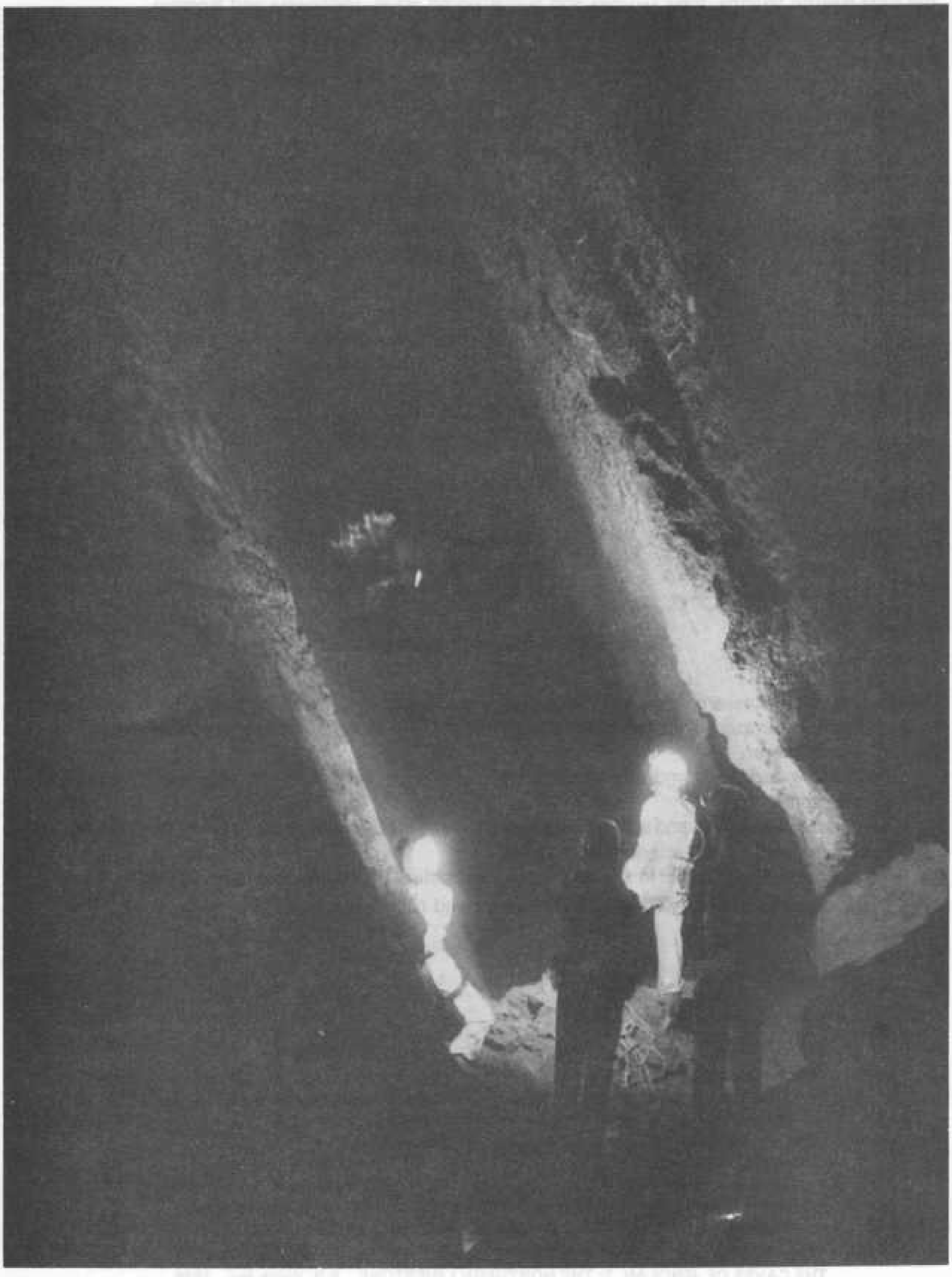
Vol. 16(2) 1978

Helictite

JOURNAL OF AUSTRALASIAN CAVE RESEARCH



Final pitch in Odyssey Cave (B24), Bungonia, N.S.W.

photo by A. Warild & J. Dyson

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

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Other publications by SRC Ltd:

CAVES OF THE NULLARBOR. T.M.L. Wigley and J.R. Dunkley 1968.
- a review of Speleological Investigations in the Nullarbor Plain.

THE EXPLORATION AND SPELEOGEOGRAPHY OF MAMMOTH CAVE, JENOLAN.
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.
J.R. Dunkley 1976. - a detailed reference list.

THE CAVES OF JENOLAN, 2: THE NORTHERN LIMESTONE. B.R. Welch (ed) 1976.

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REVIEW

THE EXPLORATION AND SPELEOGEOGRAPHY OF MAMMOTH CAVE, JENOLAN, by John Dunkley and E.G. Anderson, with additional material by P.J. Winglee. Published for Sydney University Speleological Society by Speleological Research Council Ltd., Sydney, 1978. pp x + 62; 22 x 28 cm. Price $5.

The first edition of "The Mammoth Book" has now been out of print for several years. It has, indeed, almost become a classic, and certainly a trend-setter, with its page-by-page "street directory" sectional maps, and the first-ever isometric diagram of a cave. As Peter Winglee points out in his chapter, the book also made itself out of date, by stimulating a rush of further work in the cave.

Republishing the book as it was would have been pointless, and rewriting it completely would have been costly. The publishers have therefore reproduced the original text intact, and added nine pages of additional material at the end. Three pages of this is text, written by Peter Winglee, describing the discoveries made in Mammoth in the seven years since the first edition. The text is densely packed - much more so than in the rest of the book - and full of information. However, economics has reared its head again, and the text is typeset by a cheaper process than the rest of the book. A very comprehensive bibliography and checklist of maps completes the text.

Four pages of maps, at 1:480 scale, detail most of the new discoveries in the same format as the rest of the book. The Unsurveyed Connection, now surveyed, is included, but Waterfall Passage remains unsurveyed, as do some of the most recent discoveries. The addendum is completed by a reproduction of the first map of Mammoth, made during the war years by Welch, Noske and others, and by a couple of photographs. More photographs would have been welcome, but it appears that few photographers have been willing to risk their cameras on the long trek to the far north extensions.

The economies made in the production of this second edition have paid off in keeping the selling price down to $5, and at this price it must be good value to anyone with an interest in Jenolan.

BUNGONIA CAVES AND GORGE

A NEW VIEW OF THEIR GEOLOGY AND GEOMORPHOLOGY

Julia M. James, G. Francis and J.N. Jennings

Abstract

Work done at Bungonia since 1972 has filled gaps in our knowledge of this area. Water tracing has proven the earlier inference that the waters of all the major caves of the Lookdown Limestone and the uvula containing College Cave go to the Efflux. Geological remapping shows that faulting allows these connections all to lie in limestone and accounts for the drainage of B4-5 away from the gorge. A 45 m phreatic loop identified in Odyssey Cave, exceptionally large for southeastern Australia, is also accounted for by the geological structure. Phoenix Cave has two successive cave levels similar to those of B4-5. The perched nature of the Efflux now finds a structural control in that the Folly Point Fault has interposed impervious beds between this spring and the gorge. Further analysis of the evidence relating the age of uplift and incision of the Shoalhaven and its tributaries strengthens the case for setting these in the lower Tertiary whereas most of the caves cannot be regarded as other than young. The geological remapping can partly account for the age discrepancy between underground and surface forms found at Bungonia.

INTRODUCTION

Since 1972, when Sydney Speleological Society published the book "Bungonia Caves", further cave exploration, water tracing and geological mapping have in some respects confirmed, in other respects emended, our interpretation of this small but particularly interesting karst.

Geology

Counsell (1973) reviewed the nomenclature of the Silurian sequence and advocated the scheme set out below, which was adopted by James and Montgomery (1976).

BUNGONIA LIMESTONE GROUP
- Frome Hill Formation
  - Sawtooth Ridge Limestone
  - Efflux Siltstone
  - Folly Point Limestone
- Cardinal View Shale
- Lookdown Limestone

The Lookdown Limestone is equivalent to the Lower Limestone of Gould (1966) and the Cardinal View Shale and Frome Hill Formation are equivalent to the Upper Limestone. However, strata in the type sections defined by Counsell have been omitted or repeated by faulting of which he was unaware. The available evidence now suggests that the strata which he named the Cardinal View Shale are actually Tallong Beds and the strata he named Folly Point Limestone are actually Lookdown Limestone. The eastern contact between the Lookdown Limestone and Tallong Beds which was previously regarded as an unconformity is in fact faulted (Francis, 1977d).

North of the gorge detailed geological mapping based partly on drilling results has been carried out by the quarry companies but this information is not yet publicly available (Robinson, 1972). For the present purposes the most relevant finding is that the Silurian sequence has been repeated three times as a result of faulting. South of the gorge in the main cave area, remapping in progress by Francis and Osborne indicates that considerable revision of the stratigraphy is necessary (Figure 1). Nomenclature is also not completely satisfactory. For example, although the term "Tallong Beds" was introduced by Gould (1966) and subsequently employed in another unpublished thesis by Counsell (1973), it was not validated by publication. Since Herbert (1972) has defined the Tallong Conglomerate, a Permian unit further north, the term "Tallong Beds" is no longer available.

Baker (1972) and Counsell (1973) postulated a northward plunging syncline to the east of the Folly Point Limestone. Counsell supported the idea of a syncline here in order to explain why the argillites to the west of the Lookdown Limestone did not extend down to the gorge floor. Our recent work has revealed the existence of a westerly dipping fault, the Troy Walls Thrust, which cuts off the argillites south of the gorge (Figure 2). This indicates that the structure is not synclinal in nature. Flinter (1950) and Counsell (1973) mapped the Reevesdale Fault as a strike fault, trending north-east, which was thought to lie between the Folly Point Limestone and the Cardinal View Shale. The existence of a fault was subsequently confirmed by observations in

Odyssey Cave (James and Montgomery, 1976) but the fault has a variable northerly trend and thus extends obliquely across the strike from the Folly Point Limestone to the Lookdown Limestone. Since this is not the same fault as the one at Reevesdale it is here named the Folly Point Fault. The Cooeeing Point Fault has a north-easterly trend and may be a continuation of the Reevesdale Fault. However, this remains to be proven by detailed structural studies in the area to the south of the caves.

All three limestone belts (the Lookdown Limestone, the "Folly Point Limestone" and the "Sawtooth Ridge Limestone") are broken by faulting (Francis, 1978). The Sawtooth Ridge Limestone is cut off by faulting to the south east of Adams Lookout. Southwards limestone reappears to the west of Serpentine Cave but as small lenses or fault slivers. The Folly Point Limestone is cut off on the north at the Efflux. The Lookdown Limestone is also interrupted by faulting between the Drum Cave and the Grill Cave and between the latter and Becks Gully. Near Fossil Cave, this limestone is offset to the east in a left lateral strike separation and is narrowed on the southern side of a cross fault. The breccia on the eastern contact between the Tallong Beds and Lookdown Limestone, which was previously interpreted as an intraclastic sedimentary feature by Flinter (1950), is actually a stylobreccia formed by faulting. Many other features that were formerly regarded as products of sedimentation are now known to be the results of tectonics and pressure solution.

A reconnaissance to the west of the caves area has shown that the Tangarang Volcanics are folded in a syncline which plunges gently northwards and are intruded by dykes of porphyrite and quartz porphyrite (Francis, 1977a). A number of cross faults are also present in this area.

UNDERGROUND DRAINAGE PATTERN

In 1972 there persisted important gaps in knowledge of the underground water connections despite earlier efforts. The destinations of the waters in the Fossil Cave-Hogans Hole Extension (B4-5), Drum Cave (B13) and Argyle Hole (B31) were not known, and the sources of the Efflux remain enigmatic. However, review of the available topographic, and hydrologic evidence had led to the inference that all the deep caves of the Lookdown Limestone fed Odyssey Cave (B24), which in turn supplied the Efflux. It was also argued that the large closed depressions to the southwest in both the Folly Point and Sawtooth Ridge Limestones were part of the catchment of the Efflux. All these conclusions have been supported subsequently by tracing experiments (James, 1973; James and Montgomery, 1976). The Fossil Cave-Hogans Hole Extension was proven to deliver to the Drum, which was already known to gather in the Grill Cave's supply. Then the combined waters of most of the Lookdown Limestone outcrop go from the Drum Cave to the Styx Stream in Odyssey Cave, whence they proceed along the strike to the Efflux. Argyle Hole water also reaches the Efflux but joins the artery at some point below Knockers Cavern, the bottommost point in Odyssey Cave. Even with this addition, much of the Efflux output still has to be accounted for. Some of this is now known for certain to come from College Cave (B84) in the big uvula to the southwest.

Like Hollands Hole (B35), College Cave trends north-east from the same uvula towards the Efflux. It is much larger than Hollands and lies mainly at a lower but not deep level. Presently, it receives surface runoff only in floods when it fills to the surface and releases this water slowly.

The origin of B68 Spring (and its neighbour, B128) also remained uncertain in 1972. A fluorescein test from Main Gully gave a positive result in B68 (James, 1973).

Thus many of the previous deductions about the pattern of the hydrology have been confirmed but the relationships of the pattern to the geology now takes on a different character. The connection between Drum (B13) and Odyssey Caves and also that from Argyle Hole (B31) to the west cross the surface outcrop of the argillites. When these connections were postulated previously (Jennings, James, Counsell and Whaite, 1972), cases known elsewhere of penetration of intervening non-karst rocks by karst waters were cited. However, it was also pointed out that the intervening unit probably narrowed downwards through thrusting (Jennings and James, 1973). James and Montgomery (1976), following the structural interpretation of Counsell (1973), regarded the shaly limestone at the base of the footwall in Scylla's Cleft, Odyssey Cave, as a carbonate member of the Cardinal View Shale which was stratigraphically lower in the formation than the shales higher up on the footwall. Closer examination of Scylla's Cleft has revealed that the rock at the base of the cave footwall is actually limestone on the hanging wall of the fault. The apparent superposition of the shale on this limestone is an illusion created partly by the oblique intersection between cave passage and fault trend and partly by drag which has smeared deformed limestone onto the footwall of the fault. It thus seems likely that the underground drainage from Drum to Odyssey Cave passes beneath the impervious barrier of argillites, probably following cross faults which extend down into the limestone on the footwall of the Troy Walls Thrust. The underground drainage from the Grill Cave to the Drum Cave likewise passes beneath argillites on the hanging wall of the thrust. A stylobreccia lies immediately below the thrust in the Drum Cave and the Railway Tunnel has developed in it (Figure 2, section GH).

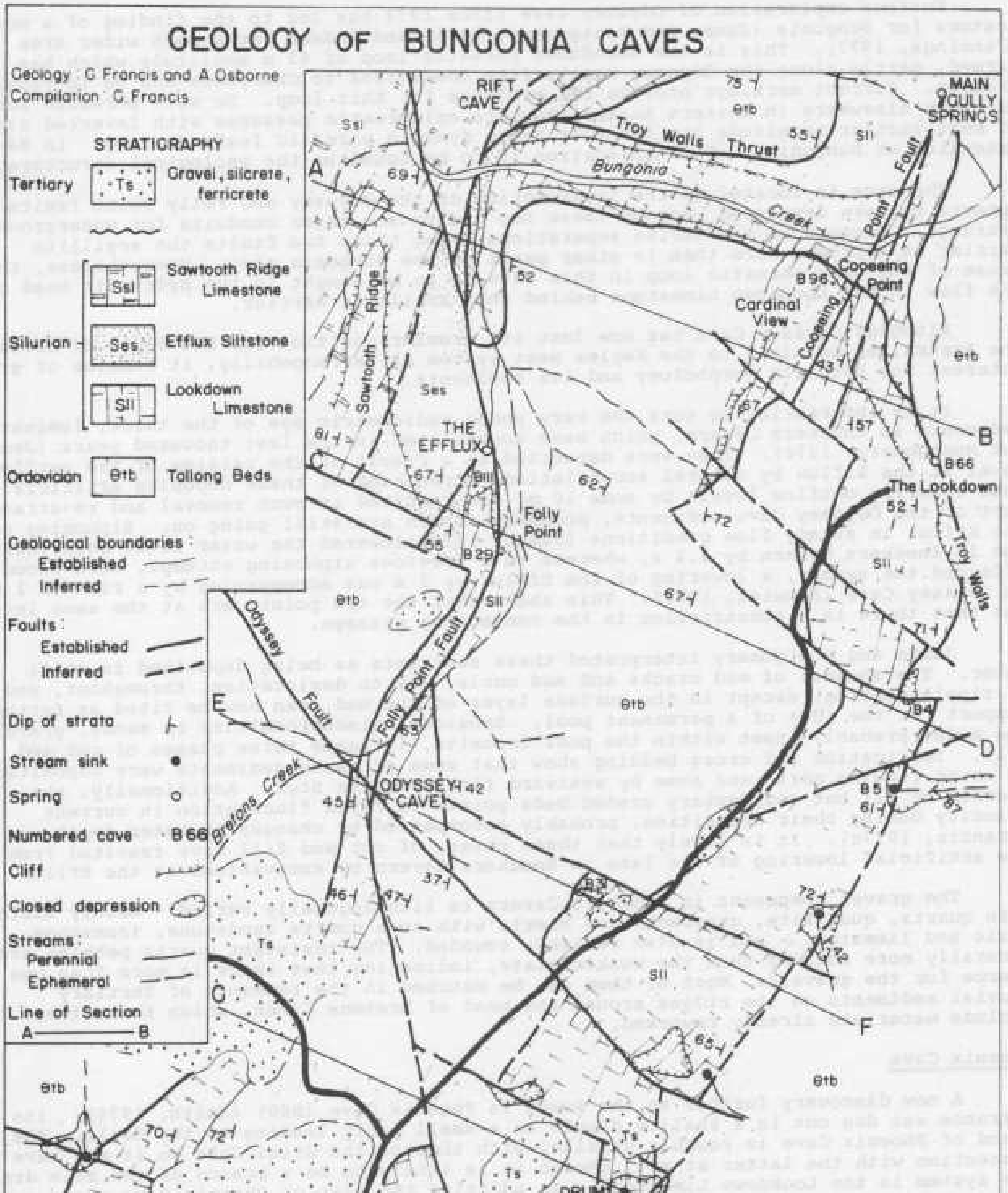
GEOLOGY OF BUNGONIA CAVES
Geology G. Francis and A. Osborne
Compilation G. Francis
STRATIGRAPHY
Tertiary
Ts
Gravel, silcrete, ferricrete
Ssl
Sawtooth Ridge Limestone
Silurian
Ses
Efflux Siltstone
Sll
Lookdown Limestone
Ordovician
Єtb
Tallong Beds
Geological boundaries:
Established
Inferred
Faults:
Established
Inferred
Dip of strata
Stream sink
Spring
Numbered cave B 66
Cliff
Closed depression
Streams:
Perennial
Ephemeral
Line of Section
A B
RIFT CAVE
MAIN GULLY SPRINGS
Troy Walls Thrust
Bungonia
Creek
Point Fault
Coppeing Point
Cardinal View
Sawtooth Ridge
THE EFFLUX
Folly Point
The Lookdown
Troy Walls
Odyssey Fault
Folly Point Fault
Bretons Creek
ODYSSEY CAVE
DRUM CAVE
GRILL CAVE
COLLEGE CAVE
HOLLANDS HOLE
B96
B66
B29
B4
B5
B3
B60
0 100 200 300
metres
Road
G.N.

