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The "Small Bit" of Deer Cave, Gunung Mulu

Geomorphology in Gulung Mulu Caves

Biology of Mulu Caves

Liverpool Jamaica Expedition

Thermal Air Currents in a Cave

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GEOMORPHOLOGICAL OBSERVATIONS IN THE LIMESTONE CAVES OF THE GUNUNG MULU NATIONAL PARK, SARAWAK

A. C. Waltham and D. B. Brook

Abstract

During the 1977-78 Royal Geographical Society Expedition to the Gunung Mulu National Park in the rain forests of Sarawak, over 50 kilometres of cave passges were explored and mapped, most of them being remarkable for their size. Briefly, the caves include passages which have formed in all hydrologic environments - deep phreatic, shallow phreatic, water table and vadose. Features of their morphology are compared, and the distinction between those in caves formed at the water table or at various depths in the phreas is shown to be questionable. Some ideas on the genetic sequence of cave development from phreatic to vadose conditions are presented. An unusual new form of calcite speleothem, the calcite fan, is described.

INTRODUCTION

The Gunung Mulu National Park lies close to the northern tip of the Malaysian state of Sarawak on the northwest side of the island of Borneo. The purpose behind the Park's creation was essentially the conservation of the very rich equatorial rain forest which covers a wide range of terrain types within the Park boundaries. Of these terrains, the most spectacular is that on the limestone, which also contains one of the world's greatest suites of caves.

Right across the centre of the Park (fig. 1) the limestone forms a towering range of hills culminating at the summits of Gunung Api and Gunung Benarat. These rise over 1500 metres above the broad alluvial plain of the Melinau and Tarikan Rivers extending to the northwest. To the southeast of the limestone, dissected shale and sandstone slopes rise to the summit of Gunung Mulu at 2376 metres above sea level. With the exception of the vertical white cliffs in the limestone the whole of this varied landscape is covered in dense virgin rain forest, and very little of it has yet been trodden by man.

Both the luxuriance of the Park vegetation and some of the land forms, particularly on the limestone, reflect the nature of the equatorial climate. Temperatures average about 27°C, and day or night rarely range outside 20° -35°C ; there are no seasons. Rainfall is an impressive 6000mm. per year with monthly figures ranging 100 to 750mm., and most of the rain falling in heavy afternoon storms which rarely fail to develop.

The Mulu Park's combination of high rainfall, massive pure limestone and considerable relief is almost the ultimate in potential for cave development. Consequently the caves in the Park - even the small proportion that have yet been explored - are on an incredible scale. Not only are the caves long, but some are beautifully decorated, others contain impressively large underground rivers, and they culminate in Deer Cave with what is believed to be the largest cave passage in the world.

HISTORY OF RESEARCH

Before 1977 hardly any research had been done in the Mulu region. The geology had been briefly studied mainly by oil geologists based on the coast (Liechti, 1960). More important, Wilford had visited the area in his wide search for caves in Malaysian Borneo (Wilford, 1964), and he made some further geomorphological comment on Sarawak karst, including the Mulu Park area, in Wilford and Wall (1965). Then in 1977 the Royal Geographical Society Mulu Expedition visited the Park for a 15 month scientific study programme. Though most work was biological, a small geomorphological team made some studies on active processes and the karst landscapes (Sweeting, 1979 and 1980; Friederich, 1980). The same expedition included a six man caving team, including the writers, whose main work over 3 months was exploration and survey but which did lead to the geomorphic observations in this paper. Full descriptions and surveys of all the caves have been published in "Caves of Mulu" (Brook and Waltham, 1978) which also contains a comprehensive photographic record of the Park caves. The cave exploration has been

THE GUNUNG MULU NATIONAL PARK
0
20
km.
River
Limestone hills
Park boundary
Path
N
Borneo
200 km.
BRUNEI
Miri
Niah
MULU
SABAH
SARAWAK
Kuching
KALIMANTAN
BRUNEI
Long Pala
Tutoh
Melinau
API
MULU
BENARAT
Medalam
BUDA

Figure 1

described separately (Brook and Waltham, 1978 and 1979; Waltham, 1979), and the role of the caves in the regional geomorphology has been considered by Waltham and Brook (1980). The cave biology is summarised in "Caves of Mulu" and aspects are described in detail by Chapman (in press). Cave minerology was studied by Laverty and his results will be published in the near future.

It should be noted that the opinions expressed in this paper can only be regarded as preliminary, because of the nature of the very rapid exploration and survey which had to be maintained on the Mulu Expedition. Not only is there an enormous amount of cave awaiting discovery in the Mulu Park but there is also great scope for much more detailed study of the caves.

LIMESTONE GEOLOGY

All the caves of the Mulu Park occur in the Melinau Limestone. This is a spectacularly massive carbonate unit of Eocene to Miocene age with a thickness of well over 2000 metres. It is developed as a massive lens, which extends little beyond the Park boundaries, dipping northwest as 20° to 40° so that Gunung Api and Gunung Benarat are southeast - facing escarpments. The limestone is extremely pure; most of it is white or pale grey calcilutite with very little textural variation. It is remarkably massive; widely spaced bedding planes do occur but they are devoid of shale partings, and in most areas joints and faults are also at wide intervals.

East of the main limestone mountains, and stratigraphically lower, are the shales and sandstones of Gunung Mulu which carry surface drainage towards the limestone. On the west lies the Melinau Plain - alluvial flood plains and terraces which post-date the late Tertiary folding and lie unconformably against the limestone. It is not known for certain whether limestone or shale underlies the Plain's thick alluvium. There are, however, isolated limestone hills, notably Bukit Berar, and many smaller limestone towers: these may be erosional remnants or separate lenses of limestone, similar to, but stratigraphically higher than the main lens of Melinau Limestone. Beyond the Plain, younger shales crop out.

SURFACE KARST

Gunung Api provides a magnificent example of tropical-equatorial mountain karst, and the other mountains formed in the Melinau Limestone are little less spectacular. All the limestone outcrops are riverless. All rain falling on to the limestone sinks underground and re-emerges at no more than a few resurgences around the margins of the 60 square kilometres of karst (this figure excludes both the isolated limestone hills to the west and also Gunung Buda beyond the northern boundary of the Park). Practically the whole of the Api drainage emerges from the Goldwater and Clearwater risings, and the only major rising from Gunung Benarat is the Tarikan River.

Regional drainage is northwestwards, from Gunung Mulu toward the Melinau Plain, and there are five major rivers which cross the limestone belt (fig. 1). The three largest all maintain surface courses. The River Melinau itself flows through the Melinau Gorge - a spectacular U-shaped valley (with no hint of glacial origins!), with a broad floor and marginal cliffs more than 500 metres high and vertical on the north side. North and south of the Gorge, the Rivers Medalam and Melinau Paku each cross the limestone in even broader valleys with precipitous marginal cliffs overlooking wide alluviated floors. The two remaining rivers off Gunung Mulu both sink underground leaving enormous blind valleys. Hidden Valley, just south of the summit of Api, is one of the wonders of the Park. Overhanging cliffs 400 metres high line both sides of this huge but narrow defile which ends beyond the river sink in a complex of enormous and precipitous dolines (fig. 2). The sink is choked with boulders and the resurgence is not proven though it is almost certainly the Clearwater River. Further south, the fifth river sinks in the Garden of Eden - a great bowl shaped blind valley a kilometre in diameter ringed on half its margin by 300 metre high limestone cliffs. The outlet of the Garden of Eden is Deer Cave, taking the river just over a kilometre through the limestone ridge to the resurgence on the Melinau Plain.

Excepting the vertical or overhanging cliffs, all the limestone is covered by a 30-50 metre thick mantle of equatorial rain forst. The major landform types are doline karst and pinnacle karst. The finest doline field is on the southern half of Gunung Api - where the entire topography is a mass of dolines of varied sizes; the larger dolines are 500 metres across but even their sides are pocked by many of the smaller depressions (fig. 2). Open shafts could easily be hidden by the forest cover, and only the largest are easily seen from the air; the Solo shaft is nearly 100 metres in diameter and 200 metres deep. Far more shafts have been discovered from underneath, in the cave systems. The dominant small scale landform is the pinnacle karst. Narrow ridges and spires of limestone are the natural weathering form in the

Fig. 2. Contour map of the doline karst on the southwest flanks of Gunung Api. Contours are at 200 feet (60 metres) intervals and rise from 60 to over 1600 metres. A = Gunung Api; H = Hidden Valley; M = Melinau Plain; S = Sandstone; hachured lines mark the main vertical cliffs. Dashed lines are contours on closed depressions. The large dolines just west of Hidden Valley are conspicuous with the floor of the largest descending more than 100 metres below the river sink in the elongate trough of Hidden Valley. The heavy dotted line marks the edge of the limestone, stepped on the fault line which locates Hidden Valley. (Adapted from Malaysian Survey map compiled from air photographs).

Figure 3

rain-forest. Where covered by vegetation, the limestone is rounded, but emergants clear of the organic soils are fluted to razor edged pinnacles. Individual pinnacles at the northern end of Gunung Api (the pinnacles as they are known) rise more than 30 metres clear of the forest canopy, but over most of the area they are more like a third of this height. Their distribution is varied but on most of the higher slopes they are so dominant that they make walking progress next to impossible. (Plate 1, Fig. 1).

An important aspect of the karst is the solutional undercutting of the marginal cliffs of the limestone where in contact with swamp environments on the alluvial plains. Cliff-foot-caves are well known features of tropical karst and Sarawak proves no exception (Wilford and Wall, 1965). They occur at flood plain level in most of the isolated limestone towers of the Mulu Park, and to a lesser extent along the margins of the main limestone mountains. However they rarely penetrate more than about 20 metres; they are quite definitely marginal features, and as such are just a component of the planar erosion eating at the bases of the limestone masses. If it is believed that the Melinau Plain is entirely floored by limestone, then this lateral planation process has seen the almost complete revival of a four kilometre wide belt of limestone upland; this is, however, open to dispute. While the scale of the planation may be debated, the existence of the process is undeniable. Its second result is the steepness of the marginal cliffs on the limestone massifs - the vertical white cliffs many hundreds of metres high lining much of the sides of the Melinau Paku valley are perhaps the finest examples in the Mulu Park.

THE CAVES

Fifty kilometres of cave passages are now known in the Gunung Mulu National Park, and most of them are marked on fig. 3. Full surveys and morphological descriptions of all the caves are in "Caves of Mulu" (Brook and Waltham, 1978) and space dictates that only a brief outline of the better known and more significant caves is included here.

The eight major cave systems in the Park, from south to north, are as follows:

Deer Cave, passes right through the limestone hill, between the Garden of Eden and the Melinau Plain (Plate 1, Fig. 2). It is just over a kilometre long, almost level,and remarkable mainly for the size. Nowhere is the passage less than 90 metres in diameter and it does reach 170 metres wide and 120 metres high. For part of its length the river occupies a parallel passage, Deer Water Cave, and there is an isolated cave segment to the south, Mayday Cave, which is a smaller complex of parallel, multi-level galleries.

Green Cave is on the same line as Deer Cave, to the north, and passes through from the Garden of Eden to the Melinau Paku valley. The through route is 2400 metres long, in a passage mostly 50 metres high and wide - enormous except when compared with Deer Cave. The main gallery is 150 metres above alluvial plain level, and due to a massive entrance ramp and deep shafts in its floor the cave has a total depth of 320 metres.

Cave of the Winds carries a distributary of the Melinau Paku river through the southern tip of Gunung Api to the Melinau Plain (Plate 1, Fig. 1). It has 2400 metres of passage only enterable at the resurgence in the bank of the Melinau. The main passage is an old phreatic tunnel with the river cut about 5 metres into its floor, but towards both ends the phreatic high levels separate from the streamway.

Clearwater Cave is the longest in the Park, with more than 25 kilometres of passage over a vertical range of 170 metres. (Plate 1, fig. 3). The main river feeds a base flow of over 5 cumecs to the resurgence on the edge of the Melinau Plain; besides draining a major portion of Gunung Api it almost certainly includes the water from Hidden Valley. The river passage is a massive canyon at least 20 metres wide and 30 metres high for nearly two kilometres. It has a huge roof tube which breaks away at sump 1, and upstream the tunnel is smaller to sump 2. A tributary complex known as the Goldwater Series has numerous inlets from the Melinau Plain, including the Goldwater River which itself emerges from another rising and accounts for most of the remaining Api drainage. The fossil series of Clearwater extends from sump 1 northwards for half the length of Api. Its main passage is again enormous, 15-30 metres square, and consists basically of phreatic conduits which maintain fairly constant elevations, though different segments range from 15 to 80 metres above alluvial plain level (the present base level for the limestone hills). Truncated branches and multiple levels add to its complexity. The series is remarkably dry, but shafts do punctuate its roof and floor. The largest of these are almost directly below Solo, a gaping open shaft on the mountainside 500 metres above plain level. A vertical drop of 140 metres leads to a sloping breakdown floor unexplored below a depth of 260 metres.

Prediction Cave lies in the southern wall of Hidden Valley. Some 600 metres of almost horizontal, very large, phreatic tube are almost filled with

sediment and end in a stalagmite choke.

Wonder Cave is entered 100 metres up the northern side of Hidden Valley. It is essentially a fossil system, with nearly 4800 metres of passage covering a vertical range of 130 metres. Beyond an entrance series of narrow rifts, lies a series of massive phreatic chambers all at around the same level. A spectacular feature of the cave is the extraordinarily profuse collection of calcite and gypsum formations.

Tiger Foot Cave opens into the northern wall of the Melinau Gorge and contains 1300 metres of passage with a depth of 128 metres. (Plate 2, fig. 2). Nearly all the passages are fossil phreatic tubes aligned in the bedding, either along the strike or stepping steeply up and down the dip.

Tarikan River Caves include over 6800 metres of passages under the northwestern corner of Gunung Banarat. The gently graded underground course of the Tarikan River, behind its rising, occupies 2 kilometres of the cave, in mainly 10 to 15 metre diameter tubes, mostly with deep canals and short sumps. Many active inlets drain from the alluvial plain and their canyon passages are tributary to the underground river. They also intersect a complex of old phreatic passages mostly 5 to 20 metres above present river levels. The source of the river is unknown, but it is the only significant rising from the Gunung Benarat limestone massif.

The geomorphology of the caves is quite obviously complex and varied, but it is significant that development has taken place in all four hydrological environments - deep phreatic, shallow phreatic, water table and vadose. Major features of the caves of each type are described below, starting with the shallow phreatic caves which appear to be dominant in the Melinau Limestone.

