, or a change in base level due to either a change in sea level or erosion at the cave entrance.

d) Large scale collapse then exposed the unconformity.

e) The coral gravel on the floor is younger than anything else in the cave and must have been deposited at a late stage in the development of the cave.

f) At present some fretting is still going on, with the production of fresh talus. Minor flowstone features are still developing, but the big flowstone areas are now dead.

It is possible that a lower sea level in the past may have provided a larger entrance. This would allow much easier transport of the gneiss fragments out of the cave by wave activity. The coral debris on the cave floor is of very recent origin, probably resulting from some rather freakish waves washing beach debris through the present cave entrance.

CAVE BURIALS

As in the Trobriand Islands (e.g. Ollier and Holdsworth, 1971) and Wooklark Island (Ollier and Pain, 1978), caves on Misima Island have been used as tombs. These cave burials follow the traditional practice, with local variations, of the two-stage burial. First the body is buried, and later it is exhumed and the bones placed in a cave, sometimes in a container, usually made of pottery. On Misima we found may of the features found elsewhere. The two-stage burial practice has, as elsewhere, resulted in the loss of many of the small bones. This means that the caves contain mainly limb bones, shoulder bones, and skulls. Bundles of roughly parallel limb bones were recorded at Weweha, but this was not common. Pots were found at 5 out of 12 caves that contained bones.

We collected a few decorated pot sherds from each of the 5 caves containing pottery, and gave them to Dr B.J. Egloff of the Papua New Guinea Museum and Art Gallery for identification. He reports (pers. comm.) that they are similar in style to those reported in caves from Paneate (Tindale and Bartlett, 1937) and resemble the modern Paneate industry. However, he points out that the pottery industries of the southern Massim and their antecedents have not been studied in detail.

Hinauta 1 (BN1) is a quite exceptional burial cave. It is typically located near the top of a 30 m limestone cliff, though access is at present easy from the top, and slopes down at about 10^{o}, being divided into two main chambers about 2 m wide with a slight constriction between. The cave floor is covered wall-to-wall with human skulls. At least one hundred skulls are prsent, seventy in the outer chamber and thirty in the inner one, but there could be more if, as seems likely, there are several layers of skulls deep in the cave. Skulls of men, women and children were present, and one skull, probably female, had a streak of red ochre on the forehead. Jawbones, a few other bones, and a few pottery fragments are present, but this is pre-eminently a skull cave. None of the skulls has marks of injury or of subsequent drilling.

Plate 1. Drawing of the interior of Wagehoea Cave. Note the section of roof with light coloured coral exposed by rockfall, and the shawls and stalactites decorating the roof and walls. The coral-gneiss unconformity is visible on the blocks in the foreground.

Plate 2. Skulls and limb bones in Hinauta 1 Cave.

No shells special to the island, and comparable to the clams of Kiriwina or the bailer shells of Vakuta, were noted. One peice of pearl shell was found at Weaweha, but this may be accidental. Megaliths are commonly associated with caves in the Trobriand Islands (Holdsworth and Ollier, 1971), but we found no megaliths on Misima.

As far as we could find out, the present inhabitants of Misima have no real knowledge of cave burials. There are no real or legendary memories, or even secondary stories to rationalise the cave burials. The age of the burials is uncertain, but they are centainly beyond living memory. The pottery styles may give an indication. The Weaweha burial, we think, must be several hundred years old at least; one of the pots present is located under a drip, and now contains a cylindrical stalagmite about 20 cm high.

CONCLUSIONS

The raised Quaternary limestone of Misima Island has not been affected by karst processes as much as we expected; in particular, we found little evidence of cave development along the unconformity between the limestone and the underlying gneiss. This lack of cave development we attribute to the location of the limestone on ridge ends between the major drainage lines that are cutting down on gneiss. The coral is a thin veneer without a large catchment, which means that cave development is retarded.

Nevertheless some caves are present, including sea caves, rifts, ledges and phreatic caves. One cave is formed entirely in gneiss, except for a small area where coral is exposed by rock fall from the roof. This cave appears to have developed by the washing out of fragments in fault-shattered gneiss. The local people had not entered this latter cave before we explored it in 1977; therefore it is interesting to learn that it was used as a refuge during the passage of a cyclone about 2 months after we visited the island (John Bartlett, pers. comm.).

Many of the caves we recorded contained human burials and associated pottery. The burial practices on Misima appear to have been similar to those practised elsewhere in the region.

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Mr Paul Bourne and Mr Jon Bartlett, Bwagaoia, assisted us a great deal with transport and hospitality while we were on Misima; we owe them our thanks. C.F.P. thanks the Research Committee, University of P.N.G., for financial support for the project.

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ILLUSTRATIONS

Figures and photographs should be kept to a minimum and generally should not duplicate information in tables or other material. Photographs should be clear black and white prints with sharp focus. Where several photographs are to form one plate they should be mounted together on white card. Any lettering required on photographs should be applied with 'Letraset'. Figures should be drawn in Indian ink on white card, heavy paper or tracing material and lettered using stencils or 'Letraset'.

All ilustrations should be drawn to fit a print area of 160 x 260 mm. They may be larger provided that these proportions are maintained, but allowance for reduction must be made when choosing letter sizes and line thickness. Several diagrams or photographs can only be included in one page if they all require the same reduction. Diagrams for inclusion in the text must be drawn to a width of either 160 mm (to appear at the same size) or 220 mm (for reduction); they must be clear and simple as they will be reproduced by a lower-quality process.

Figures and plates should each be numbered consecutively and specifically referred to in the text. The numbers should be marked lightly in pencil on the margin or back of each illustration. Captions should be typed on a separate sheet.

UNITS

The S.I. system (Australian Standard AS 1000) should be used unless citing historical data, in which case the original units should be quoted and appropriately rounded metric equivalents added; e.g. "100 feet (30 m)".

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