Figure 1.

New Aspects of Odyssey Cave

Further exploration of Odyssey Cave since 1972 has led to the finding of a novel feature for Bungonia (James and Montgomery, 1976) and indeed for a much wider area (Jennings, 1977). This is the abandoned phreatic loop of 45 m amplitude which has formed, partly along the Odyssey Fault, from the Sirens to Charybdis and on to Penelope Chamber. Current markings provide the evidence for this loop. No such phreatic loop is known elsewhere in Eastern Australia where epiphreatic passages with inverted siphons of much smaller magnitude are the rule among dynamic phreatic features (e.g. in B4-5 Extension at Bungonia). The explanation is to be found in the geological structure.

The cave is located on the intersection of the Odyssey and Folly Point faults and appears to have developed because these two faults are major conduits for underground drainage. Because of the strike separations along these two faults the argillite barrier is narrower here than in other parts of the Bungonia area. Nevertheless, the cause of the deep phreatic loop in this cave is to be sought in the hydraulic head of the flow in the Lookdown Limestone behind this argillite barrier.

Although Odyssey Cave has now lost its premier position for the depth of caves in the Australian mainland to the Eagles Nest system at Yarrangobilly, it remains of great interest for both its morphology and its sediments.

It is interesting to note the very young radiometric age of the thick, laminated sediments in Knockers Cavern, which have accumulated in the last thousand years (James and Montgomery, 1976). They were deposited as a result of the raising of the outflow level at the Efflux by natural accumulation. Trenching of these deposits artificially, thus lowering outflow levels by some 10 m, has resulted in much removal and re-arrangement of the Odyssey Cave sediments, processes which are still going on. Siphoning of the Efflux in steady flow conditions (James, 1978) lowered the water level both there and in Knockers Cavern by 2.2 m, whereas in a previous siphoning attempt, when flooding affected the system, a lowering of the Efflux by 2 m was accompanied by a rise of 1 m in Odyssey Cave (Bonwick, 1978). This shows that the two points are at the same level but that there is a constriction in the connecting passage.

James and Montgomery interpreted these sediments as being deposited in still water. The absence of mud cracks and mud curls, due to desiccation, throughout, and of ripple marking, except in the surface layer of the mud, can now be cited as further support for the idea of a permanent pool. Erosional disconformities in sands, gravels and muds, probably inset within the pool deposits, indicate three phases of cut and fill. Imbrication and cross bedding show that some of these sediments were deposited by water flowing north and some by westward flow from the Styx. Additionally, the absence of all but rudimentary graded beds points to rapid fluctuation in current velocity during their deposition, probably accompanied by changes in water depth (Francis, 1977c). It is likely that these phases of cut and fill have resulted from the artificial lowering of the lake in Knockers Cavern by excavations at the Efflux.

The gravel component in Knockers Cavern is lithologically varied - mainly slate, vein quartz, quartzite, greywacke and chert, with some quartz sandstone, ironstone, shale and limestone - and is also variably rounded. The resistant quartz pebbles are generally more rounded than the weaker slate, indicating that there is more than one source for the gravels. Most of them can be matched in the remnants of Tertiary fluvial sediments on the ridges around the head of Bretons Creek, which themselves include materials already reworked.

Phoenix Cave

A new discovery further to the south is Phoenix Cave (B60) (Smith, 1976); its entrance was dug out in a shallow dimple on a small gully leading to the Grill. The trend of Phoenix Cave is roughly parallel with that of the Grill Cave so it may have no connection with the latter at all, though it is likely to be a branch of the main drainage system in the Lookdown Limestone. In addition the plan of Phoenix Cave shows a more elaborate joint control pattern than is commonly found at Bungonia; there are three sets in evidence, bearing north-east, east and north-north-west (Francis, 1977b). The latter set are shear joints which run parallel to the Folly Point Fault. In profile the cave is chiefly remarkable for the development of two more or less horizonal levels, which must have succeeded one another in function, at depths of about 35 and 60 m below the plateau. Only in part of the Fossil Cave (B4) - Hogans Hole (B5) system is a similar situation known at Bungonia, so on present evidence these relations in Phoenix Cave do not appear to have general significance.

Phoenix Cave contains a number of sediment types, notable among which are the cyclic deposits in a wall niche about 15 m below entrance level. These grade upwards from sandy mud to mud, followed by a thin horizon of charcoal and humus overlain by a thin flowstone layer. This sequence is repeated three times and the grading is due either to declining current velocity or sedimentation from still water filling the passage. The flowstone layers record intervals of seepage between the floods that brought in the clastic sediments.

Above the 35 m level, which includes a constriction known as "The Squeeze", a striking contrast is to be seen between the smoothing of rock surfaces in vadose tunnels on passage floors and the delicate etching out of crinoids and tabulate corals in the walls and roof. In addition, in the same area, there are pebbly sandy muds and charcoal fragments lodged in passage roofs. The explanation of this combination requires that

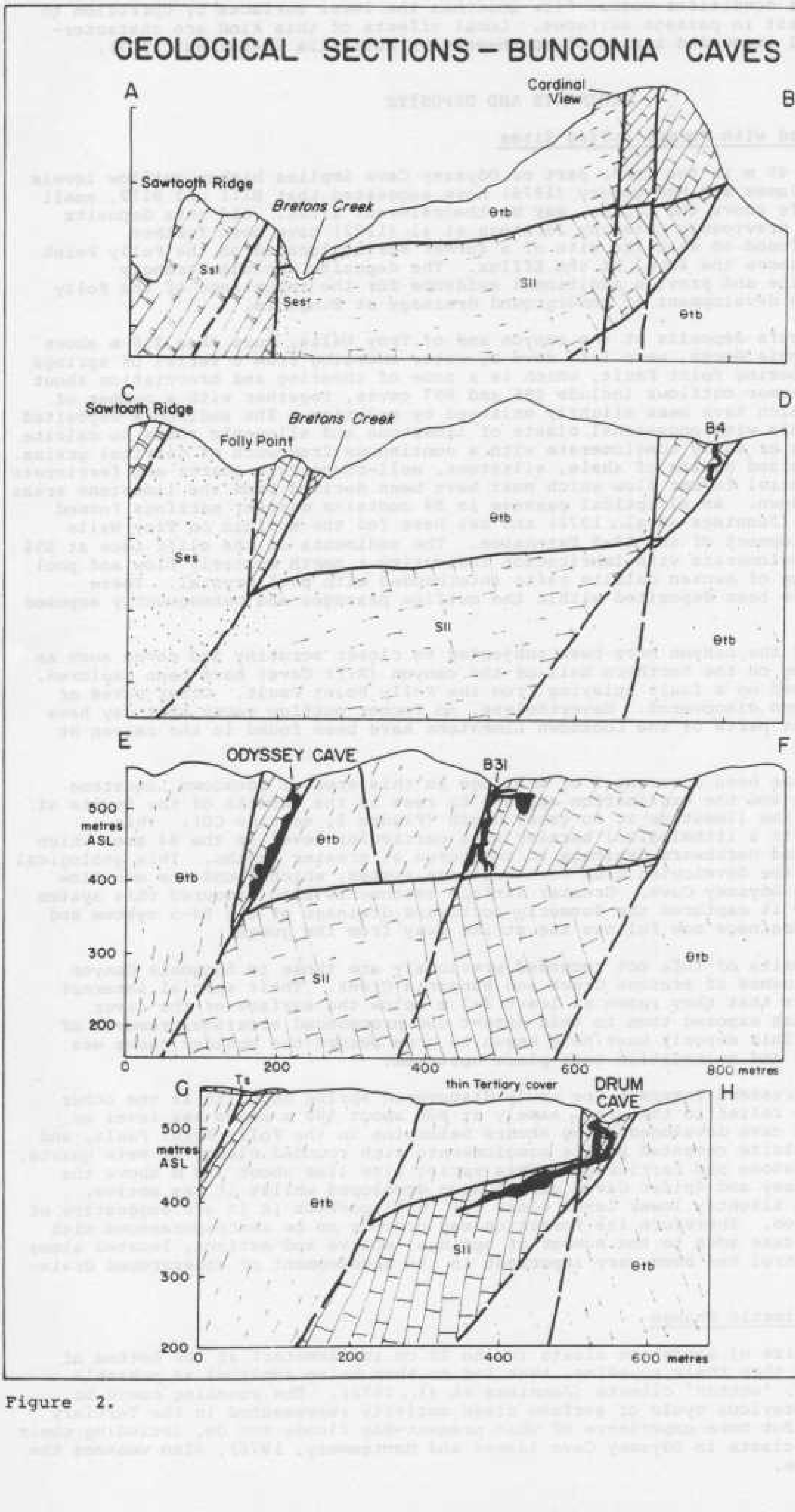
GEOLOGICAL SECTIONS – BUNGONIA CAVES
A
B
Cardinal View
Sawtooth Ridge
Bretons Creek
Θtb
Ssl
Ses
Sll
C
D
Sawtooth Ridge
Bretons Creek
Folly Point
B4
E
F
ODYSSEY CAVE
B31
500
metres
ASL
400
300
200
0
600
800 metres
G
H
Ts
thin Tertiary cover
DRUM CAVE
600 metres

Figure 2.

the coarse sediments were deposited previously. At the present time temporary blockages of the system by sediments at The Squeeze cause periods of sluggish phreatic conditions in which differential solution of the etched surfaces take place (Francis, 1977b). In normal conditions vadose flow smoothes the lower surfaces by corrosion to produce the contrast in passage surfaces. Local effects of this kind are characteristic of the small impounded karsts of south-eastern Australia (Jennings, 1977).

SEDIMENTS AND DEPOSITS

Deposits Associated with Former Spring Sites

The lift of 45 m in the lower part of Odyssey Cave implies higher outflow levels for the system. James and Montgomery (1976) have suggested that B111 and B112, small caves in the cliffs above the Efflux, may be the relevant sites. Old tufa deposits below these caves previously noted by Jennings et al. (1972) have been further investigated and found to mark the site of a former spring located on the Folly Point Fault about 20 m above the level of the Efflux. The deposits include strongly indurated travertine and provide additional evidence for the importance of the Folly Point Fault in the development of underground drainage at Bungonia.

High level tufa deposits at the canyon end of Troy Walls, more than 250 m above the floor of Bungonia Gorge, were laid down by water emerging from a series of springs located on the Cooeeing Point Fault, which is a zone of shearing and brecciation about 30 m wide. The former outflows include B96 and B97 caves, together with a number of shear fractures which have been slightly enlarged by solution. The sediments deposited here range from tufa with occasional clasts of limestone and allogenic rocks to calcite cemented sandstone or sandy conglomerate with a continuous framework of detrital grains. Pebble to cobble-sized clasts of shale, siltstone, well-round vein quartz and ferricrete indicate a substantial former flow which must have been derived from the limestone areas south of the Lookdown. An elliptical passage in B4 contains current markings formed by northward flow (Jennings et al., 1972) and may have fed the springs on Troy Walls prior to the development of the B4-5 Extension. The sediments on the cliff face at B96 include pebble conglomerate with imbrication indicating a north westerly flow and pool deposits consisting of sunken calcite rafts interbedded with pool crystal. These sediments must have been deposited within the outflow passages and subsequently exposed by cliff retreat.

The walls of the canyon have been subjected to closer scrutiny and caves such as the obvious opening on the Northern Wall of the canyon (Rift Cave) have been explored. Rift Cave has formed on a fault splaying from the Folly Point Fault. Other caves of small size have been discovered. Nevertheless, no former outflow caves that may have drained significant parts of the Lookdown Limestone have been found in the canyon at lower levels.

Thus there has been a reversal of drainage in this area of Lookdown Limestone close to the gorge and the explanation appears to rest in the effects of the faults at B4, which cut off the limestone at no great depth (Figure 2, section CD). This structure results in a lithological barrier at a particular level in the B4 area which could have inhibited northward drainage to the gorge at greater depths. This geological factor advantaged the developing Drum Cave drainage system, which found its own flow route westwards to Odyssey Cave. Greater surface catchments also favoured this system so that eventually it captured the formerly northward drainage of the B4-5 system and nearly the whole drainage now follows the strike away from the gorge.

Further deposits of tufa not recorded previously are those in Bungonia Canyon opposite the confluence of Bretons Creek and Bungonia Creek. Their special interest resides in the fact that they reach at least 2-3 m below the surface of the river alluvium. Scour has exposed them to this extent and pronounced erosional removal of tufa is evident. This deposit must have begun to grow before the boulder choke was formed by rockfall and aggradation took place upstream.

Perhaps of greatest interest are newly discovered spring deposits at the other extreme end of the relief in the area, namely at B29 about 500 m above sea level on Folly Point. This cave developed along shears belonging to the Folly Point Fault, and contains muddy, calcite cemented pebble conglomerate with rounded clasts of vein quartz, quartz-veined sandstone and ferricrete. This spring site lies about 330 m above the gorge floor; Odyssey and Spider Caves cannot have developed whilst it was active. Chalk Cave is at a slightly lower level close by; wall pockets in it are suggestive of epiphreatic solution. Therefore its formation may precede or be contemporaneous with B29 spring. This case adds to the number of springs, active and extinct, located along faults: fault control has been very important in the development of underground drainage at Bungonia.

Cave Gravel and Climatic Change

It was the size of sandstone clasts (up to 20 cm in diameter) at the bottom of Grill Cave, rather than their rounding, that led to them being admitted as possible evidence of former, 'wetter' climate (Jennings et al., 1972). The rounding could be inherited from a previous cycle of surface river activity represented in the Tertiary gravel remnants. But more experience of what present-day floods can do, including their movement of large clasts in Odyssey Cave (James and Montgomery, 1976), also weakens the inference from size.

Despite this, there are now much firmer grounds for saying that Bungonia Caves must have received more run-off in the Late Pleistocene than now. Old shorelines around Lake George 50 km to the southwest of Bungonia demonstrate that about 25,000-20,000 years ago it was very much deeper and larger than now, as a result of increased run-off. This was a consequence of reduced evaporation accompanying lowered temperatures rather than of increased precipitation (Coventry, 1976). That this 'wetter' period was not the only one of relevance has been shown by pollen analysis of Lake George bottom sediments by Singh (in Bowler, 1976). Altogether four periods of cool temperate forest, instead of the present warm temperate woodlands, have occurred around Lake George in the last 350,000 years. These alternated with drier phases when the lake was small and shallow or altogether absent. Bungonia Caves must have been affected by the climatic and run-off history revealed by Lake George.

CHRONOLOGY

The Hanging Springs and the Age of the Caves

Finally the interrelated problems of the hanging springs and the age of the caves must be reconsidered. As described above, it has been shown that the drainage of most of the Lookdown Limestone and some of the Folly Point and Sawtooth Ridge Limestones resurges some 120-150 m below the plateau after a quasi-horizontal epiphreatic course following a steep descent in vadose shafts to that level. The Efflux is, however, about 200 m above the bottom of the gorge nearby. Similarly on the other side of the gorge the Main Gully Springs hang about 100 m above it. From the latter springs limestone strikes south to Bungonia Creek. In previous studies it was accepted that there were no geological barriers to the development of connections to outflow caves at the bottom of the gorge (Jennings et al., 1972; Counsell, 1973). This situation is not found in other cave areas of the Southern Tablelands and thus the hanging springs at Bungonia are anomalous within their regional setting (Jennings, 1975). In the earlier analysis, the conclusion reached was that gorge incision became too rapid for cave development to keep pace with it, despite the inexorable tendency for water to find lower routes through limestone wherever there is opportunity lithologically and topographically (Jennings and James, 1976). Rapid incision, at an earlier stage than this, was also thought to have been responsible for the greater degree of vertical development in Bungonia Caves than elsewhere in the region. A slowing down or halt in incision of the gorge could have promoted the intervening phase of formation of the more nearly horizontal stage of cave development behind the springs.

Wellman and McDougall (1974) have dated Tertiary basalt remnants on the plateau near Bungonia at 46-44 million years and on the coastal plain on the South Coast of New South Wales at 31-26 million years. From study of the relationships between basalts and topography in several parts of the Eastern Highlands they postulated two general phases of epeirogenic uplift, the first occurring between the Cretaceous and Oligocene and the second in the last 10-15 million years. Jennings et al. (1972) had related the two phases of incision to two such phases of plateau uplift in the Shoalhaven area. Jennings and James (1976) also adduced the good correspondence of double nickpoint heights along the Shoalhaven River with those of Bungonia Creek and some neighbouring tributaries, in support of this hypothesis.

Two problems arose when this correlation was translated into rates of development. Far too much time seemed to be available for the retreat of headward erosion from the plateau margin to the rejuvenation heads. Furthermore, the deep caves at Bungonia have far too young an aspect for them to be comfortably attributed to the time before the second uplift. Here are vadose shafts of notable depth for southeastern Australia and then epiphreatic levels, all of which suffer considerable active development at the present time as recent experience of floods has demonstrated.

Only abandoned horizontal parts of certain caves close beneath the plateau surface have at all an ancient appearance. This is notably the case at Argyle Hole where this part of that cave has recently been found to be more extensive than was previously known (Pavey, 1972). There are also in some of these dynamic phreatic passages at shallow depth remnants of cemented sediments which could be of considerable age.

That there may also have been surface karst features forming at a very early stage is suggested by a ferruginous silcrete in the B74 doline, which is developed at the contact of the argillites with the limestone. This silcrete is plastered onto the argillite slope of this doline and there is no evidence of reworking and transport of the cover. The implication is that the doline developed during or before the phase of Tertiary sedimentation of the plateau surface. Preservation of this deposit has depended on the argillite beneath and it seems likely that there was also doline development at this time wholly within the limestone outcrops without survival there of *in situ* Tertiary deposits. Such deposits may have been disturbed by subsidence resulting from solution of the limestone beneath the Tertiary cover.