TYPES OF CAVE DEVELOPMENT

Shallow Phreatic Caves

Most of the trunk cave passages in the Mulu Park have the circular cross sections, arched roofs and many minor features diagnostic of phreatic development. Their generally horizontal courses suggest a shallow phreatic origin, but no conclusive evidence of their actual depths of formation has yet been recognised. They occur at various levels. Highest of all is Prediction Cave, and the massive tunnel of Green Cave is still over 100 metres above present base level. The largest passages in Wonder Cave were all formed on a level when water must have stood over 150 metres above the present floor of Hidden Valley. The long passages of Clearwater Cave's fossil system are within 100 metres of modern base level: all these four examples are now totally fossilised. The Goldwater Series, in Clearwater Cave, contains beautiful, horizontal tubes only just above present stream levels, and the Tarikan system and Cave of the Winds both contain large phreatic tunnels at current base level and therefore half-filled by slow moving rivers. Deer Cave's enormous tunnel is probably also of shallow phreatic origin, though its size and much collapse preclude the study of any evidence provided by its roof morphology. It may have developed not just as one tube, but as a series of superimposed tunnels which have collapsed into each other, and the nearby Mayday Cave may be presently half way through this process - it consists of three levels with considerable interconnection.

Most of these phreatic tunnels are oriented along the strike, and their straight-line courses in the steeply but uniformly dipping limestones account for their horizontality where controlled by individual bedding planes. A single level is, however, not maintained in the longer caves, notably Clearwater. Though individual segments are horizontal or nearly so, a degree of stepping is seen on the long profile (fig. 4). This is not necessarily accounted for by sequential phases of development, though two phases are clearly defined in the northern reaches of the cave. The scale of these steps, when matched to the length of the tubes, and even the slopes on the inclined segments of passage, do not detract from the evidence for essentially shallow phreatic origins. The old phreatic caves now occupied by the Tarikan and Winds rivers are both oriented down the dip, and hence cut through the bedding. Though the caves are both essentially level, geological structures have influenced smaller features of the morphology, notably the downloops occupied by the modern sumps along the Tarikan River. In both strike and dip oriented passages, roof domes and phreatic rifts do occur but reveal no concordance of altitude which could indicate past water table levels.

Deep Phreatic Caves

Classic cylindrical tube passages, steeply inclined over considerable ranges of altitude can only be ascribed to deep phreatic development. The Ramps in Tiger Foot Cave, 5 metre diameter tubes mostly inclined at around 45°, are among the finest examples in the Mulu Park. Similar

PLATE 1 CAVES OF MULU

Fig. 1.

The Pinnacles, mostly about 30 metres high, projecting through the forest canopy on Gunung Api.

Fig. 2.

The northern end of Deer Cave, with Dave Brook just visible standing on the middle of the shingle bank.

Fig. 3.

The Clearwater River Cave, with the normal flood level of the river marked by the dark line half way up to the conspicuous fossil notch. The canyon at this point is 30 metres high.

Photos by A.C. Waltham

PLATE 2 CAVES OF MULU

Fig. 1.

Active notch in the river passage of Cave of the Winds; normal flood level is at the roof of the notch, and the larger old section of the passage is here partly choked with debris on the left. (Photo: A.C. Waltham).

Fig. 2.

Inclined deep phreatic tube in Tiger Foot Cave; the passage climbs steeply up the bedding and a branch descends to the right, also on the bedding. (Photo: M.K. Lyon).

Fig. 3.

Calcite fans in Wonder Cave. (Photo: A.J. Eavis).

passages also occur in Clearwater Cave northeast from River Junction, and in Wonder Cave. The twin ramps at Green Cave's southern entrance extend over a vertical range of 200 metres, but because of weathering cannot definitely be ascribed a phreatic origin. In each of these cases, the inclined cave passage follows some geological structure - in Tiger Foot Cave nearly all the tubes are in a single bedding plane. It is, however, notable that, in each of these systems, segments of the phreatic tubes follow the same geological structures but are conspicuously level. The horizontal section of Benarat Walk in Tiger Foot Cave (fig. 5) could be taken as a shallow phreatic cave if it were not for its clear genetic relationship to the inclined tubes at each end of it.

Consequently there is a problem as to why deep phreatic caves should maintain horizontal courses when there is no geological control adequate to hold them at a given level. In some cases the evidence makes more sense. Flow markings in Wonder Cave show that water entered from Hidden Valley, and for 400 metres descended into Gunung Api along phreatic rift passages, until at a depth of 90 metres. From that point the flow ascended a steep tube to regain all the lost height and intersect a massive, nearly horizontal phreatic passage trending east to west. The water appears to have taken this upward course as the easiest way to join an established drainage route.

The most dramatic deep phreatic feature yet found in the Mulu Park occurs in the Dune Series of Clearwater Cave (fig. 4). The far passages from the Troll Cavern area descend gradually along beds dipping eastward until they unite with a joint-controlled phreatic series in Great Wall Chamber. The original exit for the combined waters is a vertical phreatic lift, 60 metres high and 20 metres in diameter located on a pair of cross faults. Above it, the nearly horizontal Dune Series passages are in beds dipping northwest and at the same level as Revival Passage. The Dune and Revival passages are segments of a massive horizontal tunnel whose origin is ascribed to the shallow phreas. They are now separated by a boulder choke and the cavers' route around this is a series of smaller phreatic tubes rising 50 metres above the roof of the trunk passage. If the horizontality of the trunk passage was due to the influence of the original water table, there seems no reason why the cave should have developed 50 metres below water level.

It would seem that there is no clear dividing line, at least within the caves of Mulu, between shallow and deep phreatic development. Consequently it is not always clear how water tables can have controlled horizontal development of phreatic caves - which are so common in the Mulu Park and lack any geological control over their altitude.

Water Table Caves

The various small limestone towers protruding through the alluvium of the Melinau Plain contain a profusion of foot caves which are clearly attributable to water table solution. Their main diagnostic features are perfectly flat rooves cutting through the steeply inclined limestone bedding. Rounded roof pendants and horizontal wall notches are also typical. Some occur at present river levels, and are therefore dry or submerged depending on river stage, while others are fossilised but still show correlation with terraces in the alluvium (fig. 6). Bat Cave has over half the limestone eaten away at its main level, and it is clear that tower collapse is the inevitable result of prolonged foot cave development.

Foot caves also occur along the edge of the main limestone massifs, but their development is obviously limited by the fact that solutional attack can only take place on one side, in contrast to the more effective perimeter erosion of the towers. A feature of the caves in the massifs is the proliferation of networks of passages where they break out to the edge of the alluvial plains - best seen in the Goldwater Series of Clearwater Cave and the northern inlets of the Tarikan River Caves. These horizontal networks are too easily viewed as extensions of the foot caves. However, closer examination shows that they are clearly different. Their passages are a mixture of horizontal and inclined phreatic tubes, keyhole passages and simple vadose canyons. The abundance of horizontal phreatic tubes at past and present levels of the alluvial plains does suggest a water table control, but the presence of phreatic roof pockets and the modern mainly vadose drainage both show that their origins are much more complex than simple water table solution.

Water level notches are common in the walls of the Mulu caves (Plate 1, fig. 3 and Plate 2, fig. 1). The horizontal grooves may be recessed up to 6 metres into the walls and are mostly about 2 metres from floor to roof. Their inside ends are curved, often semi-circular, and generally smooth. Active notches are conspicuous in Cave of the Winds and Deer

Fig. 4. Projected section of fossil phreatic passages in Clearwater Cave, with a vertical scale exaggeration of x 5. Most passages are roughly level and may, therefore, be shallow phreatic, but there is a major phreatic lift midway along Dune Series. Original current flow was right to left. The steep links from Revival to both Sheer Delight and Volcano Series may be of later origin.

Fig. 5. Projected section of fossil deep phreatic passages in Tiger Foot Cave, with no vertical scale exaggeration. The steeply inclined tubes are evidence of an ancient deep phreas, but there is no other evidence of the fossil water table level.

Fig. 6. Sketch section through the isolated limestone towers and their foot caves in the Melinau Plain. The scale is only approximate, and Batu Kelawar is in fact about 100 metres further from the main river. The only limestone outcrops are on the emergent hills, and the distribution of limestone beneath the alluvial sediments of the plain is unknown. The dotted line marks the normal high water level of the river, when much of the forest plain may be semi-inundated.

Cave, while fossil notches are common in the higher walls of the active caves and also occur in some much older abandoned caves such as Clearwater's Revival Passage. They are notably absent in the Tarikan Caves and do not occur at the present water level of the Clearwater River; it may be significant that the best active notch is in the Cave of the Winds river passage which is so very prone to back flooding by waters from the alluvial plain. The well developed notches right through Deer Cave suggest that similar floodwater may have played a role in the enlargement of this enormous cave from its initiation as a series of phreatic routes. Though notches are common in the caves they appear to be only minor forms of wall modification; they are cut into both phreatic and vadose caves and their presence cannot be taken as any indication of water table origins of the caves themselves.

Probably the longest set of traceable water level notches occur in the Snake Track and Sheer Delight passages which form the lower fossil level in the northern reaches of Clearwater Cave (fig. 7). These passages combine to form a single old drainage route. They are very nearly level and meander around in plan form though generally following the strike of the limestone. Their morphology is dominantly an elliptical phreatic tube 3-5 metres high and 5-10 metres wide. The smooth cross section is, however, broken by typical water level notches which are traceable in one or both walls over much of the passages combined length of 1200 metres. The northern end of Sheer Delight descends gently and loses its wall notches before dropping into two deeper phreatic loops. Except for this northern section, the almost level line of the passage suggests that it may have formed at a past water table (which had a gradient of 1 in 340, unless the passage has since been tilted by earth movements). This is in marked contrast to the higher phreatic tubes of Revival and Dunes, in the same cave, which, being sloping and stepped, are only approximately horizontal and are assigned to a shallow phreatic origin.

If Snake Track and much of Sheer Delight are true water table caves, the wall notches may represent the normal water table while their arched roofs must have been corroded during periods of flood stage. Ascribing the lower levels of Clearwater to water table development gives a new significance to the Volcano Series - passages at a similar level below Revival but a little further south. There is some evidence to relate Volcano and Sheer Delight as being parts of the same genetic unit since the Wells Series (branching off Snake Track) ends in unexplored inclines near Volcano, and they do occupy very similar structural positions and are of comparable size. Volcano Series consists also of segments of horizontal phreatic tube, but the segments occupy four different levels and as they appear to comprise merely one drainage route they can only be phreatic and not water table controlled.

Their similarity with Snake Track and Sheer Delight suggest that there is little to distinguish water table and phreatic caves, as already seen in the inclined end of Sheer Delight. Perhaps the wall notches in Snake Track are so long just because the cave is so close to horizontal - in which case the notches lose their value as evidence of water table origins (as opposed to modifications).

Vadose Caves

Due to the fact that the Melinau Limestone extends well below base level, major drainage routes have developed in the phreatic zone, and vadose cave development has only been superimposed on a network of older phreatic caves. The only major explored vadose cave in the Mulu Park is the Clearwater River Passage downstream of River Junction, and even this has a phreatic tube 30 metres up in its roof. The inlets from the alluvial plains to both the Tarikan and Goldwater systems contain some fine meandering vadose canyons, but in most cases are merely slots in the floors of older phreatic tubes. Clearly in such a mountainous karst an extensive vadose network must exist to carry surface rainfall down to resurgence levels, but little of this has been explored. Steeply descending active vadose routes have been explored as minor side passages in most of the large caves, those in Green Cave being the most notable; in addition, the great shaft of Solo, which must connect to enormous avens in the underlying Clearwater Cave, may give just a hint of the scale of vadose development yet to be revealed in the Mulu Park.

CONTROLS OF CAVE DEVELOPMENT

Geological controls

The exceptionally massive and pure Melinau Limestone, shale free and containing only widely spaced bedding planes and fractures, appears to offer few structures capable of influencing the patterns of cave development. This is, however, not the case. The water table foot caves show a classic disregard for geological detail, but a large proportion of the dominant phreatic trunk caves are aligned on bedding planes - mostly following the strike but locally climbing steeply on the dip. No pattern of lithological variation and control was recognised during the rather high-speed surveying programme, but some clear contrasts in passage shape do occur. In Tiger Foot Cave the strike-oriented phreatic passages have some very fine circular cross sections with the guiding bedding planes barely visible as small wall grooves, but in Clearwater's Inflation Passage a similar-sized phreatic tunnel has a cross sectional shape of a thin lens drawn out along the inclined bedding. Of cave passages cutting across the bedding, the Cave of the Winds river passage shows remarkably little effect by the geology while the genetically similar Tarikan River Cave has picked out every detail of the geological structure. At present it is unclear if it is just the scale of lithological variation, or if it may also be the hydrological environment which determine the extent of geological control over the cave patterns.

Joints and faults have an influence over morphological detail in nearly all the caves. The cave surveys (Brook and Waltham, 1978) show some of this, but the large scale of the passages and the small scale of the surveys serve to obscure many of the finer points. Partly aided by the more reasonable size of many of its passages, the Tarikan River Caves show a very close relationship to geological structure (fig. 8). Numerous vertical joints, with the main set only slightly oblique to the strike of the dipping limestone, exercise a tight control over the pattern of all the side passages and inlets, and a fault has an even greater influence over the line of Fault Gallery (not on fig. 8). In contrast, the largest passage, the partially drained phreatic tube containing the main river, cuts through the joint system with little deflection and only wall notches marking the joint crossings. The greatest effect of geology on the river passage is at the sumps, all of which are created where the passage plunges down with a bedding plane roof, and then emerges downstream up a vertical joint face.

From surface data, the main joint trends along the limestone outcrop appear to be roughly parallel to the strike, though the Taikan Caves reveal a much more complex structure. Horizontal phreatic caves, such as in Clearwater, could, of course, be guided by a bedding plane strike joint intersection, but the underground surveys to date do not support this possibility.

Fig. 7. Extended section of the Snake Track and Sheer Delight passages in Clearwater Cave, with a vertical exaggeration of 5. Dashed lines mark the preserved wall notches which may suggest that most of the passage was formed at an old water table. Flow was originally from right to left, and the notches maintain a downslope gradient of 1 in 340, though the statistical value of this figure must be viewed in the light of the grade 4 survey on which the section is based.

Fig. 8. Simplified plan of part of the Tarikan River Caves, with elements of the structural geology added to show relationship between geology and cave development. (Adapted from survey originally drawn for "Caves of Mulu").

Water table control

The role of the water table in controlling the overall patterns of cave development remains open to question. Preferential solution at the air-water interface has clearly dictated the form of the foot caves in the isolated limestone towers, but that is a special case. Within the main cave systems which penetrate the larger limestone mountains, the water table appears to have had only a modifying, as opposed to controlling, influence. With no evidence as to the depth of water under which the dominant major phreatic tubes formed, it is unclear what influence the water table had on the development of most of the Mulu caves beyond ensuring their phreatic morphology owing to the great depths beneath the water table to which the limestone extended. In the modern active systems, the water table level is dictated by the structure of the older invaded phreatic tunnels - notably in the Tarikan River Caves and in Clearwater II, upstream of the first sump.

Floodwaters from the alluvial plains, themselves within the range of water table fluctuations, have created the mazes of inlets in the marginal zones of the hills. This may represent a type of water table control, but it is noticeable that it does not extend far into the hills. Fossil systems of similar origin have only been found in the Tarikan Caves at levels up to 20 metres above present base level. It may be that more comparable systems await discovery, but it is equally probable that their restriction to the marginal zones of the hills ensures that they do not survive prolonged erosion where hillslope retreat matches base level lowering. Within the hearts of the mountains, the water level notches, cut in some of the old phreatic tubes, do not have associated with them mazes of side passages such as occur on the swamp margins. Water table influence appears to be minimal over the majority of the cave environment.

Topographic and hydrologic controls

Drainage of the Mulu karst has always been influenced by the broad pattern of topography dominated by non-carbonate rocks. The sandstone massif of Gunung Mulu lies to the east of the limestones and presently rises to over 1000 metres clear of the highest limestone summits, while the Melinau Plain to the west is just part of a very extensive lowland. In addition, the River Tutoh, cutting across the southern tip of the limestone outcrop, lies in a major valley which controls the regional base level. Consequently drainage of the limestone is, and always has been, either to the west or south - except at the northern end of the limestone where the River Medalam drains northwest, and where terrace slopes suggest that outlet water from the Melinau Gorge may once have flowed that way too and joined the Medalam.

This topography has produced two discrete supplies of allogenic water into the limestone, to combine with the very sizeable input from rainfall direct on to the karst. Firstly, there is drainage from Gunung Mulu on the east side, and much of this meets the limestone at levels well above potential outlet levels. Secondly, floodwater drainage from the Melinau Plain commonly enters the limestone but can nowhere have any considerable gradient to resurgences which themselves feed back to the rivers of the Plain.

Early trunk drainage routes within the limestone were established along the strike draining principally towards the southwest. This is clearly seen in the line of the Green and Deer Caves which appear to have carried the waters of what is now the Melinau Paku during their development. The same line was initially taken by the Hidden Valley water,which early on drained through Prediction Cave and along a course probably marked by some vast cave entrances seen from the air but not yet from the ground in the area between Prediction and Tiger Caves. The main high level tunnel in Clearwater Cave is again on the same line, and its size suggests that at least part of the River Melinau was responsible for its development. It is not clear whether this water originally sank underground upstream of the Melinau Gorge or flowed through an ancestor of the gorge and then only entered the cave from a higher level of the Melinau Plain.

The existence of these large phreatic caves suggest that the River Tutoh was established as the primary drainage route long before the River Melinau assumed its present role. The pattern of southerly cave drainage could only have been selected if the Melinau Plain had not existed, or at least had been at a level substantially higher than the contemporaneous River Tutoh. The next stage in the development of the karst must have been the lowering of the Melinau Plain and the cutting of the three valleys which now cross the limestone outcrops - those of the Rivers Medalam, Melinau and Melinau Paku. Though these three valleys are now cut low enough to have fossilised the old phreatic caves, it is

impossible yet to relate the successive chronological stages of the valleys' downcutting with the old south draining trunk caves. For example, the Hidden Valley water could have once drained into the Melinau Paku valley, or it could have continued through into the Green - Deer drainage line; only further exploration will resolve these points.

A consequence of the further lowering of the Melinau Plain, relative to the altitude of the limestone's eastern margin, was the re-orientation of the surface waters in taking the steeper gradients across the limestone to the Plain. The Hidden Valley to Clearwater river, and also the Tarikan River, drain westwards and cut across the line of older fossil caves. In Cave of the Winds, even a distributary of the Melinau Paku has taken a short cut west towards the Melinau.

This three stage sequence of cave development is of course a gross simplification. There are many complications and a more complete genetic history will only follow more exhaustive cave exploration. There are major missing links: no major high levels have yet been found above the Tarikan River, and an enormous entrance 500 metres up in the north wall of the Melinau Gorge vertically above Tiger Foot Cave indicates the scale of caves awaiting exploration in Gunung Benarat. There are some complications already hinted at: wall scallops in Green Cave indicate that it once carried a northerly flow - this could have been water from the Garden of Eden draining to the Melinau Paku but how it related to any earlier opposite flow is unknown. It is also unclear yet what role was played by the segments of huge east-west phreatic tunnel found in Wonder Cave, and again how the different levels in Clearwater Cave relate to each other and adjacent caves.

The high altitude of the phreatic tunnels in Wonder Cave, and also their profusion of calcite deposits, suggest that they are among the oldest of the caves so far discovered in the Mulu Park. No absolute dating of their stalagmites has been done, and the scarcity of dated surface features nearby makes estimation of their age difficult. Interpolation of levels of terraces and planation surfaces described by Liechti (1960) imply that Wonder Cave must date from the early Pleistocene or even the Pliocene. With the tectonic activity of the area through the Pleistocene and the high erosion rates, it would then be reasonable to place even the whole of Mulu's phenomenal cave development within the rest of the Pleistocene.

The segments of genetic history revealed by the caves explored to date, do show a cyclic pattern of development. The first stage is purely phreatic, though at what depth is uncertain and probably variable. Following a lowering of base level the cave drainage adjusts by cutting vadose canyons or opening new lower levels of phreatic development. A third stage then follows when a stable water table is established and is reflected in an unknown extent of true water table cave development. The main river passage of Clearwater Cave shows all three stages: it has the remains of a 20 metre diameter tube in its roof, and beneath this is a vadose canyon at least 20 metres deep, in the walls of which water level notches have been cut most conspicuously about 5 metres above present river level. Though not so neatly domonstrated elsewhere, this phreatic to vadose to water table sequence appears to have dominated through a cyclic history of the Mulu Park caves, with each cycle controlled by resurgence levels within the contemporaneous landscape.

SPELEOTHEMS AND OTHER DEPOSITS

Calcite, in its many forms typical of cave deposits, is widespread in the caves of Mulu, though, with the exception of Wonder Cave, it is normally not in the great abundance commonly associated with tropical caves. On the other hand Wonder Cave contains an almost incredible profusion and variety of speleothems and is an outstandingly beautiful cave.

As is typical of most caves, stalagmites, stalactites and flowstone dominate in the Mulu caves and there are also fine crystal and gour deposits. More unusual is the large proportion of cave coral which, notably in Green Cave, covers vast areas of walls and floor to the extent that the first explorers had no choice but to crunch a route through merely trying to avoid the better sections. Stalactites are nearly all externally thickened, and straws are generally lacking, reflecting the tropical climate of the area. Helictites are also generally rare, except in a few passages in Wonder Cave where they occur in extraordinary profusion and many individual helictites project a metre from vertical walls.

A cave deposit so far unique to the Mulu caves is the calcite fan (Plate 2, fig. 3). These fans were first found in Wonder Cave, where beautiful examples occur in profusion. Later, more fans were found in Tiger Foot Cave though these are not as delicate as those in Wonder Cave, and so far fans have not been found elsewhere. They also appear to be unrecorded from any other caves in the world. Each fan consists of a thin-walled conical cup of calcite, rarely complete around the circumference as they grow on steeply sloping walls and floors and are attached on one side. The internal angle of the cone apex is relatively constant at around 30°, and most fans are between 10 and 20 centimetres tall. Their walls are vertically folded and horizontally banded, and their interiors are filled with tangled masses of cave coral. Individually occurring fans are rare, and they tend to form in great terraced banks with the upper fans commonly growing from the inside rear of the ones below. The origin of the fans is unknown, but they appear to be a type of splash or spray deposit. It could be significant that the fans have only been found in the two oldest caves which lie at greatest depths beneath the surface.

Gypsum occurs as selenite needles in many of the caves, but the most profuse and well developed gypsum is in the dry zones of the two old and deep caves - Wonder Cave and Tiger Foot Cave. In these caves the selenite is in larger and more complex crystal forms and is joined by spectacular wall displays of gypsum flowers. The best forms are all in Wonder Cave and add to the beauty of this quite remarkable cave. In the entrance passages of the same cave, just below the Passover, are massive crudely stratified deposits of fine grained huntite - magnesium calcium carbonate (Laverty, pers.comm.). Similar stratified floor deposits are now preserved in the roof of a re-excavated phreatic tube northeast of River Junction in the Clearwater Cave. These have not been analysed; they are thought to be gypsum but could also be huntite. The origin of these bedded deposits is unknown, but in both cases is not related to any guano deposits comparable to the gypsum in Niah Cave (Wilford, 1964).

Clastic deposits - both alluvial and residual - occur in all the caves, and their distribution may well relate to the patterns of river terraces on the Melinau Plain, though detailed mapping to reveal this has not yet been carried out. Guano has accumulated in vast quantities in Deer Cave where the bat population may approach a million, and most of the roosts are not over active streamways. Swift guano is much more widely distributed, as the birds fly for greater distances into the caves than do the bats. The less gregarious habits of the swift ensure however, that their guano never accumulates on the scale of that in the bat caves.

The minerals of the Mulu caves are not restricted to calcite, gypsum and phosphate. Numerous other minerals have been identified by Martin Laverty of the R.G.S. Expedition geomorphology team, but their description awaits further study.

CONCLUSION

The suite of caves in the Gunung Mulu National Park is among the finest in the world, in terms of both size and sheer spectacle. The explorations of 1978 have only started to reveal the extent of these caves, but already some unusual features of them have become apparent. Even at this stage it is clear that the caves of Mulu must contribute data to any thoughts on cave genesis. As yet, Mulu cannot provide conclusive evidence, but there are major implications in at least three areas:-

1) The great horizontal or sub-horizontal phreatic tubes mostly have an uncertain relationship to their contemporaneous water table, and raise questions on the distinction between shallow and deep phreatic cave development.

2) Water table solution is a major process around the limestone margins of the alluvial plains yet appears to play a decreasing role further into the limestone massifs, and it is unclear what significance the water table has played in determining the initial patterns of cave development.

3) The vast dimensions of Deer Cave and its spatial relationship to the cliff-ringed Garden of Eden (Waltham and Brook, 1980) may indicate a greater importance of collapse in developing surface karst features than is commonly assumed.

Based only on the initial surveys of the caves made during 1978, this paper cannot provide firm conclusions in respect of these points. It is instead intended to stimulate thought on cave genesis, and it is anticipated that the next phase of exploration, survey and study, on the 1981 expedition, will reveal more of the significance of the very remarkable caves of Mulu.

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APPENDIX: MALAY AND ENGLISH CAVE NAMES

As the caves were explored they were all given English names, and these have been used in this paper. The original names have been translated into Malay, and these translations should be regarded as the correct names for the caves:

Deer Cave	-	Gua Payau
Deer Water Cave	-	Lubang Sungai Payau
Mayday Cave	-	Lubang Darurat
Snake Cave	-	Lubang Ular
Green Cave	-	Lubang Hijau
Cave of the Winds	-	Lubang Angin
Clearwater Cave	-	Gua Air Jernih
Solo	-	Sendirian
Tiger Cave	-	Gua Harimau
Prediction Cave	-	Lubang Ramalan
Wonder Cave	-	Gua Ajaib
Tiger Foot Cave	-	Lubang Rendah Harimau
Tarikan River Caves	-	Gua Sungai Tarikan

The spellings of Tarikan and Terikan, and of Gunung and Gunong are somewhat interchangeable though in each case the former is now regarded as correct.

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THE BIOLOGY OF CAVES IN THE GUNUNG MULU NATIONAL PARK, SARAWAK

by Philip Chapman

Abstract

Eight of the vast caves of Gunung Mulu are populated by an abundant fauna of bats, swiftlets, snakes, crabs, crickets, spiders, earwigs, wasps, flies, mites, isopods, amphipods, centipedes, millipedes, beetles, cockroaches, moths and other crustaceans and insects. Many of these depend on the mounds or beds of guano scattered through the caves. Fish and prawns inhabit the pools. Occasional vertebrate visitors include porcupines, deer and pigs. A brief review of the ecological relationships is included.

INTRODUCTION

During a twelve week visit to the Gunung Mulu National Park in 1978, I was able to visit and to collect in a number of caves. This paper describes the fauna of each cave. No attempt is made to give a systematic list of cavernicolous species or to discuss their origins or zoogeographical affinities, as these will form the subject of a future paper.

Most collections were made by hand using forceps, paintbrush or aspirator. Pitfall traps were also used (preservative-saturated picric acid solution) and were baited with various combinations of tinned fish, meat, cheese, jam, damp biscuit, human faeces and carcasses of swiftlets. In general, these produced poor and highly unrepresentative catches, but carrion baits did attract one or two otherwise scarce species particularly in deep cave environments.

Two sorts of light traps were used. One was a purpose-built moth trap using an ultra-violet light source as attractant. This was used in Gua Payau, Lubang Sungei Payau and Gua Air Jernih, but was too heavy, bulky and fragile to be of use in remote cave passages. A second type consisted of a clear polythene jar placed over the upward-directed lamp head of a rechargeable nickel-cadmium caver's lamp. Buried to its lip in guano, this produced a yellow light source shining through the preservative solution (10% ethanol or saturated picric acid solution with a few drops of wetting agent). Insects attracted to the light flew into the liquid in the jar, to be drowned and preserved. When used with dilute ethanol as the preservative, this was by far the most effective trap used (particularly for Diptera). Using dipped beam, the battery typically lasted thirty-six hours between charges. This method was unfortunately only discovered towards the end of my stay, but was used in Lubang Sungei Payau and Gua Air Jernih to good effect.

Various physical parameters of the caves, such as air and water temperatures, percentage oxygen saturation and conductivity of cave streams, and more rarely pH, were measured using an "Environmental Multiprobe" multipurpose meter (Walden Precision Apparatus). Such measurements were made in Gua Payau and Gua Air Jernih in an unsuccessful attempt to explain the seemingly haphazard distribution of aquatic invertebrates in terms of physico-chemical properties of the water. Measurements of atmospheric CO_2 and humidity (for example in guano bed interstices) were made using Dräger tubes. These gave some idea of tolerances, particularly to high levels of CO_2, of guano-burrowing invertebrates.

Considerable time was spent in observing the behaviour of various cave invertebrates. In many cases this provided clues to feeding behaviour and prey-predator relationships. Observations of behaviour also indicated the degree of cave-adaptation of certain problematical species.

There now follows in brief an account of the various cave faunas. Descriptions of the caves are given elsewhere in this journal and in Brook and Waltham (1979).