Nevertheless, these old features at and near the plateau surface do not resolve the basic conflict which is in fact exacerbated by further considerations. About 35 km south of Bungonia, Eocene basalt flows filled an ancient valley of the Endrick River to a depth of 100 m below the nearby plateau surface, though this river has subsequently cut right through it. This basalt-filled valley has a gradient of about 5 m per km. Assuming that this valley had an accordant junction with the Shoalhaven River and that below that junction the major river formerly had a gradient similar to its present one, the Shoalhaven River must have had a valley 240 m deep near Bungonia Gorge. This points to a much earlier development still for the deep caves at Bungonia, accepting the correlation set out above; on this basis the epiphreatic level at 150-200 m depth could be Eocene or older.

Other evidence indicative of earlier final uplift for the plateau of the Southern Tablelands is found on the coast between Bermagui and Narooma. Here Oligocene/Miocene marine sediments lap within a few kilometres of Mt. Dromedary, an erosional residual rising hundreds of metres above sea level and close to the coastal fall of the plateau. Young (174) describes sections at Pattimóres Lagoon, a little north of Ulladulla, that show a lateritic profile disconformably overlain by Tertiary basalts, which have been dated at 26 million years (Wellman and McDougall, 1974). On the plateau near Bungonia lateritic profiles are well developed on middle Eocene basalts but not on the mid Oligocene basalts at Caoura. Thus laterites on both coastal plain and plateau are Oligocene or older in age. Since coastal plain laterites are found in Kangaroo Valley and extent into embayments of the plateau margin west of Albion Park and south of Cambewarra, space for late warping of the plateau margin is closely circumscribed. This supports McElroy and Rose (1962) in their case against warping.

Related evidence comes from the Shoalhaven Valley floor; about 1.5 km upstream from the Bungonia Creek confluence there is a prominent terrace the top of which lies about 14 km above the present banks. The terrace deposits include manganese-cemented, muddy conglomerates, iron-cemented sandstones and iron-stained mudstones (Francis, 1977a). Petrographically similar sediments occur in a number of areas of Eastern Australia and in many cases the stratigraphic relations between these sediments and dated basalts indicate that the sediments are of mid-Tertiary age. However, ferruginous cementation of this kind can form more rapidly than the development of a full lateritic profile so the possibility that the Shoalhaven terrace may be Pleistocene cannot be ruled out.

In this impasse it is important to recognise that the inference of two phases of uplift from two phases of rejuvenation is not the only possible interpretation. A single large rejuvenation head at the coast resulting from one phase of uplift can be transformed up the valley system into several separate but lesser rejuvenation heads as parts of the one wave of erosion arrested by lithological obstacles (King, 1947). For the area in question, Young (1974) has suggested that resistant members in the Permian sequence in the lower Shoalhaven gorge have in the past split up the rejuvenation effect of a single uplift. Along Bungonia Creek itself, further examination of the reach along the Tangarang Volcanics reveals that although this stream runs along the axis of a syncline in its course above the limestone, the waterfalls at the rejuvenation head are in fact structurally controlled by dykes, faults and variations in the spacing of bedding planes within the sedimentary sequence (Francis, 1977a). Thus it is possible that the variations in the stream profile result from geological controls on river incision during a single uplift (cf. Young, 1974). If this is the case it exacerbates the geomorphological problems arising from the denudation chronology.

What explanations can be sought to resolve this apparent conflict between the long time which seems to be available for the formation of the gorge and the deep caves on the one hand and their juvenile appearance on the other? Jennings and James (1976) cited quite rapid rates of retreat of nickpoints along the Zambesi for comparison with the Shoalhaven's history. These rivers are not so different in their catchment sizes and characteristics for this to be wide of the mark. That this kind of comparison is reasonable is further indicated by the Fairlight Gorge along the Nepean River, which is an antecedent course maintained across differential uplift (Taylor, 1958); this implies no great delay between uplift and valley incision. However, it may be misleading to extend such comparison to smaller streams like Bungonia Creek. In the Cudgegong Valley of the Central Tablelands basalts dated by Dulhunty (1971) can be used to show that a rejuvenation head on the Cudgegong has retreated about 30 km in the last 15-20 million years, but rejuvenation heads have only passed 5-12 km up smaller tributaries in the same period of time. In the case of Bungonia Creek much of the retreat to the present nickpoints has been across the strike which would hinder it. It is relevant to note that Barbers Creek, the next left bank tributary of the Shoalhaven downstream, has only one clear rejuvenation head and this creek runs along the strike. Yarrunga Creek 40 km northeast of Bungonia has no upper valley at all to correspond with the earlier incision at Bungonia. Thus local factors may be operating which might account for the discrepancy between age of final uplift and surface landforms at Bungonia.

Although there can be substantial delays between uplift and rejuvenation, the new evidence for earlier uplift in the Shoalhaven region still implies that Bungonia Gorge was cut down to its present depth by the late Tertiary. The occurrence of lateritic weathering profiles in the Kangaroo Valley about 20 km upstream from its confluence with the Shoalhaven indicates that rejuvenation caused by the last uplift was well under way by the Oligocene. The limestone at Bungonia is resistant to slope processes but is much more vulnerable to stream incision because of its greater solubility. Under these circumstances the last phase of rejuvenation must have reached the Efflux before the end of the Tertiary.

Withal, there remain disturbing facts. Rapid headward recession from a lithological obstacle which acts as a local base level, when this obstacle is breached, can clearly produce a gorge of which the ultimate cause is a much older uplift. Nevertheless the halt at the next obstacle upstream should be followed by valley widening. Although the limestone stands up better in walls than the other rocks along Bungonia

Gorge, it is by no means immune to change. The huge rockfall which created the boulder choke at the foot of the other canyon wall farther upstream are eloquent testimony to present-day widening of the gorge by undercutting. If Bungonia Gorge dates from the late Tertiary then a much wider valley floor could be expected.

Nevertheless, at Burrinjuck Gorge the valley walls are as high and as steep as the non-limestone portions of Bungonia Gorge and the valley floor is equally narrow. Yet the presence of valley fill basalts which have been dated by Wellman and McDougall (1974) in smaller tributaries such as Wee Jasper Creek shows that Burrinjuck Gorge has existed since at least the early Miocene and has only been deepened by about 50 m since that time. Closer to Bungonia basalts of middle Eocene age flowed down the steep sided valley of the Endrick River, which still retains a "youthful" form today. In this particular case it might be argued that little valley widening has taken place because the river has been fully occupied in re-excavating the basalt fill. However, the plateau around Nerriga is dissected by other Shoalhaven tributaries such as Ettrema Creek and Nerrimunga Creek, which show no evidence of former basalt fills. These streams also occupy steep sided and narrow valleys similar to that of the Endrick. Thus evidence from the Southern Tablelands indicates that gorges can persist for tens of millions of years and that the geomorphic stage of "youthfulness" must not be confused with having a young absolute age (Young, 1974).

To determine the ages of the gorges around Bungonia dating of the superficial deposits within them is required. The most promising technique here is the dating of ferricretes and ferruginous cemented sediments by measurements of remanent magnetism. Because Australia has moved with respect to the South Magnetic Pole during the Cenozoic, the remanent magnetisations of Tertiary sediments differ from those of modern sediments. Moreover, numerous measurements of remanent magnetism have been performed on Tertiary basalts that were also dated by the potassium-argon method (McElhinny, Embleton and Wellman, 1974). By comparing the magnetisations in basalts of known age, the ages of the sediments can be estimated.

The evidence for earlier uplift and rejuvenation poses serious problems for an interpretation of cave development which seeks to explain the lack of caves in the lower parts of the limestone in terms of rejuvenation that was too recent and too rapid for cave formation to keep pace. If Bungonia Gorge was cut down to its present depth late in the Tertiary then there would have been ample time available for fresh cave development at lower levels in adjustment with the new gorge floor. This is the common course of landscape development at other karst areas in the Central and Southern Tablelands. For instance, at Tuglow, there is a gorge about 150 m deep and the nearby distribution of deep leads indicates that the gorge was cut after the last phase of volcanicity in early to middle Miocene times. Cave development has taken place in the limestone at a succession of levels right down to river level where caves are now actively forming. A similar situation exists in the Grand Arch System at Jenolan, further to the north. This implies that cave development can keep pace with recent and rapid river incision.

The geological discoveries which have been made at Bungonia since 1977 suggest an alternative explanation for cave development which avoids most of these difficulties. The limestones are now known to be much less extensive than was formerly believed. Furthermore they are divided into separate compartments both vertically and laterally by the infaulted argillites. Under these conditions there are geological obstacles of impervious rock which inhibit the development of caves and underground drainage. The belt of limestone which runs through Folly Point is cut off by faulting at the Efflux and does not extend down to the level of the gorge floor. In this case there is a geological barrier to the emergence of water at a lower level in the gorge.

The absence of significant caves from the Bungonia Canyon beneath Cooeeing Point can also be explained by the geological barriers between B4 and the Lookdown, which have diverted the underground drainage south towards Drum Cave. Although limestone is exposed continuously along the strike from Main Gully Springs to Bungonia Gorge, these springs lie in an area where several faults intersect. It is thus possible that underground drainage has been empeded by an infaulted wedge of Tallong Beds beneath the limestone. To resolve this question detailed geological studies of the springs and adjacent areas are required.

In discussing the proposal by Pratt (1964) that horizontal caves near the plateau surface had formed prior to the earliest phase of rejuvenation, Jennings (1965) argued that substantial cave development was unlikely to take place in a small impounded karst until rejuvenation had provided sufficient relief for outflows to develop at lower levels than the sinks. The recent advances in geological knowledge mean that this point applies even more strongly than before. Moreover, if cave development has been impeded by geological barriers rather than lack of time it is possible that cave formation may have lagged behind valley incision even during a slow rejuvenation.

Consequently, there need be no systematic relationship between the sub-horizontal levels of dynamic phreatic development that are found in the caves and former erosion levels in Bungonia Gorge. This implies that most of the caves could be considerably younger than the rejuvenation which formed the gorge. On an interpretation of this type it is no longer necessary to attribute the active levels of dynamic phreatic development in caves such as Odyssey to the early Tertiary. The different levels of phreatic development can be related to the successive positions of perched risings that existed because underground drainage was held up at particular levels by geological obstacles. It seems likely that the abandoned upper levels in B4 and B5 were part of the drainage system that formerly emerged at Cooeeing Point, whereas the B4-5 Extension and the

Railway Tunnel in Drum drained to the old spring site below B111 at the end of Folly Point. The lowest level of phreatic development includes passages such as Knockers Cavern, Odyssey Cave and formed in relation to the present Efflux.

Radiometric Dating

The need to bring to bear other approaches to the dating of the caves has already been stressed (Jennings and James, 1976). A beginning in one direction can now be reported preliminarily. A short stalagmite from the Fossil Cave-Hogans Hole Extension has been dated, by the uranium-thorium disequilibrium method of physical dating, at 22,000 ± 1,000 B.P. This result is important in showing that speleothems from Bungonia have sufficient uranium for this dating method to be used. A problem which arises with this approach, however, is that speleothems can only form in phreatic caves after groundwater levels have been lowered by further development of the underground drainage systems. This implies that speleothems found in passages of this type can all be very much younger than the passages themselves. Nevertheless more dating of speleothems in different geomorphic positions within the caves should help at least to constrain, if not resolve, the dilemma between the indications from the general denudation chronology of very great age for speleogenesis, and from the cave morphology of youthfulness.

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CAVES OF WOODLARK ISLAND, PAPUA NEW GUINEA

C.D. Ollier and C.F. Pain

Abstract

Woodlark Island consists of folded Tertiary rocks with a cover of Quaternary coral limestone that contains caves of two kinds :- river passage caves and shallow coastal caves mainly at old spring sites. Many caves contain remains of human burials and associated pottery.

LOCATION, GEOGRAPHY AND GEOLOGY

Woodlark Island is in the Solomon Sea, 270 km east of mainland Papua New Guinea, at latitude 9° S, longitude 153° E (Figure 1). The maximum length of the island is 60 km in a WNW direction, and the width at the Suloga Peninsula is 20 km. The highest point on the island is Suloga Peak, at more than 375 m above sea level. The climate is hot and wet, with annual rainfall at Kulumadau averaging 4069 mm (max. recording 6612, min. recording 1600 mm). Heavy rain falls throughout the year, with less rain in November than other months. Monthly falls range from 130 to 260 mm. Dry periods may last weeks, and storms with high intensity rains (up to 250 mm per day) are also recorded.

The wet climate supports a luxuriant tropical rainforest, which covers most of the island. The population is low (1000-1500) and the amount of land cleared for gardens is very small. Old gardens are completely overgrown; and there is now scarcely any trace of clearing associated with mining activities at the early part of this century, wartime road building, or even survey tracks put in by mining companies within the last few years. Travel on the island is therefore difficult; it is not possible to walk from one end of the island to the other, or even across the island except from Kulumadau to Decoyas and Kaurai. Native communication is mainly by coastal canoe trips, and all settlements are either on or close to the coast except Kulumadau, the old mining centre.

Geologically the island consists of a core of folded Tertiary rocks, mainly volcanics and limestone, intruded by dolerite sills and granites, and metamorphosed in places. Most of the island is covered by Quaternary coral limestone and subordinate clastic sediments. Quaternary uplift and faulting have raised the coral to its present levels (in places more than 100 m above sea level), and have produced primary structural landforms such as fault scarps. The geology of Woodlark has been described by Trail (1967) who concentrated on the older rocks in the centre of the island. The geomorphology and structure of the Quaternary coral has been described by Ollier and Pain (1978a). The main structural features are shown in Figure 1.

The coral is yellowish white in fresh exposures. If it is solid and not just a veneer the coral along the north coast is more than 100 m thick, but in the centre of the island it is only about 15 m thick. Many creeks have cut through the limestone into the underlying clay. At Kiliu the coral is about 30 m thick and appears to rest on weathered volcanogenic rocks.

Around Kulumadau Hill there is a terrace at 115 m, covered by coral limestone. This is higher than any other Quaternary limestone and possibly marks a fringing reef formed during the early stages of emergence of the hill. This may therefore be the oldest coral limestone on the island. This terrace is known to be Quaternary from examination of the foraminifera and other microfossils (kindly identified by Dr Belford of the Bureau of Mineral Resources, Canberra). No more detailed age limits can be established from the fossils.

We envisage the early island scene as one of high islands of Miocene bedrock with a fringing reef around Kulumadau Hill (and probably other islands), and a barrier reef growing to the north and east with a deep trench immediately behind it. Since then there has been continued coral growth and tectonic uplift, mainly to the north, which with complications of changing sea levels gives rise to terraces.

Faulting has produced fault scarps, tilt blocks, and fault-angle lakes, swamps and bays (Figure 1). The scarps are obvious in the field and on topographic maps and are even clearer on aerial photographs, where some faults can be traced below the sea. The fault scarps are simple slopes in the main with gradients of about 45°, dissected by only a few gullies.

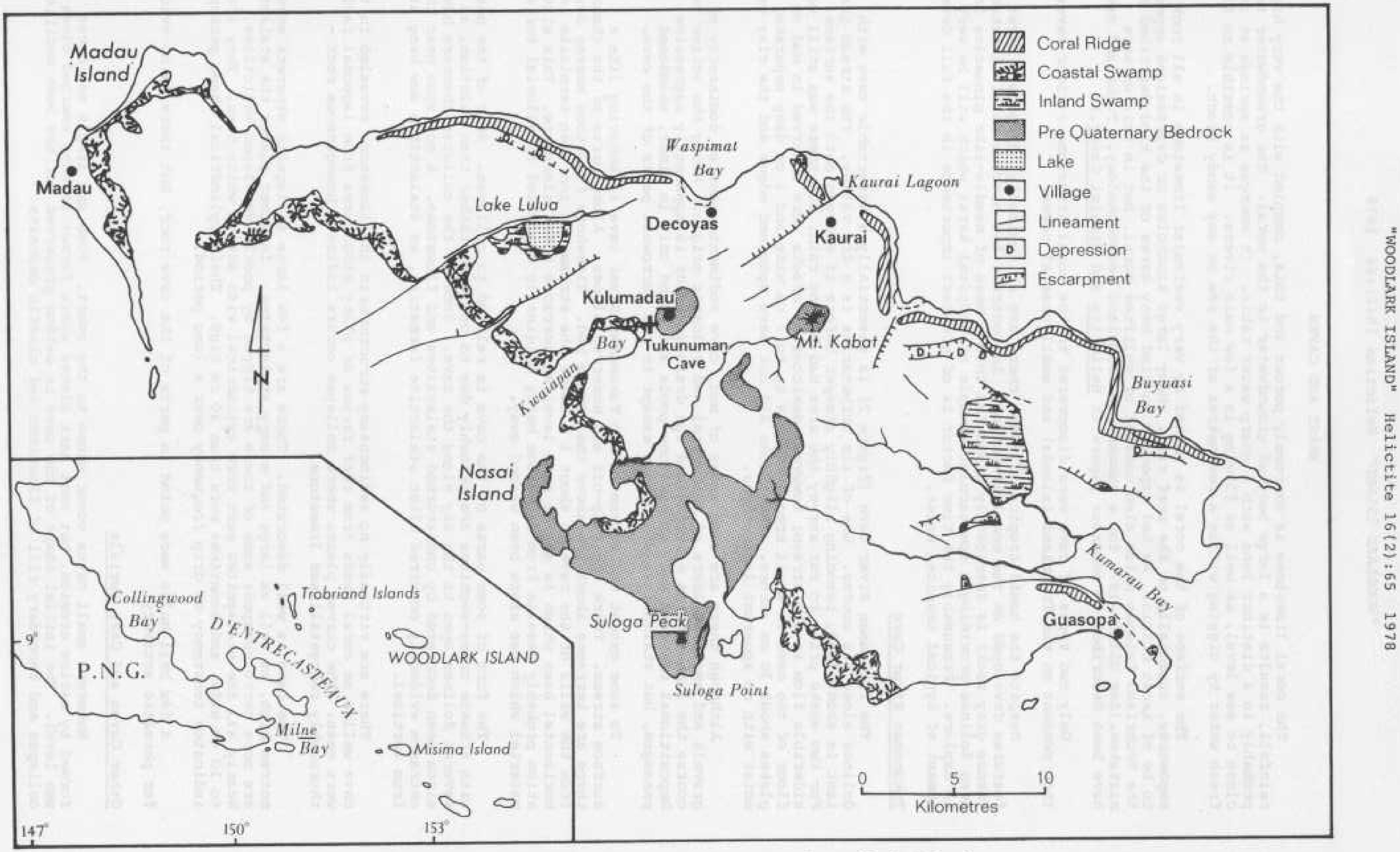

Figure 1. Location and salient features of Woodlark Island

KARST AND CAVES

The coral limestone is extremely porous and this, coupled with the very high rainfall, results in a large body of groundwater in the coral. The groundwater is probably in a distinct lens with a sharp water table. It emerges as springs at and close to sea level, as well as flowing in a few main rivers. It is possible to find fresh water by digging within a few metres of the sea on any sandy beach.

The surface of the coral is marked by very vesicular limestone in all rock exposures, especially on the reef rims. Many large sinkholes or depressions appear to be of karst origin. We had expected to find many caves of the kind described from the Trobriand Islands which also consist of uplifted coral, but in this we were mistaken.(See Ollier,1975 for a summary of Trobriand geomorphology. Trobriand caves have been described in numerous papers in Helictite and Niugini Caver.)

Only two types of cave were discovered in the coral limestone : river caves (not present on the Trobriand Islands) and small coastal caves.

Despite the humid tropical climate there are no typically 'tropical' karst features developed on the coral limestone. In contrast the Miocene Nasai Limestone (dense grey rock) is intricately dissected into a mass of needle-like pinnacles and deep dolines providing a spectacular example of tropical karst which will be very hard to explore. Presumably the time factor is of greatest importance in the full development of typical tropical karst.

Tukunuman River Cave

The Tukunuman River cave (Figure 2) is essentially a watertable cave with dolines along its course. One of its tributaries is a dry valley. The stream gradient is about 1:50, becoming slightly steeper before it emerges onto the surface. For two weeks prior to our survey the area had had no rain, but there was still considerable flow in the stream; however, desiccation cracks were observed in mud on the floor of the cave in small areas. Cracks up to 3 cm wide and 4 cm deep separated plates about 30 cm across. The plates did not have upturned edges and the clay was moist with no apparent laminations.

Although there are some areas of mud, cave sediments consist dominantly of gravels and small boulders of both coral and volcanic origin. Along the active water course the limestone is corroded and the drainage water is apparently aggressive. Depositional features such as rimstone pools are found only in minor, abandoned passages, but stalactites are common except in the narrowest parts of the cave.

To some extent the stream in the Tukunuman River cave is behaving like a surface stream. There are slip-off and undercut slopes. Along parts of the channel there are terraces about 1 m above the stream bed. Elsewhere flowstone masses descend from the walls of the cave to about 1 m above the stream bed and then terminate in a horizontal base which is at the same level as terraces noted elsewhere. This situation probably results from flowstone being originally deposited on alluvial terrace material which has since been washed away.

The form of some parts of the cave is related to collapse. Some of the passages with arcuate cross-sections are probably due to collapse rather than solution, as are several dolines open to the sky along the cave. Some of the collapse chambers have since been decorated by undisturbed stalactites and flowstone. A collapse near the entrance evidently occurred after stalactite formation, as stalactites now hang at 10° from vertical.

There are virtually no sedimentary structures in the limestone revealed in the cave walls; no coral heads from reef facies or platy structures from lagoonal facies were seen. The curved planes where collapse occurs indicate homogeneous rock - thoroughly recrystallised limestone.

The cave is well decorated. There are a few large stalagmite minarets several metres high, as well as large and stumpy stalactites. In other places the stalactites are more carrot-shaped; some of these are tipped by poorly developed helictites. Nearly all the stalagmites seen were cylindrical with active white tops. They are up to 10 cm wide, and sometimes more than 40 cm high. Their cylindrical shape perhaps indicates constancy of drip frequency over a long period.

A few bell holes were noted in parts of the cave roof, but there is no evidence for phreatic activity.

Other Caves and Cave Burials

Numerous small caves occur close to the coast. Some are simple sea caves formed by marine erosion, but most mark places where former streams emerged close to sea level. The initial shape of the cave is seldom preserved but has been modified by collapse and secondary fill of flowstone and clastic deposits.

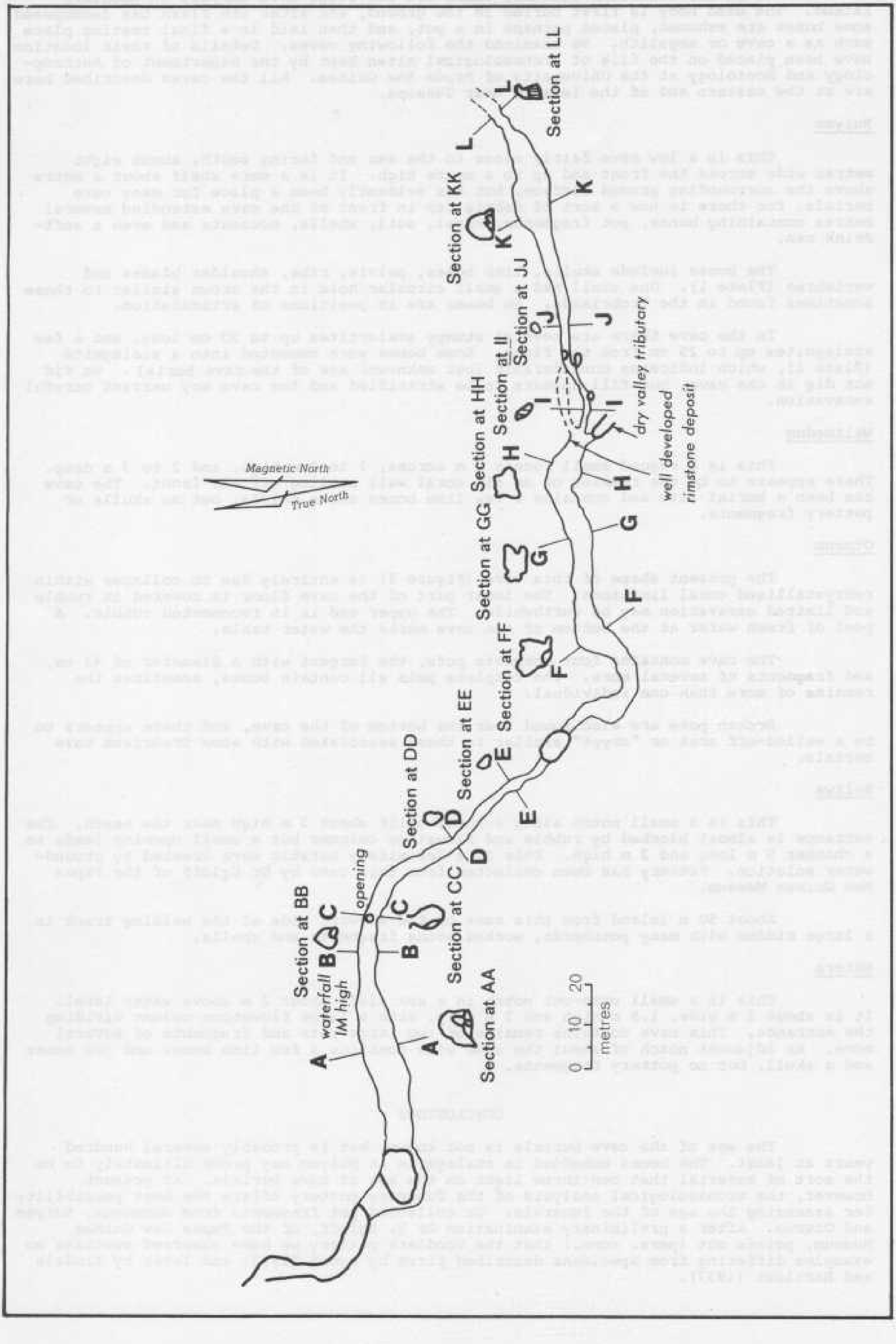

Figure 2. Tunkunuman River Cave

As in the Trobriand Islands, there are two-stage cave burials on Woodlark Island. The dead body is first buried in the ground, and after the flesh has decomposed some bones are exhumed, placed perhaps in a pot, and then laid in a final resting place such as a cave or megalith. We examined the following caves. Details of their location have been placed on the file of archaeological sites kept by the Department of Anthropology and Sociology at the University of Papua New Guinea. All the caves described here are at the eastern end of the island, near Guasopa.

Nuiyam

This is a low cave fairly close to the sea and facing south, about eight metres wide across the front and up to a metre high. It is a mere shelf about a metre above the surrounding ground surface, but has evidently been a place for many cave burials, for there is now a sort of debris fan in front of the cave extending several metres containing bones, pot fragments, coral, soil, shells, coconuts and even a soft-drink can.

The bones include skulls, limb bones, pelvis, ribs, shoulder blades and vertebrae (Plate 1). One skull had a small circular hole in the crown similar to those sometimes found in the Trobriands. No bones are in positions of articulation.

In the cave there are several stumpy stalactites up to 20 cm long, and a few stalagmites up to 25 cm from the floor. Some bones were cemented into a stalagmite (Plate 1), which indicates considerable (but unknown) age of the cave burial. We did not dig in the cave, but fill appears to be stratified and the cave may warrant careful excavation.

Walimedum

This is a rugged small recess 8 m across, 1 to 2 m high, and 2 to 3 m deep. There appears to be the remains of an old coral wall sealing off the front. The cave has been a burial site and contains a few limb bones and a pelvis, but no skulls or pottery fragments.

Oturum

The present shape of this cave (Figure 3) is entirely due to collapse within recrystallised coral limestone. The lower part of the cave floor is covered in rubble and limited excavation may be worthwhile. The upper end is in recemented rubble. A pool of fresh water at the bottom of the cave marks the water table.

The cave contains four complete pots, the largest with a diameter of 43 cm, and fragments of several more. The complete pots all contain bones, sometimes the remains of more than one individual.

Broken pots are also found near the bottom of the cave, and there appears to be a walled-off area or "crypt" similar to those associated with some Trobriand cave burials.

Neliwa

This is a small notch along a coral cliff about 3 m high near the beach. The entrance is almost blocked by rubble and flowstone columns but a small opening leads to a chamber 5 m long and 2 m high. This is a definitely karstic cave created by groundwater solution. Pottery has been collected from this cave by Dr Egloff of the Papua New Guinea Museum.

About 50 m inland from this cave on the seaward side of the walking track is a large midden with many potsherds, worked stone fragments and shells.

Nakera

This is a small wave-cut notch in a sea cliff about 2 m above water level. It is about 1 m wide, 1.5 m high and 2 m deep, with a large flowstone column dividing the entrance. This cave contains remains of two large pots and fragments of several more. An adjacent notch of about the same size contains a few limb bones and jaw bones and a skull, but no pottery fragments.

CONCLUSIONS

The age of the cave burials is not known, but is probably several hundred years at least. The bones embedded in stalagmite at Nuiyam may prove ultimately to be the sort of material that can throw light on the age of cave burials. At present however, the archaeological analysis of the funerary pottery offers the best possibility for assessing the age of the funerals. We collected pot fragments from Bunmeyuw, Nuiyam and Oturum. After a preliminary examination Dr B. Egloff, of the Papua New Guinea Museum, points out (pers. comm.) that the Woodlark pottery we have observed contains no examples differing from specimens described first by Lyons (1922) and later by Tindale and Bartlett (1937).

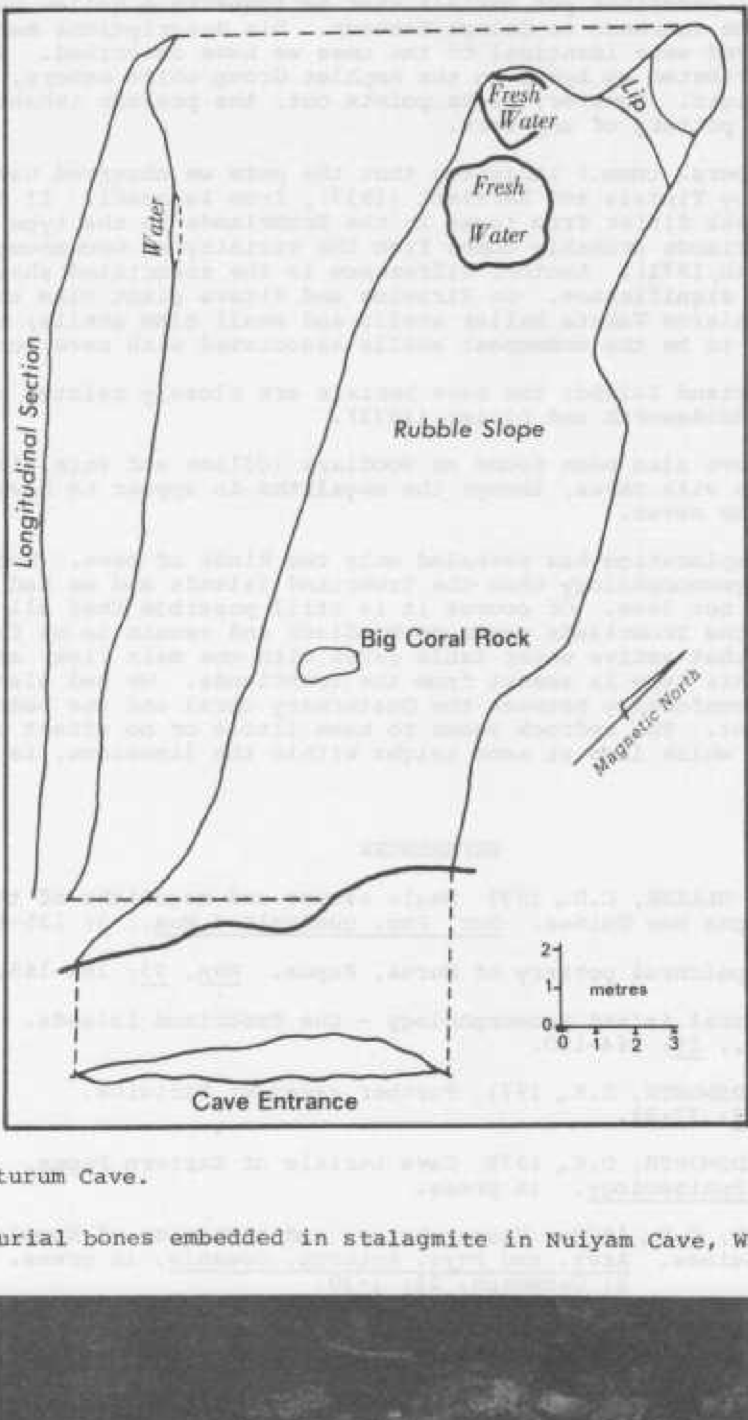

Figure 3. Oturum Cave.

Plate 1. Burial bones embedded in stalagmite in Nuiyam Cave, Woodlark Island

Lyons (1922) describes pot burials that he found in a hollow below two large basalt boulders at the entrance to Suloga Harbour. His descriptions make it clear that the burials he observed were identical to the ones we have described. Some of the pots he observed were attributed by Lyons to the Amphlet Group while others, he felt, were probably of local origin. However, as he points out, the present inhabitants of Woodlark do not make pottery of any sort.

Dr Egloff (pers. comm.) indicates that the pots we observed have similarities with pots described by Tindale and Bartlett (1937), from Panaeati. If this is the case, the Woodlark interments differ from those in the Trobriands in the type of pottery used, for that of the Trobriands probably comes from the vicinity of Goodenough and Wanigela (Ollier and Holdsworth, 1971). Another difference is the associated shell material, which may be of some significance. On Kiriwina and Kitava giant clam shells are associated with cave burials; on Vakuta bailer shells and small clam shells; on Woodlark spider shells appear to be the commonest shells associated with cave burials.

On the Trobriand Islands the cave burials are closely related to megalith sites, described by Holdsworth and Ollier (1973).

Megaliths have also been found on Woodlark (Ollier and Pain, 1978b) but have no direct association with caves, though the megaliths do appear to have been used as funeral sites like the caves.

Our brief exploration has revealed only two kinds of cave. Woodlark has more complex geology and geomorphology than the Trobriand Islands and we had hoped to find more types of caves, not less. Of course it is still possible that all the types of karst cave found in the Trobriands occur on Woodlark and remain to be found. But the high rainfall means that active water table caves with one main river are likely to be the commonest, and this type is absent from the Trobriands. We had also expected to find caves at the unconformity between the Quaternary coral and the bedrock, but no such caves are present. The bedrock seems to have little or no effect on cave formation, and the water table, which lies at some height within the limestone, is a more important factor.

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DEVELOPMENT OF A SUBTERRANEAN MEANDER CUTOFF:

THE ABERCROMBIE CAVES, NEW SOUTH WALES

R. Frank and J.N. Jennings

Abstract

The Abercrombie Caves are exemplary of a subterranean meander cutoff. The bedrock morphology, especially flat solution ceilings, permits reconstruction of an evolution from slow phreatic initiation to epiphreatic establishment of a substantial throughway, followed by progressive succession to vadose flow and phased channel incision. At two separate stages, there was twofold streamsink entry and underground junction of flow. Five ^{14}C dates from alluvial sediments show that capture of the surface stream was certainly complete before c.15,000 BP and that by c.5,000 BP the stream had almost cut down to its present level.

INTRODUCTION

The Abercrombie Caves are about 50 km south of the town of Bathurst. A brief history of the discovery and early exploration is given by Morris (1968). They were used by bushrangers as early as 1830 and, in subsequent less infamous days, visited by various government officials before commercialisation. The area was made a state reserve around 1877 and the first resident caretaker was appointed to the caves in 1889 (Leigh, 1890).

The Limestone

The limestone in which the caves occur is part of the Grove Formation of Silurian age, a series of slates, chert, sandstones, greywackes, basic volcanics and metamorphosed limestone with a maximum thickness of at least 550 m. The formation is thrust-faulted against similar rocks without limestones to the west and is in normal contact with younger volcanics to the east. The strike is north-south with a westerly dip of about 60° to 70° in the vicinity of the caves. The limestone has been named the Abercrombie Caves Marble (Hobbs, 1962) and it is probably equivalent to the limestone of the Kildrummie Group of Late Silurian age (Scheibner, 1970). It forms a lens within the formation and is thickest at the caves (about 365 m). It thins both north and south with a total outcrop length of a little over 3.5 km. Most of it has been recrystallised during metamorphism and accompanying folding and faulting have produced many small scale crenulations and shear planes which are generally concordant with the strike.

The percentage of insoluble residue of the limestone varies considerably (Table 1). The residues are almost entirely single-crystal, angular to subround quartz with straight extinction and occur in thin veins along microfractures. Their quantity and mode of occurrence are significant for the development of the cave system as will be shown later.