GUA PAYAU (DEER CAVE)

A large population of freetailed bats *(Tadarida sp(p).)* occupies two main roosts close together in the southwestern part of the cave. One roost uses a relatively flat area of ceiling, the other is in a large roof pocket to the northern side of the passage. This latter roost is

close to the main nesting colony of swiftlets as shown by eggshells and bits of moss on the cave floor. The huge bat roost in the north-eastern part of the cave is probably occupied by *Tadarida plicata plicata* (dying individuals were taken on the guano bed below it). However, the guano-associated invertebrate fauna here is different from that of the two south-western beds and it seems improbable that *Arixenia esau* (hairy earwigs said to be ectoparasitic on molossid bats) should be found below only one of three roosts composed of the same bat species. Observations of emergent bats have shown that *Tadarida* sp. make up the vast bulk of bats using both entrances, so it may be that the south-western roosts are of a different *Tadarida* species, possibly *T. mops* which is recorded from the Mulu Park. Horseshoe bats (Rhinolophidae) (Pl.1,fig.1) and small (*Myotis* or *Miniopterus*) emerge from the eastern side of the north-east entrance and one or two large, fast-flying bats were seen above the streamway, close to the south-west entrance. These last might have belonged to a predatory genus such as *Megaderma*.

Because so much of it is bathed in twilight for much of the day, or perhaps because it is the only major bat cave known in the Park, Deer Cave has a very different fauna from other Mulu caves which I visited. Tineid moths and Diptera are particularly well represented, and adults, and particularly larvae,form the main food of a huge variety of predatory arthropods. Tineid larvae are preyed on by histerid beetles and parasitised by several species of wasps. Adults are preyed on by at least seven species of spiders, although tineids may not form the main food of some of these. Dipteran larvae are preyed on by three species of pseudoscorpions, each specialised for life at a different depth in the guano, by luminous centipedes, small histerid beetles and perhaps young cockroach instars. Adult Diptera are taken by spiders and pseudoscorpions. Other guanobious animals include a snail, 4 isopods, Collembola, mites, millipedes, scarab beetles and an earwig. A second earwig, *Arixenia*, has already been mentioned. This is a prime food of several predators, notably adult cockroaches, spiders and a reduviid bug. Bat carcasses and dead invertebrates form the food of a variety of scavengers, such as aderid and tenebrionid beetles and cockroaches.

The guano community powers a number of "satellite" communities in many of the caves. In Deer Cave guano is so abundant and all-pervading that there is little space available for secondary communities to flourish. However, a few species are specialised for life around the periphery of the guano beds - notably long-legged scutigerid centipedes and the rhaphidophorid crickets on which they feed.

The aquatic fauna of Deer Cave consists largely of epigean species carried into the cave by the sinking streams. However, a small, percolation-fed stream in a high oxbow to the west of the half-way kink in the cave, contains two white, eyeless, cave-limited crustacean species. One is a minute amphipod 3 - 4 mm long,the other a small crab (*Cerberusa caeca* Holthuis 1979), about 10 mm across the carapace. The crab is omnivorous and was seen feeding on the decomposing carcass of a swiftlet, which was eventually reduced to a clean-picked skeleton.

The fish found in the small stream which emerges from the south-west entrance seem to have a very wide tolerance to eutrophication. A pool to the east of the half way kink contains 2 - 3 cm of water floored by a metre thickness of poorly compacted guano. The pool reeks of ammonia and has a 48% oxygen saturation (4 ppm, 23.7°C), yet supports a dense population of fish and prawns. Apart from their much paler colouration, these fish appear identical to those of the streamway into which the pool drains. A guano pool specimen was kept alive in a tank at base camp for two months but did not develop normal pigmentation, suggesting a genetic defect. Despite this hopeful sign, no cave-adapted (troglobitic) fish were found in the Mulu caves.

Several vertebrates make (or used to make) periodic incursions into the cave in order to feed. The Sambhur deer, whose footprints are so conspicuous in the south-west entrance are now scarce and enter the cave infrequently, judging by the rarity of fresh tracks in the periodically-inundated mud close to the stream. Nevertheless, relatively fresh tracks were seen by expedition members and I saw one of these deer by the Deer Water Cave emergent stream where it meanders through the alluvial forest less than half a mile from Deer Cave entrance. Presumably the deer either use the cave as a highway between the alluvial plain and the "Garden of Eden", or they enter the cave in order to feed on bat guano (this is the belief of the Berawans). The cave has also been visited by wild pig - a pair of pig mandibles having been found in the high-level oxbow west of the half-way kink. Striped racer snakes (*Elaphe taeniura*) were seen in this oxbow and also in the south-west entrance. They presumably enter the cave to feed on roosting bats or swiftlets (Pl.1, fig.2).

Several places within the cave are used as defaecation sites by wild cats. There were civet faeces in both the north-eastern and south-western entrances and in the high level oxbow. Leopard cat footprints were commonly seen in regularly inundated mud near the stream inside the south-west entrance. Both animals probably scavenge for bat carcasses on the cave floor and may well take invertebrates also.

LUBANG ULAR (SNAKE CAVE)

The streamway contains a thriving population of large catfish, pale brown in colour due to failure of melanophores to develop normally in the darkness of the cave, but otherwise indistinguishable from surface populations of the same species. A typical "unpigmented" cave specimen was kept alive in a tank at base camp for about six weeks (it was eventually eaten by a cat), by which time it had reached a stage of pigmentation intermediate between the cave and normal surface populations. The cave population is probably prevented from developing a distinct cavernicolous genotype due to genetic swamping by individuals from a surface population which are washed into the cave when the sinking stream is in flood. The catfish in the cave probably live as general scavengers and may also feed on the abundant prawns *(Palaemon (Macrobranchium) clymene)*. These are also much more lightly pigmented than their surface counterparts.

Small percolation inlets containing crystal clear gour pools are inhabited by a small isopod *(Stenasellus* sp. nov.) which is pale pink and eyeless and may be cave-limited.

Perhaps 100 m into the cave, the passage narrows to about 50 cm with a ledge along one wall. It was here that we found a large striped racer snake (just over 2 m long). It appeared most unwilling to move, and halted further exploration of the cave until caught and removed to base camp where it regurgitated a recently swallowed swiftlet. No swiftlets roost in the passage in which it was taken, whereas hundreds roost and nest in the chambers beyond. It was therefore assumed that the snake's strategic placement in the narrowest part of the only access passage meant that it could, and did, catch swiftlets in flight. Having caught them myself one-handed in considerably wider passages, I can well believe this. However, the snake would have to do so without the benefit of sight - not an easy task!

The swiftlet roost chambers contain much guano and old nesting material, but in common with all other swiftlet guano in Mulu caves, it supports a far poorer and less conspicuous fauna than the bat guano of Deer Cave. The larger beetle species in particular are conspicuous by their absence, their place being taken by vast numbers of small aderid beetles. The large burrowing rhaphidophorid crickets and their main predators, huge sparassid spiders *(Heteropoda* sp. nov.) are very common (Pl.2,fig.1). The other main predator slots are filled by amblypygids and harvestmen. Diptera, particularly small mosquitoes and milichiid flies, form a constant suicidal cloud around any visitor's carbide lamp.

The far end of this cave contains much damp, muddy flowstone. This is the home of several cave limited, or troglobitic invertebrates. Largest of these is a huntsman spider (Ctenidae), cream in colour, with the eyes reduced to a single, probably non-functional pair. Loss of vision is compensated for by a well-developed tactile sense - the long first pair of legs are used as antennae and the animal walks on the remaining three pairs (pl.2, fig.2). Wherever the spider is found, so is a long-legged, orange-coloured troglobitic cockroach *(Trogloblatella chapmani* Roth, 1979). The association between the two species is so reliable that there can be little doubt that the cockroach is the main food of the spider, although no instances of feeding were observed. The muddy flowstone is also the home of a minute troglobitic spider (probably an ochyroceratid) which builds a delicate sheet web in which tiny Collembola are taken. The troglophilic campodeid Diplura, and small polydesmid millipedes also found here, probably escape capture due to their larger size (though young Diplura may be taken).

LUBANG HIJAU (GREEN CAVE)

I did not look at this cave very closely and it might well repay diligent collecting. There is a large swiftlet colony, again preyed upon by striped racers *(Elaphe taeniura)*. A large population of bats of unknown species inhabit the cave entrance, but the swiftlet roosts extend throughout the cave (though not close to the damper north east entrance). Curious scratches, often in parallel sets of four, about 1 - 1½ cm apart (4 cm total width) occur on soft calcite and mud slopes throughout the cave. They conjured up fearful visions of coming

face to face with a giant monitor lizard in a narrow passage!

The bouldery, guano-coated chambers mid-way through the cave contain a very large population of huge sparassid spiders *(Heteropoda* sp. nov.) which feed on the burrowing cricket *Rhaphidophora oophaga*. A smaller cricket, *Diestrammena sarawakana*, is abundant, as are aderid beetles and tineid moths, but both are vastly outnumbered by small Diptera. Large terrestrial isopods are common on the sandy clay banks of the lower levels of the cave, together with strange, ponderous, probing, mite-like harvestmen.

Guano-floored pools a couple of thousand feet into the cave contain a flourishing population of the troglobitic crabs, *Cerberusa caeca*, which were encountered nowhere else in this cave.

In nearby Centipede Cave, the large scutigeromorph centipedes occasionally encountered in Green Cave have replaced the sparassid spiders as the dominant predators. This is the situation also in Deer Cave and in Niah Great Cave. In general, the centipede tends to predominate close to entrances, whereas the spiders rule the dark zone. It is interesting to speculate whether this situation may eventually result in the isolation of the spiders in the caves, and thus initiate troglobite evolution.

LUBANG DARURAT (MAYDAY CAVE)

This cave differs from all others that I visited in that it contains virtually no guano. About five pairs of swiftlets nest a few feet inside the tiny entrance. The small amount of guano below their nests supports a few typical guanobious invertebrates, including a second sparassid spider species, half the size of the huge species common in Green and Snake Caves.

Beyond the immediate vicinity of the entrance, the cave offers a large expanse of damp mud floor, drip-fed gour pools and glistening flowstone - precisely the sort of environment in which troglobites might be expected to flourish. Unfortunately, the cave was visited only briefly, but three troglobitic species were taken - the huntsman spider and cockroach also found in Snake Cave, and a strange, white, slug-like millipede. Tracks of a small crab were common on the smooth silt floors of gour pools in the upper level of the cave, but no living crabs were seen.

LUBANG SUNGEI PAYAU (DEER WATER CAVE)

There is a sizeable colony of horseshoe bats and swiftlets in the cave. Their guano is removed by the stream except on a pile of boulders about 100 m inside the cave where it has accumulated to form a highly populated bed. Access is easy and there is much to see. During the second half of April and May, many swiftlet nests, built at eye-level in wall pockets, contained eggs or chicks in all stages of development. Thus in one visit it was possible to observe and photograph the whole maturation process of swiftlet chicks.

The dominant predator of the guano beds is again the huge sparassid (Pl.2,fig.1) *Heteropoda* sp. and its main prey is as usual the large burrowing *Rhaphidophora oophaga*. *Diestrammena sarawakana* is abundant, and amblypygids and big-headed white juliform millipedes are common. The coprophages are dominated by small Diptera and aderid beetles, but tineid moths are surprisingly absent. Fast running, strikingly coloured carabid beetles forage on the guano, perhaps for dipteran larvae. There are two species, one electric blue with pale yellow legs *(Hyphaeron* sp.), the other boldly patterned in yellow and black *(Anaulacus sericipennis)*. Other less conspicuous guanobia include a tiny, highly ornamented, coral pink isopod *(?Hybodillo* sp.) small, predatory Schizomida, and harvestmen.

Between periods of flood, while the river is in low flow, guano accumulates among wet boulders and gravel along the edges of the streamway below swiftlet nests. It is an energy rich, but unstable and unpredictable habitat which supports three specialised species - a thysanuran, a geophilid centipede and an earwig.

The streamway itself contains a wealth of life, but most species are accidentals, washed through from the Deer Cave end. They include catfish and numerous aquatic insect larvae, notably mayflies and stoneflies.

GUA AJAIB (WONDER CAVE)

A handsome species of gecko *(Cyrtodactylus* cf. *cavernicolus)* (Pl.2, fig.3) inhabits the first small entrance chamber, together with a long legged amphibious crab *(Cerberusa tipula* Holthuis, 1979) and the cricket *Rhaphidophora oophaga*. Just beyond the first 30 m pitch is a sizeable chamber containing a small swiftlet colony. The swiftlet guano supports

PLATE 1

MULU CAVES BIOLOGY

1. Roosting bats link the forest and cave ecosystems by transferring food in the form of faeces.

2. Snakes penetrate deep into caves where they catch bats and swiftlets whether in flight or roosting and swallow them whole.

3. This undescribed ochyroceratid spider is unusual for a troglobite in spinning a complex web.

1. The fearsome huntsman spider *Heteropoda* sp. rules the guano beds.

2. This undescribed troglobitic ctenid spider compensates for loss of vision by using its first legs as antennae.

3. The Mulu cave gecko *Cyrtodactylus* cf. *cavernicolus* is a twilight zone specialist as shown by its huge eyes.

the usual fauna of sparassid spiders, rhaphidophorid crickets, aderid beetles and Diptera - plus one unusual inhabitant - a large, sandy-brown scolopendrid centipede with reduced eyes. This animal was observed digging pits in the guano with its first pair of legs, inserting the anterior part of its body, removing it and then repeating the operation a few centimetres further on. Presumably it was searching for prey, perhaps young *Rhaphidophora* in their burrows, or other guanobious insect larvae or pupae.

The tortuous, descending passages beyond the roost chamber contain harvestmen, white and marbled grey isopods, troglobite cockroaches and even an occasional *Rhaphidophora*. The fauna becomes more and more scarce until the start of the ascending gypsum passage, from which point onwards practically no life is seen. The low, wet junction just before this point contains a wealth of skeletons, including those of eight snakes, two civets and several bats and swiftlets. This suggests that there may be a sizeable cave passage directly above this junction, probably with its own separate entrance and large population of bats or swiftlets. The lower passage known to us may act as a trap from which animals entering or falling from the higher passage cannot escape.

Three species only were seen in the far reaches of Wonder Cave. Several troglobitic leiodid beetles (*Ptomaphaginus* sp. nov.) were caught in a baited pitfall trap at the entrance to the Elephant's Graveyard chamber, and two immature troglobitic cockroaches were found in a small passage just beyond it. The leiodid beetles are unusual among troglobitic species in that they have retained functional wings and the power of flight, despite loss of pigmentation and reduction in eye size. The ability to fly may be essential to such tiny scavengers whose food is unpredictably and widely dispersed within huge chambers and miles of large passages. The third species was a solitary swiftlet, presumably lost, which was seen briefly in a passage just beyond the Elephant's Graveyard. It is likely that stray swiftlets which become lost in the deep cave and which eventually die there, form the main food of the leiodid beetles.

Skeletons of bats and swiftlets (and one of a large snake) were found occasionally throughout the further reaches of the cave. They were usually intact, though the bones often crumbled to powder when touched. Considerable numbers of bat bones were found embedded in flowstone in a narrow rift beyond the Elephant's Graveyard.

LUBANG RAMALAN (PREDICTION CAVE)

This cave was not looked at in great detail. There is a medium-sized swiftlet colony in the main chamber. The guanobious fauna is dominated by the usual combination of *Rhaphidophora* and *Heteropoda* (one scutigerid centipede was also seen in the main chamber), and small rhaphidophorids of the more cave-adapted species, *Diestrammena mjobergi*, are common throughout the entrance series. Flies and aderid beetles are abundant and the tineid moths are represented by a striking golden-coloured species, *Tinea porphyropa*.

The deep cave fauna, notably around the Inca Road, is dominated by troglobitic huntsman spiders and cockroaches. The skeletons of a rat and a porcupine were found close to the Inca Road, and a water-worn pig molar was found resting on the pebbly sediment floor of the low-roofed main passage. The pig tooth is almost certainly contemporary with the sedimentation period of the cave.

GUA AIR JERNIH (CLEARWATER CAVE)

By far the largest cave explored by the expedition, Clearwater also has the most varied fauna. The swiftlet population is vast, occupying much of the sixteen miles of passage known so far, with huge individual roosts at the main river junction, the great collapse chamber nearby and the chambers of the northern part of the cave. Some swiftlets are found as much as 2 km from the nearest known entrance. The guano-associated fauna includes most of the species already mentioned in this account - sparassid, pholcid and araneid spiders, crickets, Amblypygi, Schizomida, harvestmen, scutigerid and geophilid centipedes, countless Diptera, tineid moths, aderid and staphylinid beetles, parasitic wasps, ants, etc.

Almost all of the terrestrial troglobitic species found in other Mulu caves are found in the more remote passages - cockroaches, huntsman spiders, leiodid beetles, Collembola, and isopods. The isopods (Porcellionidae) are of two sorts: the large grey and white marbled type found in Snake Cave, and an equally large, but smaller eyed, white type. Different parts of the cave contain populations varying between

the two extremes, and in a small muddy oxbow off the main streamway both types are found together. This appears to be a case either of ongoing parapatric speciation, or of hybridisation between a recent troglobite and its troglophile ancestor.

Pill millipedes (Glomeridae) of at least two species occur on the limestones outside the cave and in the cave entrances. They are olive brown to grey green in colour with compound eyes. Deep within the cave (Beckoning Finger passage) live much smaller, white troglobitic glomerid millipedes with greatly reduced eyes. Even smaller, white, eyeless polydesmid millipedes live around the edges of small drip-fed pools in Inflation Passage. A second troglobitic isopod, smaller than the large Snake Cave species, lives on a small area of muddy flowstone close to Porcupine Passage in the low level of the north west part of the cave.

Tiny white web-building spiders (probably Ochyroceratidae) live between boulders and on small patches of guano in the deep cave. The larger species builds a sheet web with superficial scaffolding which is slung between boulders (Pl.1,fig.3), whereas the smaller species has dispensed with the scaffolding and spins its smaller sheet in pockets in the guano. The two species appear identical except for size and are probably very closely related.

Andy Eavis reported seeing a pale brown scorpion with long slender chelae (total length about 5 cm) on boulders in a low level chamber close to Great Wall Chamber (far north east). Subsequently Hans Friedrich caught a similar scorpion in Lubang Angin. It is a small-eyed troglophile.

The aquatic fauna of the cave river is not particularly rich, probably because it is fast-flowing and largely floored with clean bedrock limestone which offers little shelter from the scouring effect of suspended sand particles, particularly during the frequent floods. The fauna consists of gasteropods, crabs (*Sundathelphusa tenebrosa*, Holthuis, 1979), prawns and catfish.

As is usual in tropical caves, the most interesting fauna is found in small, shallow, mud-floored drip or trickle-fed pools. These contain troglobitic crabs or tiny troglobitic anthurid isopods (*Cyathura* sp. nov.).

As well as containing a large swiftlet population, the cave is frequented by several other vertebrates. Bentwinged bats (*Miniopterus* sp.) roost in small roof pockets in a high level oxbow above the main streamway. I also saw a couple of large unidentified bats (wingspan approx. 40 cm), and a few unidentified horseshoe bats in this region. Striped racer snakes (*Elaphe taeniura*) were seen in one of the south western entrances, near the choke at the start of Inflation Passage, in a chamber above Revival passage, on the Snake Track, and just inside one of the northern entrances. We were astonished to discover that these snakes can produce a hoarse mewing warning call when alarmed (heard distinctly by at least three of the team on more than one occasion). A pale green and brown banded gecko was seen on a stalagmitic wall near one of the northern entrances close to the Snake Track. This "Snake Track" is a clearly defined band, 5 - 10 cm wide, which runs from two small entrances for about half a mile into the cave, ending near a muddy chamber containing a large swiftlet roost. The track appears as a smooth, polished ribbon running over mud and flowstone. Where it crosses mud, it is gently rippled (ripples about 1 cm apart with crest of the ripple aligned across the track). It was generally thought by the team to have been formed by the passage of innumerable snakes over a long period, and indeed a snake and two rats were observed following the track on separate occasions.

For part of its length, the Snake Track runs along a fairly straight, subway-like passage called "Porcupine Passage" because of its wealth of porcupine-introduced material. At intervals the track is flanked by shed quills which are usually covered with the small, white, stalked fruiting bodies of a fungus, and every once in a while piles of gnawed remains of large nuts are found. It would be most interesting to know why porcupines should wish to travel up to half a mile into a cave, carrying large nuts with them. Further evidence of porcupine habitation is seen in small piles of squarish chunks (typically about 1 cm x 1 cm x 2 - 3 mm thick) of slimy, leathery, olive-green plant material which were found close to one of the northern entrances. Just inside another entrance I found about a dozen neatly dismembered swiftlet wings lying close together on the cave floor. Lord Medway suggests that the predator involved may be a bat of the genus *Megaderma*. *M. lyra*, a Malayan species not recorded from Borneo, behaves in precisely this manner, carrying its prey to a feeding roost and there consuming the body and rejecting the wings (Medway, 1960).

Another interesting case of attempted predation of swiftlets was observed in the narrow link to Inflation Passage. Here a large cricket *(Rhaphidophora oophaga)* was seen wrestling with an egg in a swiftlet nest. It lifted and turned the egg using its first pair of legs and mouthparts, and appeared to be trying to bite alternately into each end of the egg or to crack it against the cave wall. It remained unsuccessful for the five minutes or so during which I watched. It seems probable that newly hatched chicks would fall prey to these powerful omnivores.

A live tortoise was rescued from a sand bar some distance into the cave. It had presumably been caught in the severe floods of the previous week and had been swept into the cave by the swollen Goldwater stream. A deer and wild pig were less fortunate. Their bones were found at the bottom of a thirteen metre pit, a hundred metres or so inside the south west entrance.

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LIVERPOOL UNIVERSITY EXPEDITION TO JAMAICA

Compiled and edited by D. A. McFarlane

During summer 1977, five members of the Liverpool University Potholing Club spent six weeks working and exploring in the caves of Jamaica. The team consisted of Don McFarlane, John Dye, Malcolm Macduff, Mike Roger and Barry Williams, all of whom contributed to this report.

The expedition base was at Troy, where the villagers are owed a debt of gratitude for their hospitality. This placed the expedition in the heart of the cave region, and a number of new caves and shafts were discovered and explored (fig. 1). The main discovery was the Still Waters Cave, located near Accompong, where 11,800 feet of passages were explored during the second half of the stay in Jamaica.

Studies were carried out not only in the cockpit karst around Troy, but also in the Hellshire Hills and Portland Ridge karsts on the south coast of the island. In addition, a flying visit was paid to the John Crow Mountains near the eastern end of the island. A single stalactite-adorned cave (Hog House Hole at Map Ref. 763 445) was discovered. Though only 30 feet long, this is significant, as it is one of the very few caves known in the John Crow Mountains, even though they consist of massive limestone in a high relief terrain with a high rainfall.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

Jamaica consists of two distinct geological units which Zans (1962) named the Eastern Mountain Mass, mainly consisting of non-carbonate rocks, and the Main Block, consisting mainly of carbonate rocks which cover nearly two-thirds of the Island (fig. 2). It is in this latter area, where the karst has its maximum expression, that the expedition was based.

During the Middle Eocene, a marine transgression took place over the main block and initiated a series of cycles of largely carbonate sedimentation. During this period the Yellow and White Limestones were laid down and it is within these lithologies that cave development is most common. These two groups can be sub-divided into nine mappable formations, three of these representing the deeper water facies with the other six the shallow water facies. The Yellow and White Limestone groups are distinguished on the basis of percentage carbonate composition and purity. The White Limestones have a carbonate composition in excess of 99%, whilst the less pure Yellow Limestones have an average content of 93%.

Caves discovered during the expedition were found in both the Yellow and White Limestone groups. Marley Stalactite Cave for example is formed in the Troy-Claremont Limestone Formation of the White Limestone, whilst the nearby Wilson's Run Cave is formed in the Chapelton Member of the Yellow Limestone. Whilst the explored caves were found in both Yellow and White Limestones, the explored shafts were found solely in the White Limestone, e.g. The New Hall and Newport-Blenheim areas. The mode of formation of these 'cockpit' shafts is debatable and, whilst some show definite evidence of collapse, others show evidence of formation by solution only, e.g. The New Hall Sink Hole 4. The reader is referred to Smith, Drew and Atkinson (1972) for hypotheses of shaft development.

Many of the caves explored are associated with river and stream sinks. Since the Yellow and White Limestones in general drain rapidly, surface drainage may be sporadic, only occurring during storms at the base of cockpits with an appreciable cover of alluvium. In larger depressions with a greater area of impermeable cover (either alluvial or, in the case of caves along the Central Inlier, impermeable Cretaceous rocks) permanent rivers may occur giving rise to larger active cave systems.

In the case of Still Waters River Cave, the course of the river underground is largely joint-controlled, vividly illustrated by the plan of Tardis series. The general trend of the system is down dip with little vertical development except for the large collapsed area around the Hall of Rains, possibly associated with a fault.

Most of the caves explored were in cockpit karst, as described by Sweeting (1958). Other caves such as those found in the area around Blenheim were situated in more subdued topography of the doline karst type. The greater ruggedness of the Cockpit Country and Dry Harbour Mountain areas coupled with the growth of dense wet forest make cave

Fig. 1.

Fig. 2. Generalized geological map.

exploration in these areas more arduous than exploration in the more open vegetation found on the subdued doline karst in the south.

CAVE DISCOVERIES

Wilson's Run Cave, Troy, Length 650 feet, Map Ref. 328 494 (fig. 3).

Where the road from Troy to Heading finally crosses over to the left side of the valley, a footpath strikes off to the north, and this can be followed for 300 yards to a depression with a small stream rising and sinking again on the left. The depression and stream are well known to locals as Wilson's Run (fig. 3).

The small stream rises from an impenetrable bedding plane and flows for thirty yards across the floor of the glade before sinking into Wilson's Run Cave. The entrance is large and obvious. Just inside, the passage lowers to a crawl over boulders, followed by a second wallow, and then hands and knees crawling in the stream with gravel banks on the left. After the floor drops, the stream disappears into a tube too small to follow. The main route continues over mud and gravel until the floor drops again into a pool. A crawling-size passage follows the water for 20 feet until it opens into a small chamber. The stream issues from a short passage with false floors, leading to a small cascade with water coming from an inlet above and on the right. To the left above the cascade, an easy squeeze leads to a second small chamber and 70 feet of flat-out and very aqueous crawling past an aven to a calcited boulder choke with the water trickling through impenetrable cracks.

Continuing along the main route, a boulder pile is crossed to a constriction past some gour formations leading into Rat Hall. From the far side, two passages diverge. The right hand passage ends after a few yards, whilst the left hand passage runs for about 20 yards to a mud choke, with a low inlet on the right. This was followed as a crawl to a tiny chamber with a substantial mud choke and a four-inch rift in the floor where water could be heard. Despite its short length, the cave is quite sporting and the flood risk is serious

York Shaft I, New Hall, Depth 100 feet, Map Ref. 4787 4812 (fig. 4).

A large open shaft about 300 yards south of the road, reached via a path running past two houses which are set back from the road along a short track.

The shaft is most easily descended at the south end where a descent over two ledges leads to the top of a large boulder pile. There is no obvious way on at the bottom of the shaft, and loose rocks are a constant danger. (Plate 1, fig. 1).

Berry's Sinkhole, New Hall, Depth 180 feet, Map Ref. 4863 4765 (fig. 5).

A shaft in a shallow valley behind a house with a water-tank and a rain-catcher. It lies some 250 yards to the east of the road.

A small opening leads on to a 120 foot pitch to a small ledge where the rope can be rebelayed for a second pitch of 50 feet to the floor of the shaft. The bottom of the shaft is choked with boulders and a mudbank, and there is no way on.

New Hall Pot II, New Hall, Depth 25 feet, Map Ref. 4858 4728

Some one hundred yards further along the road from New Hall Sinkhole 1, and in the next depression, was a 25 foot deep shaft measuring 30 feet in length and 10 feet in width, with no obvious way on.

New Hall Pot III, New Hall, Depth 200 feet, Map Ref 4876 4712 (fig. 6).

Just before the road deteriorates into a path, a group of houses are passed. The shaft is located on the south of the road in the bottom of a shallow depression behind these houses.

The shaft is descended as a single pitch. At 75 feet the shaft divides in two, but both shafts continue side by side to join again at the bottom at a boulder floor with no way on.

New Hall Pot IV, New Hall, Depth 105 feet, Map Ref. 4868 4719 (fig. 7).

Located to the north of the road from New Hall Sinkhole 1. A ten-foot climb amongst tree roots leads to the head of the first pitch, a narrow sharp rift. A descent of 41 metres lands on a false boulder floor with a broad ledge and choked hole 4 metres above. A small hole between the boulders (caution - these are precariously jammed) leads directly onto a second pitch of 21 metres, also very sharp, landing on a floor of rock and boulders. A very small water worn passage leads off but is obstructed by mud and rocks. The shaft was unique amongst those examined by the Expedition in that it ended in a solid rock floor with some evidence of subsequent horizontal development.

Fig. 3.

WILSON'S RUN CAVE
TROY TRELAWNY JAMAICA
B.C.R.A. Grade 5C, Surveyed JULY 1977
Surveyed by M. ROGER, D.A.McFARLANE, M.McDUFF, and J.M.DYE
Drawn by J.M.DYE
5 0 5 10
METRES
GRID NORTH
-2·0
-2·0
ENTRANCE
328
1284
1197
1186
ENTRANCE
2046
494
Reading
Troy
LOCATION MAP

Fig. 4.

YORK SHAFT I

G.R. 4787 4812
B.C.R.A. GRADE IV.

Fig. 5.

BERRY'S SINKHOLE

G.R. 4863 4765 NEW HALL, JAMAICA.
B.C.R.A. GRADE IV.

Fig. 6.

NEW HALL POT III

G.R. 4876 4712 NEW HALL, JAMAICA.
B.C.R.A. GRADE IV.