Physiography

The caves are at an altitude of 580 to 620 m A.S.L. (Figure 1). Local relief is high with predominantly straight or convex hill slopes up to 50°. The V-shaped valleys contain streams flowing on bedrock but in places, as immediately downstream of the caves, small floodplains and terraces are developed. Burrangylong Creek rises about 25 km north of the caves, flows through the caves as a free-surface stream, and continues another 5 km where it joins the Abercrombie River, a major tributary of the Lachlan River. The creek flows most of the time and only dries up during the worst droughts. On one occasion it was observed to be sinking at the north end of the caves and rising again near the south end.

The caves are developed beneath three hills of limestone which rise 50 to 70 m above the present stream bed and are separated from each other by saddles (Figure 2).

In the West Saddle there is a doline with two entries into a small but tall cave, which is only separated by a little breakdown from Cathedral Cave below (Figures 3, 5). Nevertheless, although the topography permits the conception that the saddle was formed by Burrangylong Creek, there is no positive evidence in support.

The East Saddle has such evidence in river gravels which are too large and too rounded to be attributed to sidestreams. One occurrence at 008004 (Figure 8) could be related to a course through either saddle but two others lie entirely within the East Saddle. One of these at 012024 is about 5 m lower than the last and associated with two small holes near the base of the cliff. They are blocked by alluvium and talus at about 2 m and are probably due to collapse into the largest room of Bushrangers Cave, which they overlie. Southwest of these holes is a large doline, 12 m deep and 40-80 m across. The central portion is shown as 9A at 017015 of Figure 8. Bedrock crops out down its northern side but elsewhere there are thick covers of superficial deposits chiefly as part of a fan built by a small stream from the volcanics to the east.

There are two sets of terrace remnants in the doline due to two cycles of fan building and dissection. A great deal of material has been fed into the caves below. The doline overlies a large mass of breakdown between the Eastern Gallery and Kohinoor Cave so that it is likely that collapse has contributed to the formation of this doline. From time to time pools as much as 2 m deep form in the bottom of the doline but at other times water drains into Kohinoor Cave below, as, for example, observed in 1975 by K. Keck (pers. comm.).

The East Saddle south of this doline is about 8 m lower than it is to the north and furthermore is covered by fan material. This lower level may in part be due to erosional work of the main sidestream here which has deepened the valley between the limestone hills above the Arch Cave and Grove Cave (Figure 8). Although this stream is ephemeral, it has a much larger catchment than the stream which has built the fan. On the side of this valley at 034027 (Figure 8) is the third deposit of river gravel, of cobble and boulder size, which is about 10 m lower than those at 014024. Though these gravels must have come from Burrangylong Creek, they have probably been lowered to their present level by erosional work of the tributary.

In the north-facing cliff of the hill above Grove Cave, there is a stream-cut notch at a level below that of the saddle south of doline 9A. If formed by Burrangylong Creek, the creek must then have had a much steeper gradient from the northern end of the East Saddle than it possesses today through the Arch Cave. It may, however, have been formed by the tributary.

Thus, although the East Saddle is the work of Burrangylong Creek when it flowed over the surface of the limestone, the topography has been modified since.

THE CAVES

The Arch Cave, with its extensions, Cathedral Cave, Bushrangers Cave and the Long Tunnel, is the largest underground system in the area. The Grove Cave and the Bushrangers Stable Cave make up most of the remaining underground passageway.

The Arch Cave

The Arch Cave (Figures 3,4,5) is a large through-cave, 200 m long, averaging about 40 m wide, and with a maximum height of about 32 m. Burrangylong Creek flows through it on an alluvial bed within an incised channel about 6 m deep. That the alluvium may not be thick is suggested by gently sloping bedrock extending a few metres from the walls into the incised channel and by flat outcrops at the same level in the middle. The walls of the incised channel show signs of solution (scalloping) in most places, but there is also evidence that lateral enlargement has taken place by the breaking off of slabs of bedrock along the bedding planes or shear planes, especially along the right bank and the downstream end of the left bank. There are additional indications of this bedding-plane control on the walls at higher levels (shown on most cross-sections, Figure 4).

Flat solutional ceilings at various levels occur throughout the cave (Figure 6). Minor relief is minimal on these ceilings and is invariably in the form of scallops whose depth does not exceed 5 cm and is usually less. Circular spider webs obscure the scallops over large areas. Where there is a change from one level of flat ceiling to another the transition zone is a smooth double curve as in profile A-P1 near the south end at cross-section A-8. Where the flat ceilings make the transition into walls and meet a floor as in cross-section A-1 (east-side, half way up) the cross-section is a flat half ellipse; if the floor is alluviated the resultant bedrock part of the cross-section is similar to a quarter-ellipse cavetto moulding ('quad' in the Australian vernacular). The ceiling areas which are not flat show a hackly surface and are due to bedrock removal by breakdown. Small holes lead up into the ceiling especially in the southern half of the Arch but their nature and extent remain speculative because of their inaccessibility.

A description of the significant features in the Arch Cave will begin at the north (upstream) end near the east wall and continue south to the downstream exit. The features along the west side will then be described also from north to south.

The lower entrance to Bushrangers Cave opens above the stream bed at the north east end of the Arch. Immediately south, within the Arch (020031, Figure 3), there is an undercut, 20 m long and 3 m deep, with scallops developed on its wall and ceiling. Short solution tubes extend from the back wall of this undercut for a few metres. Directly above the undercut is another, whose bedrock floor is about 10 m above the stream bed; it carries flutes (in the sense of Curl (1966)), as well as scallops on its wall and ceiling. From its speleothem choked north end it extends about 30 m south to open out into a large, partly breakdown-floored recess known as the Kohinoor Cave. A small hole in the ceiling leads to the surface and near the south wall a tiny inter-

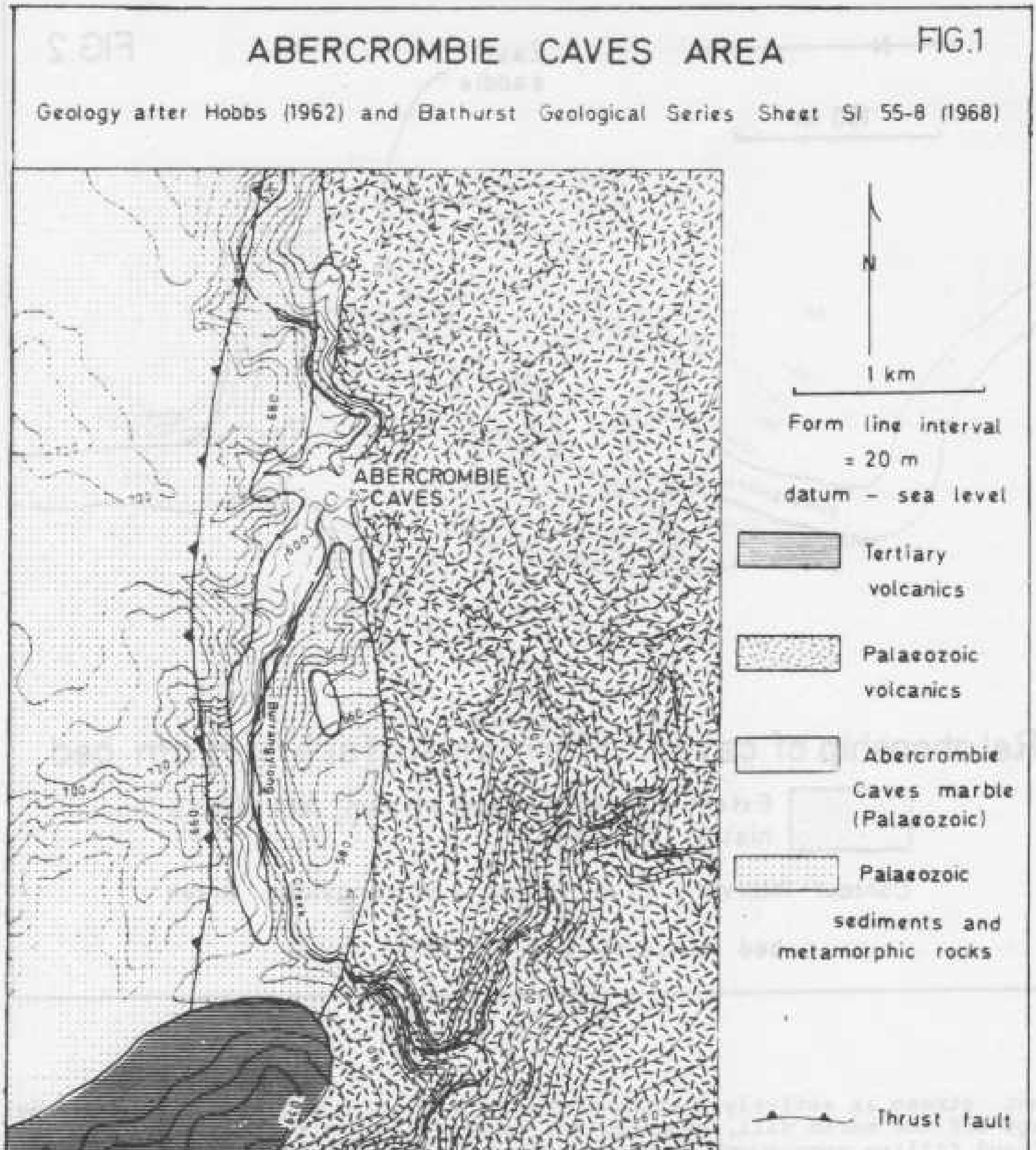
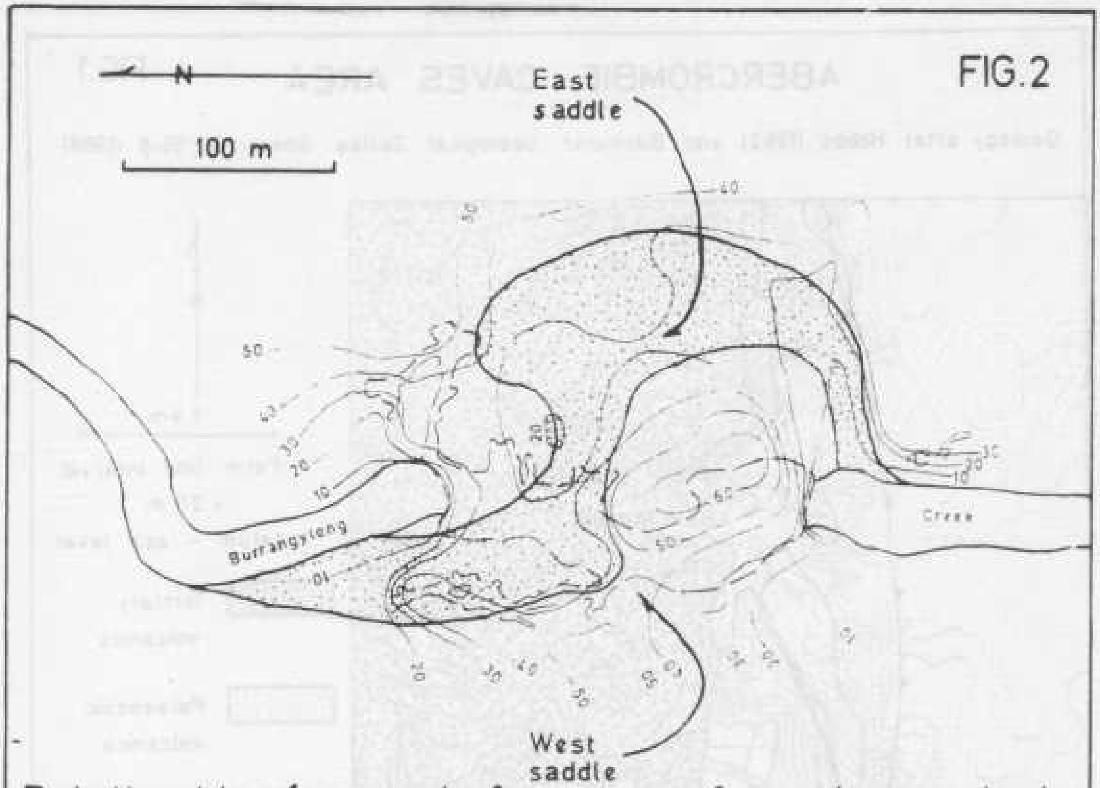


TABLE 1 WEIGHT PERCENTAGES OF INSOLUBLE QUARTZ RESIDUES FROM ABERCROMBIE CAVES LIMESTONE

Samples collected across the strike from east to west.

Sample	% wt of ins. res.
1	0.70
2	0.64
3	4.44
4	5.99
5	0.35
6	10.45

FIG.2



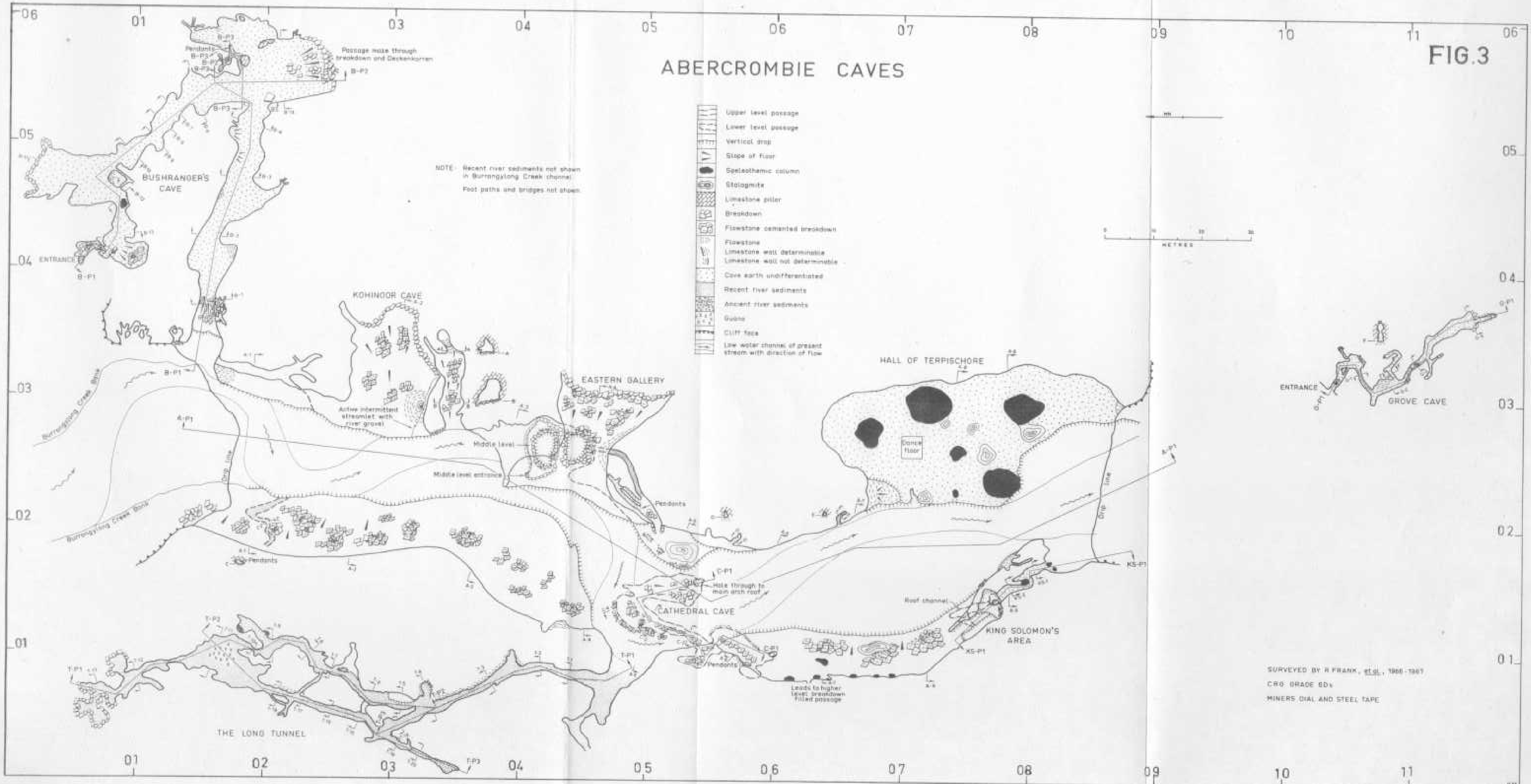
Relationship of caves to former surface stream bed

Extent of old surface stream bed during history of caves

Contour interval = 10 m Datum – Burrangylong Creek bed at south end of Arch Cave

mittent stream is actively cutting down into flowstone and bedrock. In a small passage off the north wall, cemented and rounded allogenic gravels, of cobble size, are found filling spongework. Just south of the Kohinoor Cave an elongate passage with walls and ceiling of bedrock and floor of breakdown and flowstone opens out onto the Arch at the level of the stream bed. It is choked with speleothems at its far end. Just south of this passage Burrangylong Creek flows beneath a deep undercut for about 30 m. The walls and ceiling of this undercut are scalloped. Near the back part of the undercut a small solution tube leads off at the level of the stream bed and makes a loop back into the Arch at a higher level close to where the stream leaves the undercut. Two large holes in the ceiling of the undercut lead to two higher level rooms. The smaller of the two (the middle level) has walls and ceiling of flowstone-cemented breakdown. The larger, upper-level room, known as the Eastern Gallery, has a floor of breakdown and flowstone. Its ceiling and walls are of bedrock with scallops. Stream undercuts with scalloped bedrock walls and ceilings extend south from the Eastern Gallery at the level of its ceiling for about 30 m. At a lower level, about 3 m above the stream bed, is a small undercut with cemented stream gravel in cavities and solution tubes of its back wall and ceiling. A large eroded stalagmite rests on a higher ledge above this undercut. Small solution tubes plugged with alluvium extend back into the wall near the rear of this ledge. The wall of the Arch is nearly vertical from stream bed to ceiling (15 m) for the next 25 m. Speleothems cover most of it here but bedrock is exposed in a few places.

The last upper-level balcony room at the southeast end of the Arch is called the Hall of Terpsichore. It is the largest and most impressive of the balcony rooms in the Arch and contains numerous large stalagmites and speleothemic columns. The floor consists of sand, partly deposited by a high flood in 1950 (Morris, 1968), with small patches of flowstone and a single small exposure of scalloped bedrock. The walls are almost all bedrock and are scalloped. Flutes (Curl, 1966) occur on the northeast wall. The various levels of flat ceiling are scalloped over much of their surface.