Fig. 7.

NEW HALL POT IV

G.R. 4868 4719 NEW HALL, JAMAICA.
B.C.R.A. GRADE IV.

Marley Stalactite Cave, Auchtembeddie, Length 200 feet, Depth 100 feet, Map Ref. 333 378 (fig. 8).

Difficult to find. Follow the path down into the Marley River depression. Once past the last houses start to descend, and half way down and 30 yards to the left is the entrance to the cave, beneath a small cliff located in thick bush.

Several holes lead down through large jammed boulders to the Upper Chamber. Two holes in the floor lead down climbs into the Middle Chamber, a larger chamber with much flowstone, notably some large stalactites hanging from the roof. At the very bottom of the chamber a small hole leads into the most impressive Lower Chamber. The copious flowstone assumes many forms - huge stalagmite bosses, curtains, pillars, flows and stalactites. On the right a short climb down leads to a boulder choke which can be penetrated for 30 feet before becoming impassable. (Plate 1, figs. 2 and 3).

Too Far Stream Cave, Mouth River, Length 280 feet, Map Ref. 351 544.

At the far end of Good Hope Cave Two, one emerges into Far Enough Glade and continuing northwards through the obvious gap into Guinea Grass Glade, and beyond another more spacious grassy glade is reached. The cave is situated in the latter glade opposite the point of entry where a small stream sinks beneath a low cliff.

A hole leads to a drop into a narrow vadose trench which can be followed to the left. After 30 feet a larger phreatic roof tube can be entered above the trench, but this is soon choked at either end. The vadose trench continues for 180 feet round several sharp bends until it closes down and becomes too tight immediately after a small inlet enters on the left.

Old Man's Gully, Breeze Hole, Depth 140 feet, Map Ref. 338 479.

At the end of the road towards Breeze Hole a footpath can be followed until a small path turns downhill to the right towards Breeze Hole. Just before this is reached a large depression is passed on the north of the path, and Old Man's Gully is located at the bottom of this depression.

A large shaft gives a single pitch of 140 feet against the wall to a boulder choked floor.

STILL WATERS CAVE, Whitehall, Length 11800 feet. Map Ref. 287 477 (fig.9)

The cave is located at the sink of the Tyne River near Accompong. Although the Tyne River is very small in the dry season (it can hardly even be called a river) it responds very rapidly to rain. Due notice should therefore be taken of the weather conditions and pattern at the time of year before going underground as the entrance and several parts of the streamway are low and aqueous.

During the expedition, 11800 feet of passage were explored, and the following brief description should be read with the survey. (Fig. 9).

A few yards inside the entrance are two ducks or sumps, (Plate 2, figs. 1 and 2). Between the two, the more obvious passage is a large, normally dry, flood level on the left - Gillette Passage.

Gillette Passage. This can be followed along a walking size passage (Plate 2, fig. 3) to the start of a short low canal, and then continues on through a series of low canals and short climbs to a large sump pool - the Deep. In the first section, four passages on the right lead into the Tardis Series, and just before the Deep, a passage on the left leads to the Lair of Grendel and the downstream cave.

The Grey Flood. Flowing into the far side of the Deep is a river, known as the Grey Flood. The large stream passage continues through deep pools until a junction is reached - the Parting of the Ways. To the left here is the Mersey Way - another downstream continuation of the Grey Flood. Upstream from the Parting of the Ways leads via a short section of large streamway to a complex massive rockfall with a large aven overhead - the Kaled Dome.

There are two routes through the boulder complex of the Kaled Dome. To the right in the stream leads to a large pool with the aven above and a large dry passage leading straight on into Tardis Series. The other route leads over boulders to the left to a pool where Forbidden Swamp Series enters the Kaled Dome. Both routes continue to rejoin the Grey Flood. Upstream leads in a high narrow streamway to another rock fall - the Pillars of Hercules. The stream can be followed to the right to an inlet - Sesame Passage, or to the left under a boulder arch to the upstream continuation of the Grey Flood. On the other side of the boulder pile one can descend to yet another section of streamway - the start of Forbidden Swamp Series.

MARLEY STALACTITE CAVE
TROY MANCHESTER JAMAICA
B.C.R.A. Grade 5C Surveyed AUGUST 1977
Surveyed by M. ROGER, M.Mc DUFF, J.M. DYE
Drawn by J.M. DYE
Fig. 8.
0 1 2 3 4 5
METRES
GRID NORTH
CLIFF
ENTRANCE
FLOWSTONE WALL
PILLAR
STALAGMITE

Fig. 9.

STILL WATERS RIVER CAVE
WHITEHALL
ST ELIZABETH
JAMAICA
B.C.R.A. Grade 5C
Published by LIVERPOOL UNIVERSITY POTHOLING CLUB
Surveyed AUGUST 1977
Surveyed by M.ROGER, D.A.McFARLANE, M. McDUFF, J.M.DYE, B.WILLIAMS
Drawn by D.A.McFARLANE and J.M.DYE
METRES
FEET
Grid zero is 285000/475000
Elevation of entrance 282m O.D.
Entrance GR = 285677/475836
THE RIVER
Entrance
Traced Course of Flow
Link Line 1
Link Line 2
Link Line 3
TARDIS SERIES
GILLETTE PASSAGE
Grade 3
The Deep
Lair of Grendel
Axel Passage
THE HALL OF RAINS
SUEZ
FINAL SUMP
Grid N
True N 30°14'W
Mag N 00°50'W
Mag. Dec. as at Jan 1973
Annual change 8' West
SESANE PASSAGE
THE GREYFLOOD
Sump
The Pillars of Hercules
The Kaled Dome
FORBIDDEN SWAMP SERIES
The Parting of The Ways
THE MERSEY WAY
MIRRORS OF GALADRIEL
700
600
500
400
900

Upstream in the Grey Flood leads through deep water past a couple of low sections to a swim with about six inches airspace. Just beyond this the stream appears to rise from amongst massive blocks on the right. A low section leads to a further continuation to the left to a boulder choke.

The Tardis Series is a complex series of passages connecting between the Grey Flood and the entrance area. Most are dry walking passages or crawls, but these are relieved by some long and deep pools. Sesame Passage is a very aqueous upstream route ending in a flooded boulder pile.

Mersey Way. From the Parting of the Ways the Mersey Way leads on down a short section of streamway to a rockfall. Straight ahead over the boulders leads down to a low canal and duck before the streamway gathers height until another rockfall is met. More streamway and a third choke lead to a junction, and the left returns to the streamway and a couple of lakes - the Mirrors of Galadriel. To the right, a bouldery passage leads along a section of streamway through a couple of ducks until progress is blocked by calcited boulders, where the streamway can be heard beyond.

The Lair of Grendel and the downstream cave. Just up Gillette Passage from the Deep a crawl leads off to the right into the Lair of Grendel. The crawl emerges into a large canal passage and beyond a low wet muddy crawl leads on to a large chamber - the Hall of Rains. Straight ahead through the Hall leads to a climb down into a rift taking the river. A climb onto boulders at the far end of the rift takes one out of the river. From this pool a short upstream passage can be followed to a boulder choke - this is the downstream end of the boulder choke encountered at the end of the river in the Lair of Grendel. The main canal passage straight ahead continues downstream, as Suez.

Suez consists of a long section of canal passage with a couple of active oxbows on the right and two high level dry oxbows on the left. The river eventually runs into a sump at the start of a series of boulder chambers. Up over the boulders leads to a short high level passage on the right which ends in a static canal and sump. Down between the boulders the stream can be rejoined flowing into a deep sump between massive collapsed boulders. No way can be found beyond this point.

KARREN MORPHOLOGIES IN CONTRASTING KARST AREAS

The aim of the study was to see if the shape of karren as expressed by the width, depth, length ratios differed significantly between the Troy, Portland Ridge and Hellshire Hills areas, and to establish the cause of any variations that might be found.

Descriptions of areas.

The selection of the three areas was designed to give three contrasting environments of study. The Troy area is situated in the Cockpit Country, an area of classic cockpit karst, supporting dense wet forest under a mean annual rainfall of over 250 cm. Mean monthly temperatures range from 24 - 28° C, and thus precipitation probably exceeds evapotranspiration in most months of the year. The soil cover is generally discontinuous though plant litter forms a fairly extensive cover. The sample area was underlain by the Troy Limestone, a dolomitised micrite.

The Portland Ridge area is one of subdued relief, relative to the Cockpit Country. Rainfall is in the region of 80 cm. per year with mean monthly temperatures from 27 - 29° C. Portland Ridge is covered in a thick scrub of xerophytic plants such as cacti and thorn scrub producing a discontinuous and generally thin canopy. Soil cover is sparse; the surface consists of case-hardened Newport Limestone, a micrite which has weathered to razor-sharp irregular surfaces. Evapotranspiration exceeds precipitation in most months of the year and it should be noted that on the extensive unshaded rock surfaces temperatures will often exceed 40° C.

The Hellshire Hills show similar environmental conditions to the Portland Ridge, differing only in the more extreme nature of the environment. The vegetation is very sparse and soil is almost non-existent; rainfall is in the region of 40 - 50 cm. which, coupled with the high temperatures and permeable nature of the bedrock, produces a desert scrub-like landscape. The area consists of Newport Limestone which has weathered to a case-hardened, razor sharp karren form. The study area was located at around 10 m. O.D., where the effect of marine-boring organisms may have been important in the higher sea levels of the mid-Flandrian.

1. York Shaft.

2. Speleothems in Marley Stalactite Cave.

3. Surveying in Marley Stalactite Cave.

PLATE 2. STILL WATERS CAVE JAMAICA

Fig 1. Sump/duck in Entrance series.

Fig 2. Beyond the Entrance sump/duck.

Fig 3. Flood levels in the Entrance series.

Method of Study

One-metre quadrats were set up and within each quadrat the depth of 10 randomly sampled solution pits was measured. A photograph was taken of each quadrat so that length and width measurements could be made later. For each quadrat the following variables were noted:

1. Slope of the surface.
2. Aspect of the slope.
3. Lithology.
4. Dip of Bedrock.
5. Frequency of jointing.
6. Soil cover (%).
7. Vegetation cover (%).
8. Orientation of karren.

The position of each quadrat was selected to give a reasonable representation of the range of environmental variables found within each area. It should be noted that logistics imposed by accessibility, density of vegetation (in the Cockpit Country Area each quadrat had to be cleared by machete) and intensity of mosquito infestation influenced the location of quadrat location. In the Troy area 21 quadrats were evaluated, in the Portland Ridge area 14, and in the Hellshire Hills area 20.

In each area the following parameters of each karren feature were utilized:

1. Depth.
2. Length of the long axis (L).
3. Width of the widest part at right angles to long axis (W).
4. The width-length ratio ($\frac{L}{W}$).
5. Orientation of the long axis of each pit.
6. Orientation of axis about the direction of slope (aspect).

Using this data certain statistical tests were carried out by computer analysis, using package programmes on the University of Liverpool computer facilities. The object of the statistical tests was to see if any significant variation in karren form occurred between the areas, and what, if any, environmental factor was responsible for variations in depth and the $\frac{L}{W}$ ratio within each area.

Comparison of Areas.

Portland Ridge showed a highest mean depth of 8.18 cm, with Troy and Hellshire Hills with mean depths of 7.71 and 6.43 cm. respectively. The range of depth valves was also highest in Portland area - 74.2 cm. compared with 39.8 and 37.6 cm. for Troy and Hellshire. A Kruskall-Wallis Analysis of Variance for all sample depths reveaked no significant difference between the karren depth data of the three areas.

Troy shows the smallest mean width value of 2.30 cm., with Portland at 3.37 cm. and Hellshire the highest value of 4.10 cm. Kruskall-Wallis analysis showed that there is no significant difference between Troy and Portland, and a significant difference between Troy and Hellshire, with respect to karren width data.

Troy has the outstanding mean length of 23.05 cm., while Portland and Hellshire have much lower mean lengths of 5.97 and 6.30 cm. respectively. Kruskall-Wallis analysis showed no significant difference between Portland and Hellshire while the length data from Troy was significantly different.

The mean width/length ratios for Hellshire and Portland show the karren to be sub-circular; Hellshire with a mean ratio of 1.61 has the most circular form followed by Portland with a mean ratio of 1.99. The Troy karren however, have a markedly linear form of mean ratio 30.38.

Spearman-Rank analysis of site environmental factors showed poor correlation of factors on individual sites except that there does exist a strongly positive correlation between lithology and width-length ratio, ($r = 0.8447$, Sig. level = .001). The joint frequency also has positive correlation with width-length ratio ($r = 0.6388$, Sig. level = .001).

The orientation of karren was plotted for each area to see if slope orientation exercised a strong control on the orientation of karren. None of the areas shows preferred orientations in a downslope direction. Troy area however, shows two orientation maxima, the first from 0° - 9°, the second from 80° - 99°. It is possible that these preferred orientations are determined by the direction of jointing of the bedrock.

Summary of Results and Conclusion.

The relief of karren as expressed by the depth parameter, does not particularly vary between the three areas. The form of karren as expressed by the width-length ratio, does show a difference between the

areas, particularly at Troy, where the karren are of a linear nature, unlike the dominantly sub-circular karren of Portland and Hellshire. If length of karren can be equated with stage of development then Troy shows well-developed karren, whilst the other areas have more immature features. The width data showed only slight differences between each area, and in themselves are not regarded as indicative of any particular factor.

The site factors investigated have little or no influence on karren depth, form, or orientation. It can thus be postulated that the differences in karren form and development are dependant upon climatological or lithological factors.

The Troy area experiences much higher rainfall than Portland Ridge or the Hellshire Hills. The excess of rain over evapotranspiration, coupled with the acid nature of the leached soils and organic matter, produces faster rates of solution. The more arid areas of Portland Ridge and Hellshire, where evapotranspiration exceeds rainfall, have lower rates of solution. It is thus possible that the different rates of solution produce the different karren forms. Furthermore the effects of rain-pitting under the intense rainstorms experienced on an unprotected surface might favour the development of sub-circular rather than linear features.

The variation in lithology is probably the most important factor. The Newport Limestone occurs at Portland and Hellshire, between which there are the smallest differences in form. Troy, with Troy Limestone, exhibits not only the largest range of form, but is also significantly different from the other two areas. The cause of these differences in form may be of a structural nature, e.g. the nature and frequency of jointing, or of a mineralogical nature. The micro-structure of an initially exposed limestone surface will have an immediate effect in the initial stages of solution of the surface. Weaknesses in the crystalline structure may favour the concentration of solution favouring the production of linear karren.

Another factor to take into account is the possible effect of marine-boring organisms in the Hellshire Hills area. A higher sea-level in the past would have submerged most of the Hellshire Hills sample area. Marine-boring organisms (Trudgill, 1972) produce sub-circular pits, within which solution is concentrated. Since the rate of solution in the Hellshire Hills is relatively low, the effect of boring mechanisms would tend to last over long periods.

To conclude, it is probable that no one particular factor is responsible for the form of karren produced in a particular area, but rather a combination of factors. This study has established that the site factors investigated have, surprisingly, no influence on karren form. Climate, in terms of precipitation, and lithology can be seen to be the dominant controls, but the relative importance of these two factors remains to be investigated.

THE CHIROPTERA COLLECTION

During the course of the expedition, efforts were made to undertake a programme of collection and observation of cavernicolous bats. The collection was designed to assist the British Museum (Natural History) in the establishment of a representative sample of Jamaican bats, and the Museum's assistance in the provision of equipment, references, and facilities is grateful acknowledged.

Chiroptera were collected from three important roosts, Oxford Cave (G.R.332 475), Wallingford Roadside Cave (326 465) and Windsor Cave (326 528). Collection in St. Clair Cave (518 454) and Swansea Cave (497 484) was interrupted by the discovery of Still Waters Cave which absorbed the efforts of the whole team. In addition, the expedition biologist, B. Williams, was incapacitated for a week during an epidemic of Dengue fever, and a second visit to Windsor Cave was prevented by local hostilities.

Methods.

In all cases the bats were taken in mist nets set up near the cave entrances. It should be noted, however, that the use of these nets is illegal in many countries, and their acquisition by the local populace is in any case extremely undesirable, so that discretion should be used and the nets must never be left unattended. It was found that live bats left in the nets for more than a few moments become hopelessly entangled in the fine mesh and that it was therefore preferable to kill the specimens in situ as they were caught. This was conveniently and humanely achieved by means of a direct intra-cardiac injection of Euthatal (sodium pentabarbitol) which could be administered swiftly

and resulted in extremely rapid death.

Although rabies is unknown in Jamaica, its prevalence in Central America and Trinidad was considered adequate reason for expedition members to avail themselves of the new rabies vaccine. In addition, thick gloves were always used whilst handling the live animals.

Captures were reduced by bats veering away from cavers' electric headlamps and so missing the mist nets. Future workers might try masking headlamps with a red filter as bats are probably unable to see red light.

Once killed, the bats were removed from the net and placed in individual polythene bags for transportation back to the laboratory. After examination for ectoparasites, each specimen was individually identified with a label attached to the leg, and had its mouth stuffed with cotton-wool to facilitate examination of the teeth and palate at a later date. Subsequent preservation was by immersion for 48 hours in 90% ethanol followed by permanent transfer to 70% ethanol.

Identification was most kindly carried out by Mr. J. E. Hill of the British Museum, where the collection is now lodged.

Results.

Fifty-four specimens of seven species of bat were collected. These and their distribution were as follows:

	Species	Number of specimens
Wallingford Roadside Cave	*Tadarida molossa*	11
Windsor Cave	*Pteronotus parnellii parnellii*	3
	Macrotus waterhousii jamaicensis	1
Oxford Cave	*P. fuliginosus fuliginosus*	17
	Mormoops blainvilli	10
	Monophyllus redmani	6
	P. macleayii grisea	1
	P. parnellii parnellii	4

Fig. 10 summarises the morphological data collected from the specimens before preservation.

Discussion. Very little has been published on the ecology, or even the status, of Jamaican bats. Indeed, the sole paper on the ecological aspects is that by Goodwin (1970) and it is the current author's opinion that this paper is both inadequate and misleading in its coverage of the subject for the following reasons:

Firstly, Goodwin recorded *Pteronotus fuliginosus fuliginosus* only from St. Clair Cave, even though he spent sufficient time collecting at Oxford Cave to be able to give a species list, population estimate, and behavioural data. In our experience, *P. fuliginosus fuliginosus* was the commonest species we collected from Oxford Cave. Secondly, Goodwin missed *P. macleayii grisea* which we collected from Oxford Cave, and also *Macrotus waterhousii jamaicensis* which we recorded from Windsor Cave. Although Goodwin did not visit Wallingford Roadside Cave (very obvious and only a few miles down the road from Oxford Cave) he did not record *Tadarida molossa* anywhere on the Island. Koopman and Williams (1951) have suggested from their own studies of fossil material that *T.molossa* may prefer roosting sites not frequented by other species, and our collection of living specimens tends to support this, there being no other species associated with Wallingford Roadside Cave.

Secondly, it may be that Goodwin's omissions may arise from his collecting technique. During our own work, it was noticed that in a mixed species colony, as at Oxford Cave, the bats leaving the roost at any one time do not represent a random sample of the total population. This was particularly well shown at Oxford Cave, where it was found that for fifteen minutes after the emergence of the first bat, only male *Pteronotus fuliginosus fuliginosus* were caught. In the subsequent five minutes female *P. fulinginosus fuliginosus*,and *P. parnellii parnellii* began to emerge, and the last specimen to be collected was *Macrotus waterhousii jamaicensis*. It therefore seems reasonable to conclude that any collection which does not include samples at short intervals throughout the whole period of activity of the bats is likely to produce a highly biased picture both of species and of sex ratios. The period of activity extends throughout the night, making such observations a long task.

Thirdly, with the thoroughness of his collections in doubt, a number of Goodwin's behavioural observations may be viewed with scepticism.

Fig. 10. Wing span v. body weight for five species of Jamaican bat.

+ = males o = females

We found all the bat colonies we visited to be very sensitive to disturbance, and human approach caused great activity amongst the bats, many retreating into the depths of the caves well ahead of the advancing biologist. Further, many of the species proved extremely difficult to identify even in the hand, and impossible when forty feet up in the roof, so that it is difficult to see how valid observations on roosting behaviour could be obtained. Also, in Oxford Cave, specialized climbing techniques not available to Goodwin enabled us to scale the huge aven frequented by a large proportion of the bat fauna. Even so it proved impossible to estimate the number of bats present accurately, so that it is difficult to see how Goodwin could confidently quote not only total population size, but also numbers of each species.

An effort was made by the author to test a new technique for estimating numbers in a bat roost. The principle was to take photographs at right angles to the cave entrance at regular intervals throughout the evening exodus, and having calculated the speed of movement of the bats from the length of the blur on a long exposure photograph and the number of animals on each of a series of flash photographs, to extrapolate an estimate of population size. The technique requires a fast, high resolution black and white film and powerful electronic flash, neither of which was available to us at the time. Nevertheless trials at Oxford Cave were encouraging.

In conclusion, it must be said that although there is an urgent need for a proper study of Jamaican bat ecology, indiscriminate collecting and disturbance must be avoided. During our own work, we attempted to restrict the size of our samples to the specific quota of each species requested by the British Museum in advance of the expedition. This policy was hampered, however, by the extreme difficulty involved in identifying many Jamaican species without first killing and returning them to the laboratory. The author has therefore undertaken a preliminary study of Jamaican bat hairs, with a view to enabling future workers merely to return hairs to the laboratory and release the bats unharmed. The results of this work will be published elsewhere.

The key provided with this report is that compiled for the expedition by Mr. J. E. Hill of the British Museum, without whom none of this work could have been attempted.

A KEY TO THE BATS OF JAMAICA:

1.	Tail thick, long and extending for about one half its length beyond well developed tail membrane.	MOLOSSIDAE
	Tail, if present, not extending much beyond tail membrane.	2.
2.	Muzzle with definite chin or nose leaves.	3.
	Muzzle without definite terminal foliations.	5.
3.	Chin with flat dermal plates provided with numerous papillae, no nose leaf.	MORMOOPIDAE
4.	Prominent nose leaf, its vertical part lanceolate, no plates on chin.	PHYLLOSTOMATIDAE
5.	Two phalanges on third finger.	NATALIDAE
	Three phalanges on third finger.	6.
6.	Tail partly enclosed in tail membrane, free portion emerging dorsally from its centre.	NOCTILIONIDAE
	Tail entirely enclosed in tail membrane or extending very slightly beyond its posterior edge.	VESPERTILIONIDAE

NOCTILIONIDAE

Noctilio leporinus mastivus only Jamaican representative.

MORMOOPIDAE

1.	Ears noticeably separated, but may be connected by a low, inconspicuous ridge.	*Pteronotus (= Chilonycteris)*
	Ears united on the rostrum by a prominent band.	*Moormoops blainvillei*

Pteronotus (=Chilonycteris)

1.	Length of forearm exceeding 50 mm.	*P.parnellii parnellii*
	Length of forearm less than 50 mm.	2.
2.	Length of forearm 41-46 mm.	*P.macleayi grisea*
	Length of forearm 37-40 mm.	*P.fuliginosus fuliginosus*

PHYLLOSTOMATIDAE

1.	Noseleaf rudimentary, without distinct upright process, tail present.	Phyllonycterinae
	Noseleaf well-developed, tail absent if noseleaf rudimentary.	2.
2.	Tongue very long, upper surface of lower lip divided centrally by a deep groove, head long, narrow.	Glossophaginae
	Tongue normal, upper surface of lower lip not grooved, head short, blunt.	3.
3.	Tail membrane a very narrow band along legs and posterior body; calcars indistinct or absent.	Sturnirinae
	Tail membrane moderate to well developed.	4.
4.	Upper molars normal, with W-pattern.	Phyllostomatinae
	Upper molars abnormal, W-pattern lacking, obscured or distorted.	5.
5.	Upper molars narrow, trenchant.	Carolliinae
	Upper molars short, wide, the cusps rising from a broad, flattened crushing surface.	Stenodermatinae

Phyllostomatinae

1.	Length of forearm 49-55 mm.	*Macrotus waterhousii jamaicensis*
	Length of forearm exceeding 100 mm.	*Vampyrum spectrum*

Carolliinae

Carollia perspicillatum the only Jamaican representative.

Sturnirinae

Sturnira lilium the only Jamaican representative.

Stenodermatinae

1.	Length of forearm less than 45 mm..	*Ariteus flavescens*
	Length of forearm 56-66 mm.	*Artibeus jamaicensis jamaicensis*

Phyllonycterinae

1.	Second and third lower molars without distinct cusps.	*Phyllonycteris (-Reithronycteris) aphylla*
	Second and third lower molars dinstinctly cusped.	*Erophylla sezekorni syops*

Glossophaginae

1.	Tail short, not extending beyond tail membrane, upper premolars in contact, filling space between canine and first molar, lower incisors well developed.	*Glossophaga soricina antillarum*
	Tail long, extending a little beyond tail membrane, a gap between premolars and between these and the adjacent teeth, lower incisors minute or absent.	*Monophyllus redmani*

NATALIDAE

Chilonatalus micropus the only Jamaican representative.

VESPERTILIONIDAE

1.	Upper incisors 2-2	*Eptesicus*
	Upper incisors 1-1	*Lasiurus degelidus*

Eptesicus

1.	Length of forearm less than 45 mm.	*E. lynni*
	Length of forearm exceeding 46 mm.	*E. fuscus hispaniolae*

These are difficult to separate externally and discrimination by length of forearm is probably purely arbitrary. *Eptesicus lynni* has a smaller skull than *E. fuscus*.

MOLOSSIDAE

1.	Palate deeply emarginate between incisors.	*Tadarida*
	Palate without a deep emargination between incisors.	2.
2.	Length of upper incisor along cingulum equal to its height; one pair lower incisors.	*Molossus milleri*
	Lengh of upper incisor along cingulum less than its height; two pairs lower incisors.	*Eumops glaucinus*

Tadarida

	Length of forearm 36-46 mm.	*T. murina*
	Length of forearm 58-64 mm.	*T. molossa*

The character used to separate *Tadarida* from *Molossus* and *Eumops* is rather difficult but externally there are no good diagnostic features. It is easy to confuse *Tadarida murina* with *Molossus milleri* which has a forearm length of about 40 mm. or *T.molossa* with *Eumops glaucinus* in which the forearm length is about 58-61 mm.

Koopman however, separates Tadarida from *Molossus* and *Eumops* as follows:

a. Upper lip wrinkled, antitragus of ear not constricted at base. *Tadarida*
   1. Small size, ears hardly meeting at midline. *T. murina*
   2. Large size, ears united at base. *T. molossa*

b. Upper lip smooth or slightly warty.
   1. Large size, nose snoutlike, antitragus of ear flaplike and not constricted at base. *Eumops*
   2. Small size, nose not snoutlike, antitragus of ear lobate and constricted at base. *Molossus*

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EVIDENCE FOR THERMAL AIR CURRENTS IN A SMALL CAVE WITH A SINGLE NARROW ENTRANCE FROM AN OUTER CHAMBER

by John Letheren

SUMMARY

Monthly temperature readings in the inner chamber of Foxes Hole, Burrington (Mendip) during the cold weather in early 1979 showed temperature anomalies of as much as 3°C, even though this section of cave has only one narrow entrance, from an outer chamber. There is no noticeable air or water circulation in this inner cave, and the anomalies can now be shown to be due to thermal air currents.

INTRODUCTION

The original object of this study was to take temperature readings in a suitable Mendip cave at approximately one month intervals so that they could be compared with Meteorological Office data from two nearby sites (Downside Abbey and Rodney Stoke) with the intention of determining the relationship between cave temperatures at different points within the cave and the mean monthly, seasonal and annual surface temperatures. However, during the unusually cold winter of 1978/9, particularly in January 1979, the temperature readings became very erratic and it is the investigation of these anomalies which is the present subject.

CHOICE OF CAVE

It was assumed that ideally the cave should be horizontal in nature to minimise convection currents, have no air or water circulation, have a single very narrow entrance to avoid both wind and convection effects, and should not be popular with cavers.

Foxes Hole in Burrington Combe (Mendip) (Barrington and Stanton 1970) was considered to be the nearest approximation to this ideal and had the added advantage that the main part of the cave has a single narrow entrance passage which leads from an outer chamber which should have a considerable stabilising effect.

DESCRIPTION OF FOXES HOLE

Foxes Hole has an almost horizontal first chamber with two small entrances from the combe, one above the other. From the opposite side of this chamber a fairly narrow passage 10 m long leads down into the main inner chamber which splits into two terminal passages. A seasonal pool or lake is situated at the bottom of the right hand passage (looking down). Apart from the horizontal first chamber, the whole system has a general downward slope of about 30° (fig.1).

TEMPERATURE MEASUREMENT DETAILS

A mercury in glass thermometer was used initially with a range of +5 to 15° C over 9.5 cm of scale, calibrated in 0.1° C intervals. If due attention were paid to parallax the scale could be interpolated to about 0.02° C but readings were in most cases rounded off to the nearest 0.1° C. The absolute accuracy of the thermometer has not been determined, but for the purpose of this paper relative values are sufficient.

Initially the thermometer was laid on rock slabs or ledges in various locations to take the readings, but it was soon found that at least twenty minutes were required at each point for the reading to stabilise, even from one 'cave' temperature to another. An attempt was made to compute the theoretical steady state temperature from a number of readings taken at each location, but this was not successful. The method and theory are set out in appendix A.