ABERCROMBIE CAVES
FIG.3
BUSHRANGER'S CAVE
ENTRANCE
Pendants
Passage made through breakdown and Deckenkarren
KOHINOOR CAVE
EASTERN GALLERY
HALL OF TERPISCHORE
Dance floor
Active intermittent streamlet with river gravel
Middle level
Middle level entrance
Pendants
Hole through to main arch roof
CATHEDRAL CAVE
Roof channel
KING SOLOMON'S AREA
Leads to higher level breakdown filled passage
THE LONG TUNNEL
GROVE CAVE
Burrangylong Creek Bank
Drip line
NOTE: Recent river sediments not shown in Burrangylong Creek channel
Foot paths and bridges not shown
Upper level passage
Lower level passage
Vertical drop
Slope of floor
Speleothemic column
Stalagmite
Limestone pillar
Breakdown
Flowstone cemented breakdown
Flowstone
Limestone wall determinable
Limestone wall not determinable
Cave earth undifferentiated
Recent river sediments
Ancient river sediments
Guano
Cliff face
Low water channel of present stream with direction of flow
METRES
SURVEYED BY R FRANK, et al., 1966-1967
CRG GRADE 6Ds
MINERS DIAL AND STEEL TAPE

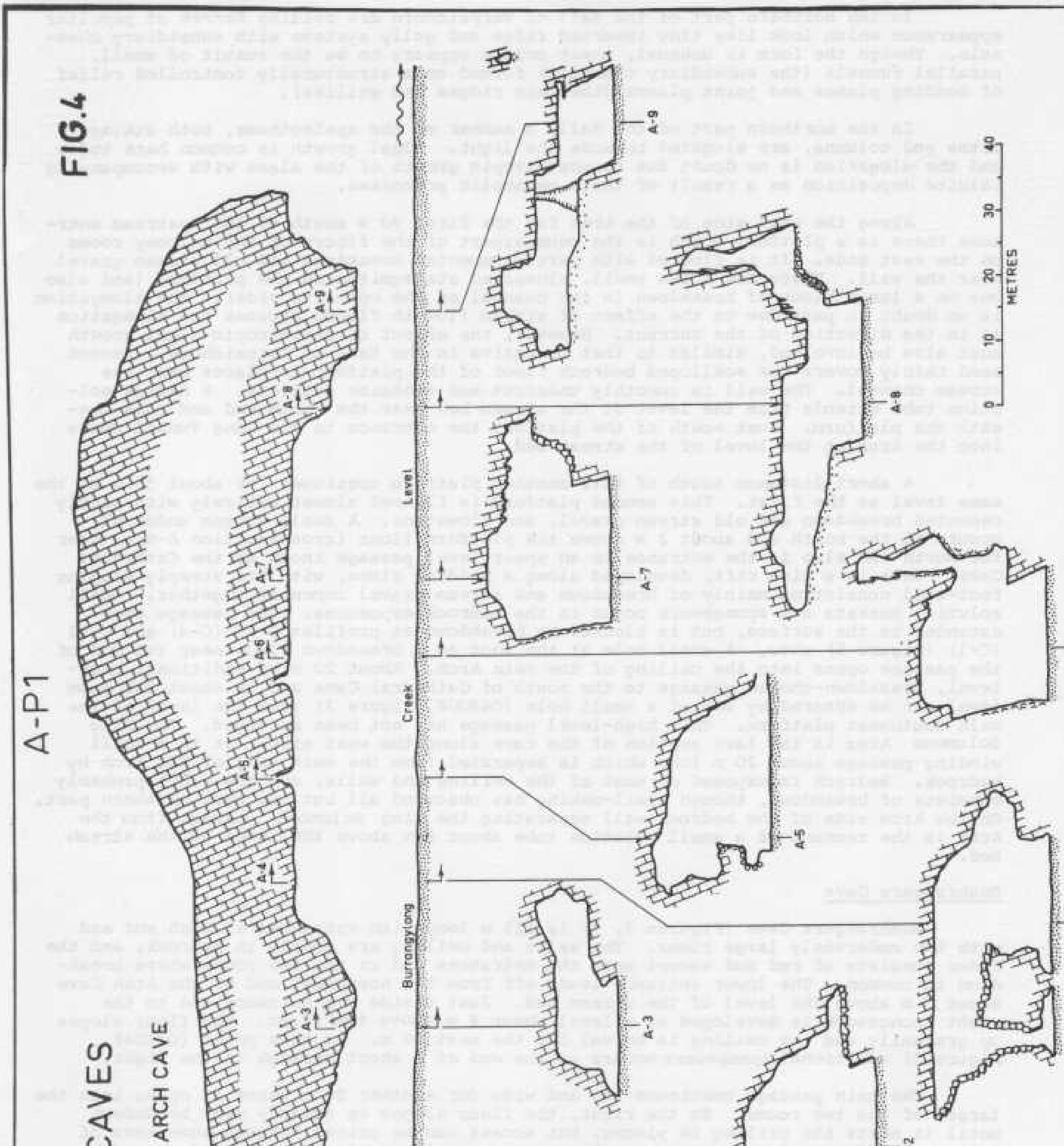


FIG.4
A-P1
ABERCROMBIE CAVES
PROFILE AND SECTIONS ARCH CAVE
Burrangylong Creek Level
Hole to surface
A-1
A-2
A-3
A-4
A-5
A-6
A-7
A-8
A-9
0 10 20 30 40
METRES
KM

In the northern part of the Hall of Terpsichore are ceiling *Karren* of peculiar appearance which look like tiny inverted ridge and gully systems with subsidiary channels. Though the form is unusual, their origin appears to be the result of small, parallel runnels (the subsidiary channels) formed on a structurally controlled relief of bedding planes and joint planes (the main ridges and gullies).

In the northern part of the Hall, a number of the speleothems, both stalagmites and columns, are elogated towards the light. Algal growth is common here today and the elogation is no doubt due to phototropic growth of the algae with accompanying calcite deposition as a result of their metabolic processes.

Along the west side of the Arch for the first 90 m south of the upstream entrance there is a platform which is the counterpart of the floors of the balcony rooms on the east side. It is floored with partly cemented breakdown and old stream gravel near the wall. There are a few small, elongated stalagmites on the platform (and also one on a large block of breakdown in the channel on the opposite side). The elongation is no doubt in part due to the effect of stream flow in floods because the elongation is in the direction of the current. However, the effect of phototropic algal growth must also be involved, similar to that operative in the Hall of Terpsichore. Recent sand thinly covers the scalloped bedrock floor of the platform in places near the stream channel. The wall is smoothly undercut and contains scallops. A narrow solution tube extends from the level of the stream bed near the north end and runs beneath the platform. Just south of the platform the entrance to the Long Tunnel opens into the Arch at the level of the stream bed.

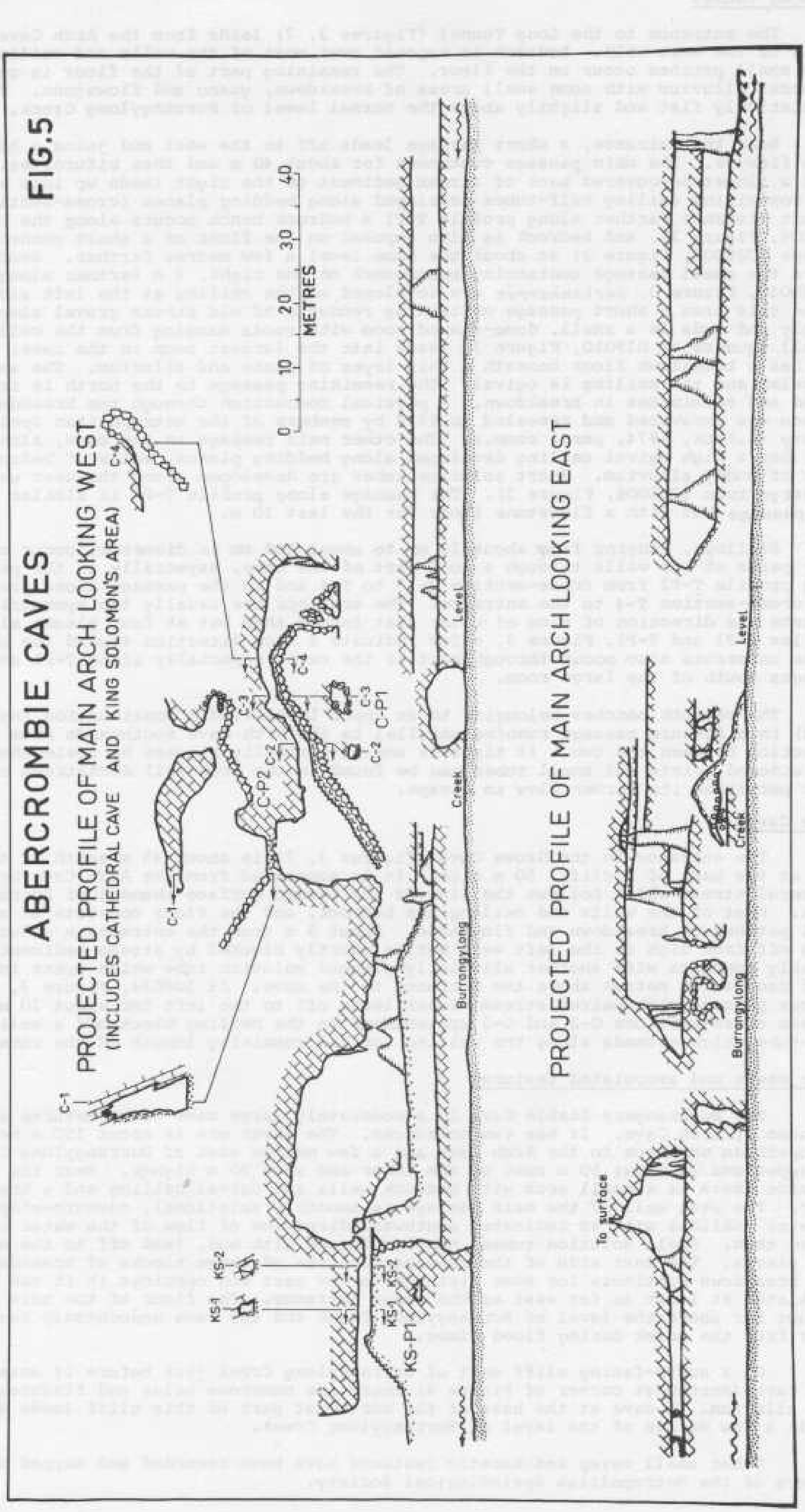
A short distance south of this another platform continues for about 55 m at the same level as the first. This second platform is floored almost entirely with partly cemented breakdown and old stream gravel, and flowstone. A small stream undercut occurs at the north end about 2 m above the platform floor (cross-section A-6). Near the north end also is the entrance to an upper-level passage known as the Cathedral Cave. This is a high rift, developed along a bedding plane, with its steeply sloping foot-wall consisting mainly of breakdown and stream gravel cemented together. Small solution pockets and spongework occur in the bedrock exposures. The passage once extended to the surface, but is blocked by breakdown as profiles C-P1 (C-4) and C-P2 (C-1) (Figure 5) show. A small hole at the foot of a breakdown slope near the end of the passage opens into the ceiling of the main Arch. About 20 m of additional high-level, breakdown-choked passage to the south of Cathedral Cave and at about the same level can be entered by way of a small hole (062008, Figure 3) from the level of the main southwest platform. This high-level passage has not been surveyed. The King Solomons Area is the last section of the cave along the west side. It is a small winding passage about 20 m long which is separated from the main body of the Arch by bedrock. Bedrock is exposed on most of the ceiling and walls, and the floor probably consists of breakdown, though trail-making has obscured all but the most northern part. On the Arch side of the bedrock wall separating the King Solomons passage from the Arch is the remnant of a small solution tube about 8 m above the level of the stream bed.

Bushrangers Cave

Bushrangers Cave (Figures 3, 7) is 125 m long with entrances at each end and with two moderately large rooms. The walls and ceiling are mostly in bedrock, and the floor consists of red mud except near the entrances and in the two rooms where breakdown is common. The lower entrance leads off from the northeast end of the Arch Cave about 3 m above the level of the stream bed. Just inside the entrance and to the right spongework is developed at a level about 4 m above the floor. The floor slopes up gradually and the ceiling is ogival for the next 30 m. At this point (021048, Figure 3) additional spongework occurs at the end of a short passage to the right.

The main passage continues low and wide for another 20 m where it opens into the larger of the two rooms. To the right, the floor slopes up steeply over breakdown until it meets the ceiling in places, but access can be gained through some tens of metres of additional passage by crawling among the large blocks of breakdown and by negotiating the spaces among the large *Deckenkarren* on the ceiling. On the east side of the room, solution tubes and spongework occur, and a high, steep passage containing pendants and stream gravel (profile B-P3) extends upward for about 20 m where it ends in a solution dome decorated with speleothems. The ceiling of the large room shows signs of bedding-plane control especially along profile B-P2. Near the exit of the room (at 014060, Figure 3) a long solution tube leads off to the east.

The irregularly shaped passage leading from the large room to the smaller room is nearly filled with mud and the commercial trail has been cut deeply into it. Spongework is present near the entrance to the smaller room on both sides of the passage. The smaller room has a flat mud floor and bedrock walls on three sides. It is abruptly terminated at the north end by large blocks of breakdown. The short passage leading from the smaller room is almost filled with mud. It opens into an irregularly shaped, low, wide passage with abundant breakdown. Formerly a steep laddered route led up through cemented breakdown and alluvial material to a high entrance here. After heavy rains in 1974 part of this fill fell down so this entrance was closed and a new, horizontal cut made through the mixed materials. Here the bedrock has a solution ceiling (Figure 7).


ABERCROMBIE CAVES
FIG.5
PROJECTED PROFILE OF MAIN ARCH LOOKING WEST
(INCLUDES CATHEDRAL CAVE AND KING SOLOMON'S AREA)
0 10 20 30 40
METRES
C-1
C-P2
C-2
C-3
C-P1
C-4
KS-1
KS-2
KS-P1
Burrangylong
Creek
Level
PROJECTED PROFILE OF MAIN ARCH LOOKING EAST
To surface
Burrangylong
Creek
Level

The Long Tunnel

The entrance to the Long Tunnel (Figures 3, 7) leads from the Arch Cave near the middle of the west wall. Bedrock is exposed over most of the walls and ceiling and three small patches occur on the floor. The remaining part of the floor is composed of recent alluvium with some small areas of breakdown, guano and flowstone. The floor is relatively flat and slightly above the normal level of Burrangylong Creek.

Near the entrance, a short passage leads off to the west and joins a high bedding-plane fissure. The main passage continues for about 40 m and then bifurcates. At this point a flowstone-covered bank of stream sediment on the right leads up into a small dome containing ceiling half-tubes developed along bedding planes (cross-section T-4). A short distance farther along profile T-P1 a bedrock bench occurs along the right wall (030006, Figure 3), and bedrock is also exposed on the floor of a short connecting passage (028006, Figure 3) at about the same level a few metres farther. Bedrock also floors the small passage containing spongework on the right, 7 m farther along T-P1. At 020010, Figure 3, *Deckenkarren* are developed on the ceiling at the left side. Just beyond this area a short passage containing remnants of old stream gravel slopes up steeply and ends in a small, dome-shaped room with roots hanging from the ceiling. A small squeeze at 019010, Figure 3, leads into the largest room in the cave. This room has a breakdown floor beneath a thin layer of guano and alluvium. The walls are irregular and the ceiling is ogival. The remaining passage to the north is irregularly shaped and terminates in breakdown. A physical connection through the breakdown to the surface was excavated and resealed in 1974 by members of the Metropolitan Speleological Society (K.Keck, 1974, pers. comm.). The other main passage in the cave, along profile T-P2, has a high ogival ceiling developed along bedding planes, walls of bedrock, and a floor of muddy alluvium. Short solution tubes are developed along the west wall near the large room (021006, Figure 3). The passage along profile T-P3 is similar to the T-P2 passage but with a flowstone floor for the last 10 m.

Scallops, ranging from about 10 mm to about 200 mm in diameter, occur on the lower parts of the walls through a good part of the cave, especially in the passage along profile T-P2 from cross-section T-17 to T-4 and in the passage along profile T-P1 from cross-section T-4 to the entrance. The scallops are usually too symmetrical to indicate the direction of flow of water that formed them but at four places along profiles T-P1 and T-P2, Figure 3, a few indicate a flow direction toward the entrance. Stream undercuts also occur through most of the cave, especially along T-P1 and T-P2 passages south of the large room.

The bedrock benches belonging to an upper level find a continuation (not surveyed) in a fissure passage running parallel to the Arch Cave southwards from the connection between the two. It tightens and is partially blocked by speleothems. Only widened joints and small tubes can be found in the Arch wall downstream of this which permitted its former flow to escape.

Grove Cave

The entrance to the Grove Cave (Figures 3, 7) is about 45 m south of the Arch Cave at the base of a cliff, 50 m high. It is separated from the Arch Cave by an ephemeral stream which follows the line of the former surface channel of Burrangylong Creek. Most of the walls and ceiling are bedrock, and the floor consists of mud with small patches of breakdown and flowstone. About 8 m from the entrance a solution tube leads off from high on the left wall but is shortly blocked by stream sediment. It probably connects with another alluvially plugged solution tube which opens in the cliff face a few metres above the entrance to the cave. At 106034, Figure 3, a short sinuous passage with paired stream niches leads off to the left for about 10 m. Between cross-sections G-2 and G-3 speleothems on the ceiling block off a ceiling half-tube which extends along the ceiling for the remaining length of the cave.

Other caves and associated features

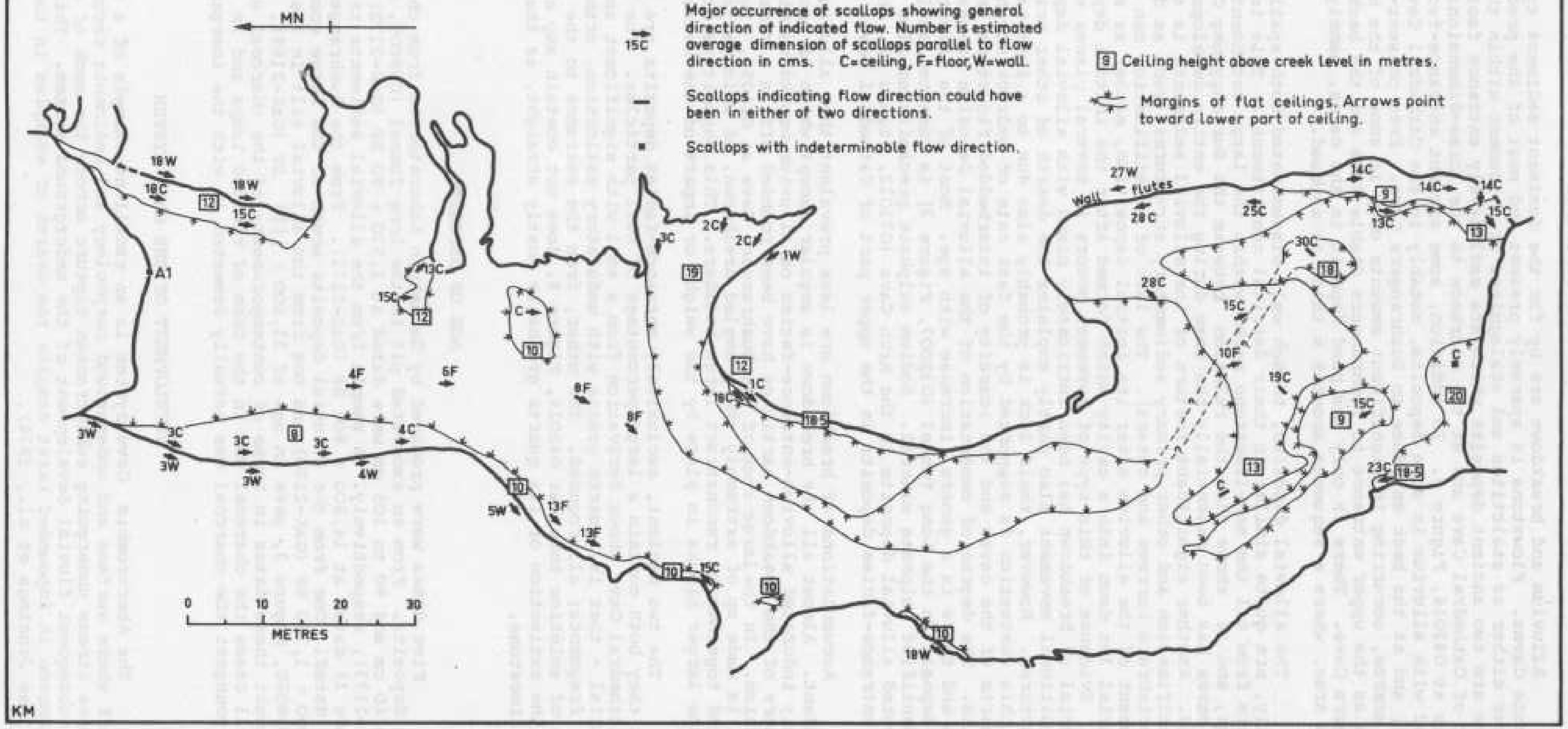
The Bushrangers Stable Cave is a moderately large cave with features similar to those of Arch Cave. It has two entrances. The lower one is about 150 m north of the upstream entrance to the Arch Cave and a few metres east of Burrangylong Creek. The upper one is about 50 m east of the lower and some 30 m higher. Near the lower entrance there is a small arch with bedrock walls and ogival ceiling and a breakdown floor. The west wall of the main passage is smoothly solutional, cavetto-shaped, and contains scallops with an indicated southward direction of flow of the water that formed them. Small solution tubes, nearly plugged with mud, lead off to the west in some places. The east side of the passage consists of large blocks of breakdown. This breakdown continues for some distance to the east and openings in it can be negotiated at least as far east as the upper entrance. The floor of the main passage is not far above the level of Burrangylong Creek and the cave undoubtedly receives water from the creek during flood times.

On a north-facing cliff west of Burrangylong Creek just before it enters the Arch Cave (northwest corner of Figure 8) there are numerous holes and fissures plugged with alluvium. A cave at the base of the northeast part of this cliff leads down to within a few metres of the level of Burrangylong Creek.

Other small caves and karstic features have been recorded and mapped by members of the Metropolitan Speleological Society.

PROMINENT FLAT CEILINGS AND MAJOR OCCURRENCES OF OLDER SCALLOPS IN ABERCROMBIE CAVES

FIG.6



THE SEDIMENTS

Alluvium and breakdown are by far the dominant sediment types in the Abercrombie Caves. Flowstone is sparsely present and most of the precipitates in the caves occur either as stalctites and stalagmites or as cement within the clastic deposits. There are two ancient deposits which are exclusively entrance facies - in the upper part of Cathedral Cave and at the entrance to the three-dimensional maze of solution tubes at 042016, Figure 8. In addition, some ancient entrance-facies material is mixed with alluvium in some deposits, notably in the Cathedral Cave along the west wall, and at the back entrance to Bushrangers Cave. Even present-day entrance facies are scarce, occurring in significant amounts only in some of the high-level entrances such as the upper entrance to Bushrangers Stable Cave and the back entrance to Bushrangers Cave. There is only one pond deposit in the caves, namely in the King Solomons Area, where a sequence about 5 m thick is exposed.

The alluvial deposits, though well disseminated both spatially and chronologically, are quite similar in their detrital constituents. This is because they are a sample from all the non-limestone rocks within the large catchment of Burrangylong Creek, and it shows that the relation between the Burrangylong Creek catchment and the caves has been essentially the same during the entire developmental history of the caves. Another significant feature of the alluvial sediments is the general lack of stratification and other primary sedimentary structures (such as desiccation cracks, invertebrate burrows and cutans). The lack of stratification can be explained by movement of the alluvium after its initial deposition, either as slope material or as material let down into a cavity which formed after the initial deposition of the alluvium. Evidence of this type of movement occurs in several places where entrance-facies material or breakdown has been intricately mixed with alluvial deposits. This post-depositional movement also partly explains the dearth of other primary sedimentary structures. However, their lack is probably also due to a fast rate of sedimentation, and this contention is supported by the fast rate of bedrock morphological development of parts of the caves and the scarcity of interbedded flowstone in the clastic deposits. The degree of cementation of the alluvial deposits ranges from none to very high and there is a general increase with age. Most of the cement is calcite though one deposit in the Long Tunnel (032007, Figure 3) is cemented exclusively with an unidentified sulphate mineral. Sodium sulphate precipitates also occur in calcite-cemented alluvial deposits in the Arch Cave (071012, Figure 3), and on the surface of the entrance-facies deposits in the upper part of Cathedral Cave.

Accumulations of breakdown are less prevalent than alluvium though still abundant. Almost all the breakdown is angular except where it occurs as a part of the highly indurated alluvium-entrance-facies or alluvium-breakdown mixtures. Here the corners of the breakdown particles have been rounded off as a result of post-depositional solution. In the large room of the Bushrangers Cave at 025056, Figure 3, a part of one wall is made up of extremely sharp angled breakdown, of which adjacent fragments can be fitted together to reconstruct large boulders. This deposit is attributed to splitting of the larger blocks in place by the weight or impact of the overlying breakdown.

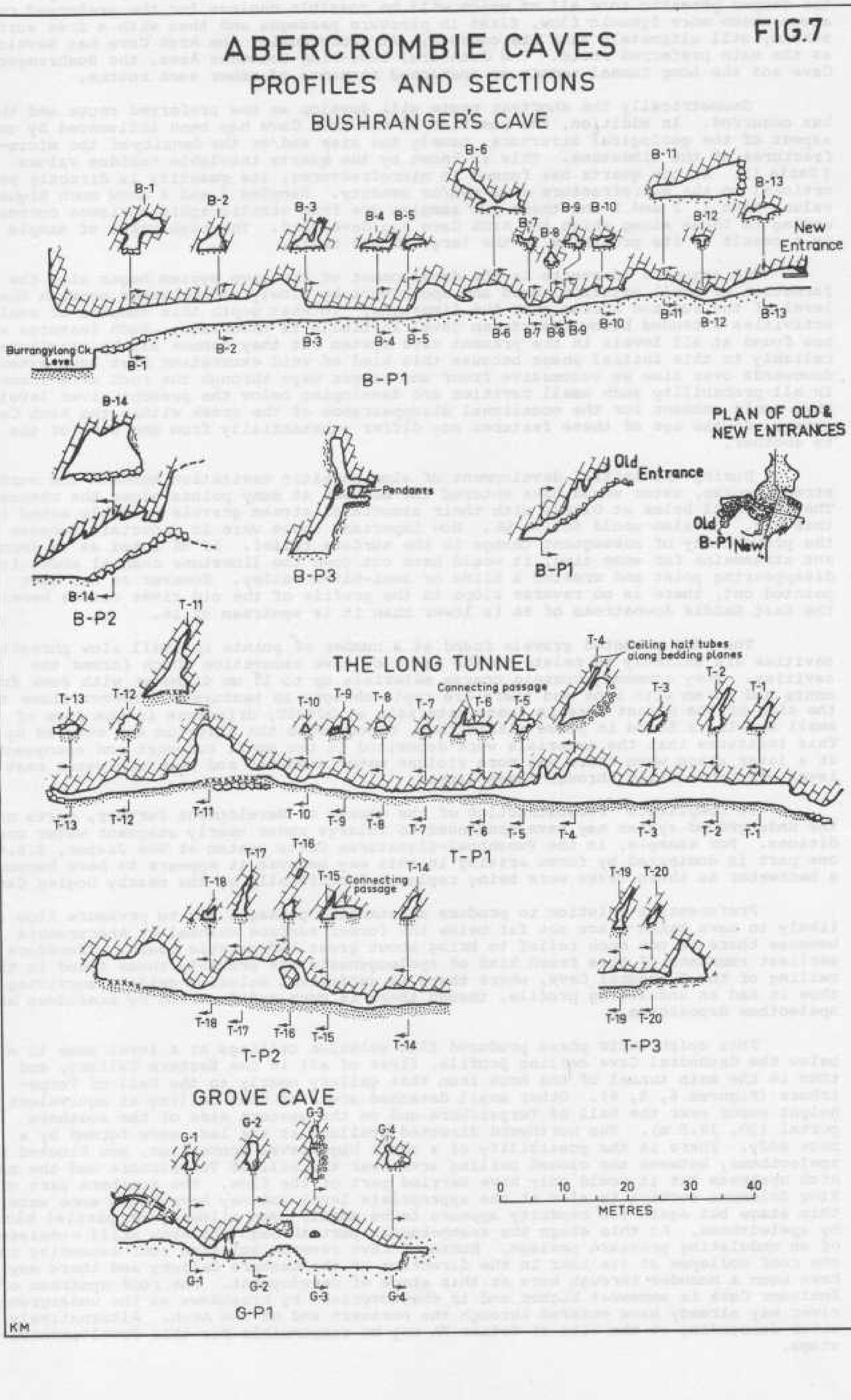
The two ancient, exclusively entrance-facies deposits are fairly typical in that they both contain a large percentage of soil particles. The one in the upper part of Cathedral Cave shows derivation from a soil with significant amounts of alluvial material - that is, quartz grains with undulatory extinction, orthoclase, metamorphic rock fragments; all rounded. The other, from the entrance to the three-dimensional maze of solution tubes at 042016, Figure 8, does not contain any alluvial constituents and the extinction of its quartz grains is mostly straight, as that of the quartz from the limestone.

AGE OF DEPOSITS

Five dates were produced by Gakushuin Laboratories from charcoal out of the cave deposits. From an excavated pit in the Long Tunnel (039009, Figure 3) two samples from 40 cm and 90 to 105 cm were dated at 1,530 ± 90 BP (GaK-2172) and 4,170 ± 110 BP (GaK-2173), respectively. A sample from the alluvial sediments in Grove Cave (108033, Figure 3) dated at 14,800 ± 600 BP (GaK-2171). From the Bushrangers Cave two samples were dated. One from the alluvial deposits south of the large room gave an age of 19,400 ± 1,700 BP (GaK-2170) and one from the alluvial silt in the spongework cavities at 008050, Figure 3, gave an age of 33,600 $\pm ^{1900}_{1500}$ BP (GaK-2169). There is no reason to doubt these dates in terms of contemporaneity of the charcoal with the sediment. In all cases the charcoal was in the form of rounded lumps and in all samples except the youngest the charcoal was actually cemented in with the inorganic constituents.

DEVELOPMENT OF THE CAVE SYSTEM

The Abercrombie Cave system is an excellent example of a subterranean meander cutoff where surface and underground morphology and sediments record the sequence of a surface stream undergoing subterranean capture across the neck of a meander loop and the subsequent fluvial development of the underground system. This is not an uncommon phenomenon in impounded karst despite the dearth of examples in the recent literature (but see Jennings et al., 1976).


ABERCROMBIE CAVES
FIG.7
PROFILES AND SECTIONS
BUSHRANGER'S CAVE
B-1 B-2 B-3 B-4 B-5 B-6 B-7 B-8 B-9 B-10 B-11 B-12 B-13
New Entrance
Burrangylong Ck. Level
B-P1
B-14
B-P2
Pendants
B-P3
Old Entrance
PLAN OF OLD & NEW ENTRANCES
Old
B-P1
New
THE LONG TUNNEL
T-1 T-2 T-3 T-4 T-5 T-6 T-7 T-8 T-9 T-10 T-11 T-12 T-13
Ceiling half tubes along bedding planes
Connecting passage
T-P1
T-14 T-15 T-16 T-17 T-18
Connecting passage
T-P2
T-19 T-20
T-P3
GROVE CAVE
G-1 G-2 G-3 G-4
G-P1
0 10 20 30 40
METRES
KM

In this type of karst system evidence for the sequence of epiphreatic and vadose processes is strongly dominant though remnants of the prior phase of deeper phreatic development are usually present. Numerous cavities will have developed in the deeper phreatic zone all of which will be possible choices for the preferred route along which more dynamic flow, first in pressure passages and then with a free surface stream, will ultimately take its courses. At Abercrombie, the Arch Cave has developed as the main preferred route. The Cathedral Cave-King Solomons Area, the Bushrangers Cave and the Long Tunnel remain as abandoned remnants of other such routes.

Geometrically the shortest route will develop as the preferred route and this has occurred. In addition, the position of the Arch Cave has been influenced by one aspect of the geological structure, namely the size and/or the density of the microfractures of the limestone. This is known by the quartz insoluble residue values (Table 1). As the quartz has formed in microfractures, its quantity is directly proportional to the microfracture size and/or density. Samples 3 and 4 show much higher values than 1, 2 and 5 and these two samples are from stratigraphic horizons corresponding to those along which the Arch Cave has developed. The high value of sample 6 is a result of its proximity to the large thrust fault.

The sequence of events in the development of the cave system began with the formation of small solution tubes and spongework by slowly moving water beneath the level of the surface stream over the limestone. To what depth this complex of small activities extended below the stream level initially is uncertain. Such features are now found at all levels in the present cave system but they cannot all be attributed reliably to this initial phase because this kind of void excavation must have extended downwards over time as successive freer and larger ways through the rock were formed. In all probability such small cavities are developing below the present river level; this would account for the occasional disappearance of the creek within the Arch Cave today. So the age of these features may differ substantially from one part of the cave to another.

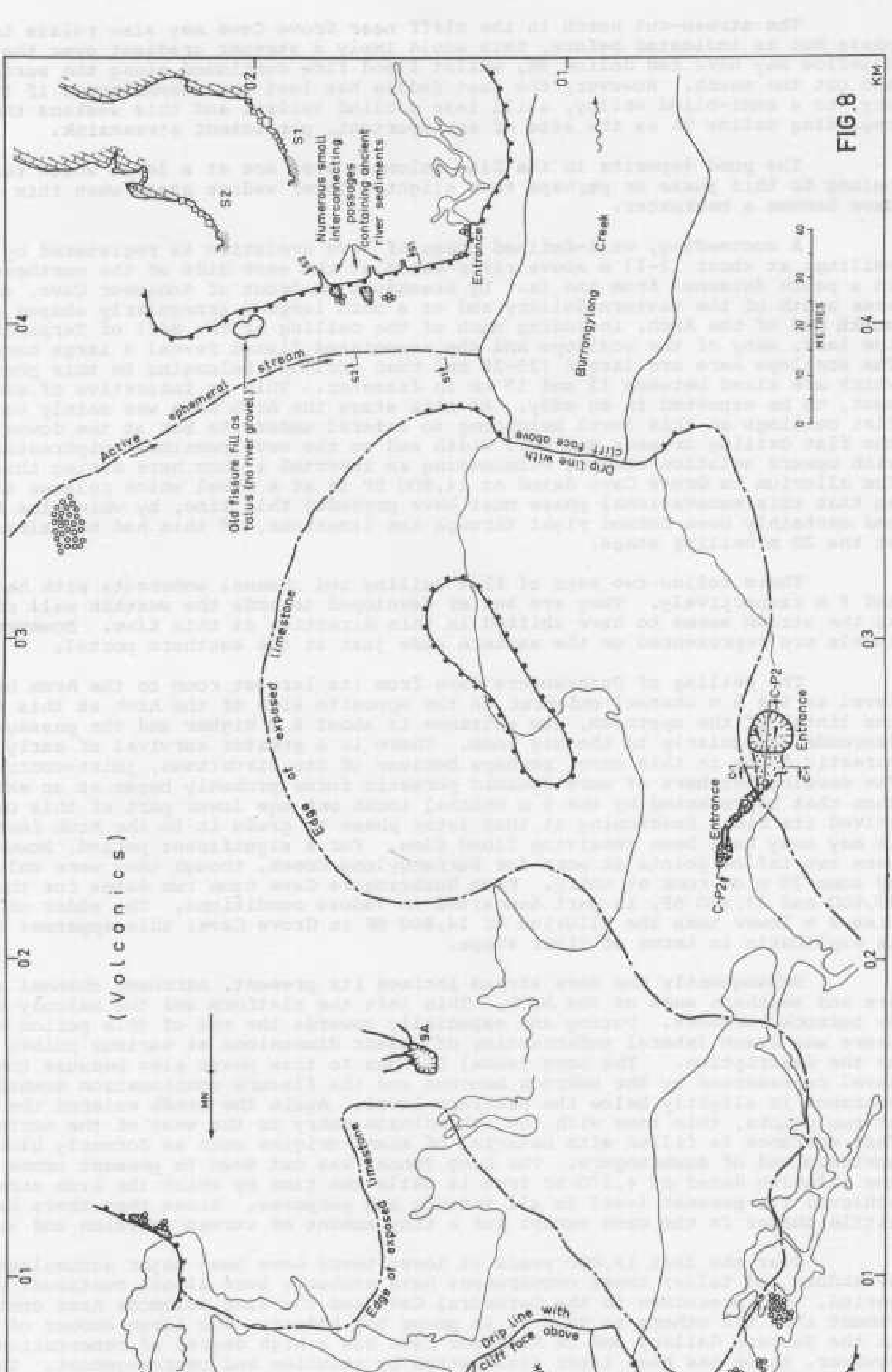
During the initial development of slow phreatic cavitation beneath the surface stream course, water would have entered the bedrock at many points along the channel. The two small holes at 012024 with their associated stream gravels probably acted in this way. So also would doline 9A. How important these were is uncertain because of the probability of subsequent change in the surface relief. If 9A acted as an important streamsink for some time, it would have cut down the limestone channel above its disappearing point and created a blind or semi-blind valley. However as has been pointed out, there is no reverse slope in the profile of the old river course here; the East Saddle downstream of 9A is lower than it is upstream of it.

The old, cemented gravels found at a number of points in small slow phreatic cavities are unlikely to relate to the phase of cave excavation which formed the cavities. They commonly contain coarse materials up to 15 mm diameter with rock fragments and 20 mm with bone and there are rapid changes in texture. Moreover close to the site of the oldest date in these materials at 008050, dripstone in the form of small shawls is found in place within them, depositedon the alluvium and covered by it. This indicates that the materials were deposited in the small tubework and spongework at a later stage when there was more violent water movement and when the water rest level was oscillating through these sites.

To complicate reconstruction of the course of development further, parts of the underground system may have continued to enlarge under nearly stagnant water conditions. For example, in the Punchbowl-Signatures Caves system at Wee Jasper, N.S.W., one part is dominated by forms arising in this way because it appears to have become a backwater as these caves were being replaced functionally by the nearby Dogleg Cave.

Preferential solution to produce substantial passages due to pressure flow is likely to have taken place not far below the former surface channel at Abercrombie because there is not much relief to bring about great hydrostatic heads. Therefore the earliest remnants of this fresh kind of speleogenesis are probably those found in the ceiling of the Cathedral Cave, where there is sufficient solution ceiling surviving to show it had an undulating profile, though there is much modification by breakdown and speleothem deposition.

This epiphreatic phase produced flat solution ceilings at a level some 10 m below the Cathedral Cave ceiling profile, first of all in the Eastern Gallery, and then in the main tunnel of the Arch from that gallery nearly to the Hall of Terpsichore (Figures 6, 5, 6). Other small detached areas of flat ceiling at equivalent height occur over the Hall of Terpsichore and on the western side of the southern portal (20, 18.5 m). The northward directed scallops at the last were formed by a back eddy. There is the possibility of a small high level connection, now blocked by speleothems, between the closed ceiling area over the Hall of Terpsichore and the main Arch upstream but it could only have carried part of the flow. The southern part of King Solomons section is also at the appropriate level and may have taken some water at this stage but again its capacity appears to be small, even allowing for partial blockage by speleothems. At this stage the southernmost part through the Arch still consisted of an undulating pressure passage. Kohinoor Cave reveals solution roof extending into the roof collapse at its rear in the direction of the Eastern Gallery and there may have been a meander through here at this stage of development. The roof upstream of Kohinoor Cave is somewhat higher and is characterised by breakdown so the underground river may already have entered through the northern end of the Arch. Alternatively water descending at the site of doline 9A may be responsible for this developmental stage.



(Volcanics)
Active ephemeral stream
Old fissure fill as talus and river gravel
Numerous small interconnecting passages containing ancient river sediments
Edge of exposed limestone
Drip line with cliff face above
Burrongylong Creek
Entrance
Numerous small caves and fissures in cliff face filled with ancient river sediments
METRES
KM.

FIG.8

The stream-cut notch in the cliff near Grove Cave may also relate to this phase but as indicated before, this would imply a steeper gradient over the limestone. Baseflow may have fed doline 9A, whilst flood flow continued along the surface course and cut the notch. However, the East Saddle has lost any resemblance, if it ever had any, to a semi-blind valley, still less a blind valley, and this weakens the case for regarding doline 9A as the site of an important, persistent streamsink.

The pond deposits in the King Solomons area are at a level which suggests they belong to this phase or perhaps to a slightly later vadose stage when this area would have become a backwater.

A succeeding, well-defined phase of cave evolution is registered by flat ceilings at about 12-13 m above river datum at the east side of the northern portal, in a patch detached from the last by breakdown in front of Kohinoor Cave, another tiny area south of the Eastern Gallery and as a much larger, irregularly shaped area at the south end of the Arch, including much of the ceiling of the Hall of Terpsichore. In the last, many of the scallops and the associated flutes reveal a large back eddy here. The scallops here are larger (25-28 cm) than scallops belonging to this phase elsewhere, which are sized between 13 and 19 cm in diameter. This is indicative of slower movement, to be expected in an eddy. At this stage the Arch Cave was mainly vadose, its flat ceilings at this level belongong to lateral undercuts but at the downstream end, the flat ceiling crosses the full width and so the cave remained epiphreatic here, but with upward solution stoping eliminating an inverted siphon here during this stage. The alluvium in Grove Cave dated at 14,800 BP is at a level which relates to this phase so that this excavational phase must have preceded this time, by which the Arch Cave had certainly been formed right through the limestone, if this had not already happened at the 20 m ceiling stage.

There follow two sets of flat ceiling and channel undercuts with heights of 10 and 8 m respectively. They are better developed towards the western wall of the Arch as the stream seems to have shifted in this direction at this time. However these levels are represented on the eastern side just at the southern portal.

The ceiling of Bushrangers Cave from its largest room to the Arch has the same level as the 8 m channel undercut on the opposite side of the Arch at this end. However the lintel of the upstream, new entrance is about 6 m higher and the passage ceiling descends irregularly to the big room. There is a greater survival of early slow phreatic forms in this cave, perhaps because of its circuitous, joint-controlled plan. The development here of more dynamic phreatic forms probably began at an earlier phase than that represented by the 8 m channel incut but the lower part of this cave received its final fashioning at that later phase to grade it to the Arch feature when it may only have been receiving flood flow. For a significant period, however, there were two inflow points at work for Burrangylong Creek, though they were only separated by some 20 m of rock at entry. From Bushrangers Cave came two dates for the alluvium, 33,600 and 19,400 BP, in part deposited in vadose conditions. The older of these two lies 2 m lower than the alluvium of 14,800 BP in Grove Cave; this apparent discrepancy is explicable in terms of river stage.

Subsequently the cave stream incised its present, narrower channel at the northern and southern ends of the Arch. This left the platform and the balcony room floors as bedrock terraces. During and especially towards the end of this period of incision there was fresh lateral undercutting of modest dimensions at various points mentioned in the description. The Long Tunnel belongs to this phase also because the upper level represented by the bedrock benches and the fissure continuation downstream of the entrance is slightly below the platform level. Again the creek entered the limestone at two points, this time with the subordinate entry to the west of the northern portal. That entrance is filled with material of mixed origins such as formerly blocked the upstream end of Bushrangers. The Long Tunnel was cut down to present creek level and the alluvium dated at 4,170 BP from it tells the time by which the Arch stream had achieved its present level to all intents and purposes. Since then there has been little change in the cave except for a tiny amount of stream incision and some collapse.

Over the last 19,000 years at least there have been major accumulations of breakdown and talus; these occurrences have probably been almost continual over a long period. The breakdown in the Cathedral Cave and the King Solomons Area contains more cement than the others so that it is among the oldest. The large amount of breakdown in the Eastern Gallery and in Kohinoor Cave has a high degree of cementation also; however, there has been later dislocation by solution and rearrangement. The breakdown in the large room in Bushrangers Cave is virtually devoid of cement and its fresh appearance in some places shows that some movement has been quite recent. This and the breakdown at the rear part of the Long Tunnel, in the small room of Bushrangers and at the upstream entrance of that cave suggest a greater prevalence of collapse here because of a thinner roof. Similarly in the Arch Cave, the ceiling shows more evidence of rockfall than at the southern end, again related to a thinner roof (profile A-P1, Figure 4).

SUMMARY AND CONCLUSIONS

Although the Abercrombie Caves are far from devoid of cave decorations of beauty and interest, they are more outstanding for the excellence and plentifulness of the speleogens which reveal the story of their excavation. Not many tourist caves in southeastern Australia can match them in this respect. A surface meander of Burrangylong Creek was eliminated by the development of the Abercrombie Caves system, possibly progressively with the main streamsink shifting upstream. Tubework and spongework of a preparatory slow phreatic character survive at numerous points but in the main Arch have been practically obliterated and replaced by a magnificent sequence of flat solution ceilings and large channel undercuts. Epiphreatic action was eliminated from the main Arch by about 15,000 BP and the Arch had also been driven right through the limestone by that time, but possibly much earlier than that, before 34,000 BP. The creek entered the underground at two points during two periods of the caves' history. Well developed rock benches or terraces resulted from renewed incision late in the caves' history but even this phase was virtually complete 5,000 years ago. The final course the stream assumed along the strike of the limestone was partly a result of a higher density and/or larger size of microfractures in the particular beds selected.

ACKNOWLEDGEMENTS

The bulk of the work incorporated in this paper was carried out by Dr Frank when he was a member of the Department of Biogeography and Geomorphology at the Australian National University. The interpretation of the evidence presented here has benefited greatly from much discussion in the field with Mr A.P. Spate, Dr R.S. Nicoll and Mr A. Goede, to whom we express very real thanks. The hospitality of Mr Brian Crick, past superintendent of Abercrombie Caves, and the stimulating speleological discussions with him made my work there pleasant and profitable. More recently Mr George Knox, present superintendent, has provided the same helpful welcome. Ken Keck kindly provided information about the Metropolitan Speleological Society's activities at Abercrombie during the last three years.

Numerous other persons assisted with field and laboratory work and the list following is not exhaustive: Mr K. Pitchett, Dr G. England, Dr J.J. Stipp, Prof. P.W. Williams, Mr A. Hodgkin, various members of the Canberra Speleological Society.

Except for Figures 1 and 2, the maps were drawn by Mr K. Mitchell, Cartography Section, Department of Human Geography, Australian National University. The New South Wales Department of Tourist Activities gave permission to work in the caves.

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LETTER

A NOTABLE LIMESTONE HYDROLOGY INVESTIGATION IN AUSTRIA

About one-seventh of Austria is built of limestone or dolomite, notably in the plateaux and ranges of the High Calcareous Alps, where surface karst forms (other than poljes) are well developed and where there are magnificent caves such as the Eisriesenwelt in the Tennen range near Salzburg and the Rieseneis and Mammut caves in the Dachstein plateau farther east. About one quarter of Austria's precipitation falls on these karst areas and nearly another quarter runs off surrounding areas into their underground systems. So a high proportion of drinking water for such cities as Vienna, Salzburg and Innsbruck comes from karst springs.

Therefore it is not surprising that over the years very important research into underground water systems has been done in Austria. Speleologists are probably most aware of Dr J. Zötl's method of water tracing by the use of spores, whereby as many as five different waters have been tagged and traced at the same time (Jennings, 1957). Use of this technique in conjunction with others has been very fruitful in Austria since 1956. Seepage water entering high plateau surfaces such as that of the Dachstein (perhaps the best known to Australian cavers because of the cable car to the Krippenstein overlooking it) was found to radiate in more or less all directions and was likely to reappear at many different springs in the peripheral valleys. Major streamsinks on the other hand were more tightly linked to particular springs to which they delivered large quantities quickly. This water in particular was likely to be unfiltered and problematic from the point of view of drinking water supplies. Older findings such as the crossing of different underground rivers at different levels without affecting one another and the fact that underground connections could vary with different weather and discharge conditions were substantially reinforced by such Austrian work. The diversity in behaviour from one karst area to another was made abundantly clear.

Some of the most exciting results of late have emerged from an almost unique opportunity which Dr Fridtjof Bauer (1969, 1970) of the Institute of Speleology in Austria seized upon when between December 1965 and July 1968 a tunnel was put through the high limestone plateau of the Schneealpen to increase Vienna's water supply from this area. This tunnel runs 10 km through the bottom of this limestone mass, mainly just above its impervious basement though partly through the latter. It is also just a little below the level of the Wasseralm springs on the northern side of the range, already tapped for Vienna, and of the Sieben springs on the southern side, which were to be deflected north by the tunnel.

The limestone is more than 900 m thick over 5 km of the tunnel and many flows of water were tapped from fissures and caves (some filled with sand or rock fragments) as the adits were gradually driven in from both ends of the tunnel. From water tracing the only definite indications we get of the hydrology are what links there are between water sinks and risings; we have to infer what happens inside the limestone mass. But here was a fine chance to get direct information all the way through the limestone and so, whilst the tunnel was constructed, the discharges, temperatures and chemistry of all the outflows encountered were monitored. The natural springs of the area were also monitored before, during and after the construction of the tunnel.

There was great variety in character of the waters encountered as the tunnelling progressed, even from points quite close together, and the complexity of karst underground water movements was once more underlined. Nevertheless along the tunnel five zones and one point of outflow could be distinguished clearly on the basis of the nature of the water and its behaviour over time.

About 1 km of the tunnel lay in the impervious basement rocks and yielded little or no water. From this zone to the southern end of the tunnel was less than a kilometre and here big outpourings of water made the tunnelling very difficult. Here there was much variation in amount and character of the discharge according to the precipitation and temperature of the plateau above. These outflows caused the Sieben springs to dry up completely but when the tunnel was sealed off from the fissures, these springs quickly returned to normal. It was possible to calculate that the volume of cave filled up to restore the output of the springs to normal was 12,000 m^3. Also measurements of prssure of water against the tunnel and of the discharge of the Sieben springs showed a close correlation between the two.

From the northern end, the first kilometre had the same characteristics. Fairly substantial flows of water came in at various points which responded quickly in amount, temperature and total hardness to rainfall or snowmelt on the plateau above. The next 1700 m of tunnel was transitional in nature with a weakening response to surface weather and runoff conditions.

Virtually all the rest of the tunnel as far as the section in the basement rocks, 5 kilometres of it, behaved differently. The waters tapped might differ in their characteristics between one another but each maintained practically constant flow, temperature and hardness. This part was obviously very much insulated from the surface though there was no change in geology to account for it. This was demonstrated in most interesting fashion in the part between 3 and 4 km in from the northern end where the waters had a fluorescein content. This could only have come from a particular water tracing experiment on the plateau above carried out in June 1963 and the water with fluorescein in it was thus more than 5 years old here. This was indicative of very slow water movement. It also has a lesson for all those of us who carry out fluorescein tests!

There was one sharp exception along this 5 kilometre stretch; at 6445 m from the northern end a significant flow was tapped which varied seasonally with surface conditions as did the marginal parts of the tunnel inputs. At this one point in 5 kilometres there must be easy connection with the plateau 1 kilometre above.

With that exception these inner waters had the least limestone in solution. This was to be expected from a number of other investigations since the middle of the plateau was bare karst whereas the flanks had soil and forests which would provide more carbon dioxide for corrosion of the limestone.

After the tunnel went into use, watch continued to be maintained on the natural springs of the area. Initially at least only the Wasseralm springs at the northern end of the tunnel suffered a reduction in flow, in association with this deflection of water from the southern flanks of the range to the northern, i.e. the engineering capture of the Sieben springs flow.

From all the evidence, Dr Bauer came to the conclusion that in this karst system there were two bodies of water arranged one above the other. In an upper and marginal part, the waters moved rather quickly to the peripheral springs and consequently there is much variation in discharge, temperature and chemistry over time. Then there is an inner and lower inert core of water, with much more slowly moving water responding practically not at all to the surface conditions, even though variations in this water still pointed to independent threads of water from the surface. Indeed the flow at 6445 m was a reminder that even in the heart of the plateau a very free channel could link the base of the limestone sensitively to the surface.

This is an important elaboration of the picture so far established of karst hydrology in high alpine karst plateaux and Dr Bauer must be congratulated on this excellent work. However, as his own writings make evident, we cannot yet be sure where this pattern will recur; virtually every karst needs investigating independently yet. Furthermore he points out the need for much more work in his own country in two directions. First there is a need for broader, long term surveys of all karst springs of importance. This is now in hand. Also he points to the need for particular studies in depth, using more techniques of karst water study in combination and more sensitively. For example, Dr Bauer now considers he can detect fluorescein in as low a concentration as 0.001 mg/m³ and can separate fluorescein from rhodamine B extra or G extra when these are used simultaneously, this of course with charcoal bags and a spectrofluorometer.

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INFORMATION FOR CONTRIBUTORS

SCOPE

Contributions from all fields of study related to speleology will be considered for publication. Suitable fields include Earth Sciences, Speleochemistry, Hydrology, Meteorology, Conservation, Biospeleology, History, Major Exploration (Expedition) Reports, Equipment and Techniques, Surveying and Cartography, Photography and Documentation. Comprehensive descriptive accounts of the exploration and morphology of individual caves will be welcomed, but simple trip reports and brief cave descriptions are not adequate. Papers overall should not exceed 20 printed pages in length. Contributors intending to write at greater length or requiring any advice on details of preparation are invited to correspond with the Editors. All manuscripts will be read by referees. Short 'Letters to the Editor', expressing a personal view or giving a preliminary report of interesting findings, are welcomed, and will be given preference for speedy publication.

MANUSCRIPTS

Submitted manuscripts should be in a final form ready for publication. As proofs are not normally sent to authors particular care should be taken to check for typing errors. Manuscripts should by typed, double spaced, on one side of the paper. The title should be uppercase and underlined, and the authors' names should follow. A brief and explicit summary of the notable aspects of the paper, headed Abstract, should precede the main text.

Throughout the main text major headings should be in upper case, centred and not underlined, while subheadings should use lower case, underlined and aligned with the left hand margin. Acknowledgements should be placed at the end of the text before the references, and the authors' addresses for correspondence should follow the references.

Authors with access to an IBM Golfball typewriter may wish to submit their papers in 'camera-ready' form. They should request our leaflet "Helictite Typographic Style". Papers should still be submitted in the above form in the first instance.

REFERENCES

References should be listed alphabetically at the end of the manuscript and cited in the text by the author's name and the year of publication (e.g. "(Grey, 1973)"). Where there is more than one reference to the same author in one year the letters a,b, c, etc. should be added. If there are more than two authors, they should all be named at the first citation and in the reference list, but the first name followed by 'et al.' should be used in subsequent citations. References should be checked particularly carefully for accuracy. Journal titles should be abbreviated following the "World List of Scientific Periodicals", which is available in most large libraries. The following examples illustrate the style:

GRAY, M.R., 1973 Cavernicolous spiders from the Nullarbor Plain and south-west Australia. J. Aust. ent. Soc., 12: 207-221.

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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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