Inserting the thermometer into pools or mud banks gave very speedy results, and although a rise of about 0.1° C was observed due to the energy in pushing the bulb into a mud bank, this heat was very quickly absorbed and only ten seconds or so were required to obtain a steady state reading. As the cave always contains some pools, wet mud and some wet walls, the humidity was assumed to be at or very near saturation, although it was not measured. The temperature anomalies appeared only in cold weather which suggests that latent heat of evaporation is not the cause. In any case,

Fig.1. FOXES HOLE based on a B.E.C. survey

Fig. 3. Temperature profile across the entrance to the inner chamber (^{o}C). Point G equals point 5 on Fig.1.

sufficient dry readings were taken to rule this out. Barometric pressure was not considered to be a significant factor, but this data could be obtained from the Meteorological Office for the period in question if subsequently found to be necessary.

The effect of body heat, often referred to in the literature, was considered both in theory and in practice. On one occasion, the thermometer was laid on a ledge well down into the cave and allowed to settle. Three volunteers then moved into a slightly lower part of the chamber and spent 30 minutes talking and smoking after which time the reading was unchanged. It is shown in appendix B that a rise would in any case have been most unlikely, and that, apart from standing directly beneath the thermometer, or breathing on to it, the effects of body heat for a reasonable length of time could safely be ignored for readings taken at or near the cave walls. All readings were taken in the evenings, mostly between 20.00 and 22.00 hrs. To follow up these readings, a thermistor bridge probe was designed and constructed as described in appendix C. This was used in the following winter (1979/80) for direct measurement of air temperature profiles, which confirmed the suspected situation.

RESULTS FROM THERMOMETER READINGS

The readings obtained using the mercury thermometer during 1979 are shown in Table 1. Although readings were in fact taken from May 1978 onwards, they were initially taken at random locations throughout the inner cave and were consistently equal to within about 0.5° C. Only from early 1979, when the anomalies appeared, were the readings taken at the same repeated locations on each visit so that the trend at each point could be followed.

SITE	JAN 13	JAN 27	MAR 17	APR 22	JUN 30	SEP 8	DEC 31
1	9.45	9.3	8.8	8.85	9.2	9.65	9.75
2	9.2	8.9	8.7	8.9	9.3	9.6	9.5
3	8.9	8.65	8.5	8.8	9.3	9.8+	9.4
4		8.5	8.5		9.4	9.8	(9.5)
5	7.7	6.4	7.0	8.3	9.2	9.6	7.9
6	9.25	9.3	9.3	9.1	9.6*	9.9	9.7

Table 1. Mercury in glass thermometer readings (in degrees centigrade) 1979

Notes: + recently disturbed (9.5°) reading from thermistor bridge
* pool dry, residual mud used for reading.

The data are plotted in fig. 2 for the six sites in the inner cave shown on fig. 1. They have been superimposed in a single graph for comparison and although the lines are somewhat confused for the summer months, their separations and inter-relationships during the winter months are most significant. The sites used for thermometer readings have been numbered as follows:

1: the upper of three small gour pools at the top of the inner chamber, situated on the opposite side to the 'entrance' from the outer chamber, 0.5 metres below the roof,
2: the middle level gour pool of these three, 0.8m below site 1,
3: the lowest level gour pool of these three, 0.5m below site 2, and 1m above the floor,
4: a small dome in the roof of the inner chamber about 1m in from the 'entrance' and 0.5m in diameter,
5: the floor of the 'entrance',
6: the water in the terminal lake or pool.

On occasions when the outside temperature was very low there was some temperature inversion in the final pool. On January 13th for example the surface water gave a reading of 9.2° C but about 20cm below the surface a reading of 9.3° C was obtained. These readings were checked several times, disturbing the water as little as possible. In Table 1 and the graph (fig. 2) a mean figure of 9.25° C has been taken as the pool temperature. Unless the surface was being continuously cooled, this inversion condition would be unstable and could not exist for any length of time.

The differences between high level site readings and low level site readings obtained on the first January visit suggested convection currents as being a possible cause, and the following results obtained in January (second visit), March and April followed the same trends, the differences

Fig. 2. Thermometer readings plotted from Table 1 for six sites.

decreasing as the outside temperature rose, and increasing again in the following December as the outside temperature fell again.

It is worth noting that apart from the terminal pool, which is at the lowest part of the cave system, all the readings taken at the top end of the inner chamber followed the same pattern, i.e. the higher they were located (as a proportion of the passage height), the higher was the temperature, with the exception of the dome in the roof (site 4) which had a lower temperature than the highest gour pool, in fact, lower than any of the three gour pools for the January 27th readings. This point is taken up later.

Following the cold weather in the early part of 1979, it was decided to carry out further investigations with an air temperature measuring probe, and the thermistor bridge probe was constructed and calibrated against the mercury thermometer. However, except where clearly stated, no attempt has been made to compare readings from the two different instruments.

RESULTS FROM THE THERMISTOR BRIDGE PROBE READINGS

Before presenting the readings obtained, a few words about an instrument designed and constructed by the author would not be out of place.

Many years have been spent designing circuits of this type, making full allowance for worst case and statistical variations of circuit parameters. The scale of the instrument (alongside the slider of the RV1 potentiometer) could be read to an accuracy equivalent to better than 0.1° C, and repeatability was tested by returning the probe to previous locations, without reference to the readings first obtained at those locations, and comparing the second readings with the first. In all cases they agreed to 0.1° C.

A temperature profile of the entrance to the inner chamber was obtained while standing well below and to one side of the anticipated airstream, the effective length of the four feet (1.2 metre) long probe being increased by holding it at arms length. A sketch of this entrance passage and the readings obtained are shown in fig. 3. Sites used for thermistor readings are lettered to distinguish them from thermometer sites. The actual thermistor, in its protective cage, was about 4.5 cm from the wall of the passage.

The differences between the readings at B and G, and between C and F, for example, are those to be expected for cold air flowing in at low level and warmer air flowing out at higher level. One would expect there to be less mixing of the two currents at B and G, and more mixing between C and F. The differences between J and E might be due to the curvature of the entrance passage from the outer cave, which would tend to direct the cold air to E, but if so, it would not account for the comparatively high reading at D. However, the overall pattern is clear.

Further readings were taken at roof and floor level from the top to the bottom of the inner cave (taking the right hand passage to the lake). These are shown diagramatically in fig. 4 where K was directly above R, M was above Q and N was above P. The roof dome L was not paired with a floor reading. Also on the diagram are shown the temperature differences between the roof readings and the floor readings beneath, which reduce from 1.6° C at the 'entrance' to 0.15° C at the lake (from just above the surface to the roof).

Although it would be unwise to compare the mercury thermometer readings with the thermistor bridge readings, it may be stated that the two instruments were in good agreement, and if the air temperature above the lake on December 31st (9.1° C) and the water temperature (9.7° C) are accurate, it would explain the temperature inversion noticed in the lake.

All the thermistor readings were taken at one session (December 31st, 1979 in the evening, outside temperature minus 1.5°C).

BREATHING EFFECT

It is an established fact that any single-entrance cave 'breathes' to some extent due to changes in atmospheric pressure. This effect would be expected to draw cold air in at floor level (due to its higher density) in cold weather with rising pressure, and to expel warmer air at roof level, again in cold weather, with falling pressure. This would have the effect observed in that the low level sections near the entrance would be colder than the equivalent roof sections, and that these differences would attenuate down the cave. However, there is one very significant difference between the breathing effect and the proposed convection current effect. If these effects in the winter months were caused by breathing, it follows that in the summer months differences between high and low sites should also occur due to the cave air being breathed out (low pressure) and much warmer air being breathed in (high pressure).

Fig. 4. Roof v. floor readings by thermistor probe.

Fig. 5. Postulated air circulation:

cold air flowing down • • • • •

warm air flowing up — — — —

rising or mixing currents ⟶

From Meteorological Office data, the cave temperature of about 9°C is very close to the annual mean temperature, so it follows that there should be equally large anomalies in summer and in winter, assuming similar changes in pressure. These differences were not observed; in fact the summer temperatures throughout the inner cave were remarkably similar.

There is one final point which perhaps should be considered, and that is that summer readings were taken in the evenings when the outside temperature was not far from the cave temperature, but it is inconceivable that the walls of the cave, and the lake, could have cooled down between mid-afternoon (1500 hours) and evening (20.00-22.00).

DISCUSSION AND CONCLUSIONS

Readings obtained with the mercury thermometer in 1979 show that in cold weather, and only in cold weather, temperature anomalies of several degrees centrigrade occur in the inner cave system, and that higher sites tend to be warmer than lower sites (as a proportion of passage height). The final lake or pool was also observed to exhibit temperature inversion on more than one occasion during the cold weather. This alone suggests the existence of thermal air currents.

Temperature profiles obtained with the thermistor probe both laterally at the entrance to, and longitudinally down the length of the inner cave provide further evidence to support this theory. The air circulation route suggested by the author is shown in fig. 5. There are two effects to consider, one is the air simply circulating around the chamber, i.e. down at floor level and back at roof level, and the other is air rising directly from floor to roof to 'short circuit' this route. This latter effect might be due to physical mixing of the two air streams as they 'passed' one another, and/or the cold air being partially warmed by the floor and rising into the upper outgoing air stream. In the suggested air flow diagram (fig. 5) the cold air is shown as a dotted line, the warm air as a dashed line and the 'short circuit' flow as continuous lines. The short circuit effect is highly conjectural at this stage and might repay further study, as indeed might a measurement of the air currents generally.

To return to the question of the temperature of the roof dome being lower than that of the three gour pools in January 1979, it appears that cold air was flowing down from the entrance to the inner cave at floor level and returning, warmer, at roof level. The gours are to one side of this route, and might well escape the main air currents. The dome, however, is directly in this path and could be partially cooled by the outgoing air, particularly if a portion of the incoming cold air was being mixed with it. Since the entire inner cave system has a downward trend, including its entrance passage from the outer chamber, it would be expected that the convection currents would appear in the cold months and not in the hot months, which is borne out by the observations. It would be interesting to carry out similar measurements in a cave with an upward slope to see whether anomalies appeared in the summer and not in the winter.

Geiger (1965, pp 462-7) preferred the concept of cold air drainage to that of convection to describe thermal currents of this type. Whether the thermal air currents should be attributed to warm air rising out of the cave thereby drawing in cold air, or to cold air pouring into the cave to displace the warm air is a question beyond the scope of this paper. However, even when outside temperatures were -6 to -8°C, there was no evidence of the cave being completely filled with cold air to be classed as a 'sack cave'.

If the thermal air current theory is correct, and the anomalies are certainly proved, then it implies that cave temperature measurements may be seriously affected by these currents, even in inner chambers such as the one described, and that while these currents are flowing, measurements of the air, water and even rock surfaces will be seriously in error unless these effects are taken into consideration. For this reason, the original study of cave temperature versus outside temperature had to be abandoned since the term 'cave temperature' in this context is meaningless.

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Appendix A. Prediction of final reading from the exponential curve.

It is possible from three points on an exponential curve to calculate the final value, that is, the steady state value after infinite time. It is assumed that a rise (or fall) of bulb temperature starts at some unknown time t_o and at an unknown temperature T_o. Readings are taken at times t_1, t_2 and t_3 giving temperature values of T_1, T_2 and T_3 respectively. This is illustrated in figure A1. At any time t, the temperature reading T is given by the exponential law: $T = T_o + (T_f - T_o).(1 - e^{-t/k})$ where T_f is the final or steady state temperature reading, and k is the time constant of the measuring device. This may be rearranged in the form: $T - T_f = (T_o - T_f).e^{-t/k}$
If the three readings are taken at equal time intervals, so that $t_2 - t_1 = t_3 - t_2$ then the following formula may be derived:

$$T_f = \frac{T_2^{\,2} - T_1.T_3}{2T_2 - (T_1 + T_3)}$$

This formula applies equally to a temperature rise or fall. Although this formula is mathematically exact, it is liable to give very large errors from very small errors in the three readings. To give a numerical example, let T_1 be 9.70, T_2 be 9.50 and T_3 be 9.40 (in degrees centigrade, but the formula is independent of units). The computed value for T_f is 9.30. However, if T_1 and T_3 have an error of -0.02^o and T_2 has an error of $+0.02^o$, the computed final value becomes 8.40^o, an error of -0.9^o. The error in computed final temperature is thus 45 times greater than the errors in each of the readings, and is totally unacceptable. To use the 'least squares' method would require a lot more readings, and would defeat the object of trying to predict the final value from a quick set of readings.

Appendix B. Theoretical effect of body heat on cave wall or near-wall temperature

Figures quoted for the design of cooling or ventilating systems for aircraft cabins, concert halls, etc. suggest that an average adult at rest generates about 80 watts of heat, so 100 watts will be taken to represent one person working without undue exertion.

Considering first a spherical chamber 3 metres in diameter containing a heat source of 100 watts: taking the specific heat of air as 1.006 joule/gm/^{o}C (this is the value for dry air at 20^oC - Kay and Laby (1959 p.57) - but will do for a first approximation) and density as 1.28 gm/litre, a temperature rise of about one degree per 3 minutes would be expected, or 0.1^oC every 18 sec. This is for the air alone, without any cooling from the walls. Let us now consider the chamber to have a wall of limestone one centimetre thick. Taking the specific heat of limestone as 0.8 joule/gm/^{o}C (Kaye & Laby 1959, p59) and its density as 2.7 gm/cc (ibid p.132) a

Fig. A1 Exponential temperature rise against time.

Fig. C1 Circuit diagram for thermistor bridge temperature probe.

source of 100 W would cause this shell to rise one degree per 1.7 hours, or 0.1°C every ten minutes.

In practice this one centimetre shell is surrounded by a massive 'heat sink' but great care is needed in constructing a rigorous model. It is felt that the foregoing calculations serve to indicate that for a reasonable length of time, one man in a small chamber would have a negligible effect on the temperature at or near the cave walls.

Appendix C. Thermistor Bridge temperature probe.

The circuit diagram for this instrument is shown in fig. C1. It was designed for worst-case component tolerances to avoid any selection of components and for easy resetting in the event of the thermistor needing replacement. All resistors are 5% tolerance (or better) and potentiometers are 20%. The operational amplifier (op.amp.) was a National Semiconductor LM124, but any good op. amp. with a gain of 1000 or more would do; The thermistor was a bead type, Fenmore UUA 35 J1, having a resistance of 5K ohms at 25°C, and about 10K ohms at 9 or 10°C (20% tol. at 25°C); The 10K preset potentiometer (RV2) is designed to cater for all component tolerances and is used to 'balance' the bridge at the desired centre temperature, in this case 8°C. The balance pot. (RV1) should then achieve a balance from 6 to 10°C. The 82K resistor may be changed to increase or decrease the operating range (without affecting the centre value). The balance pot. (RV1) was a linear sliding type, but a rotating version with a circular scale could equally well be used; The two LED's (light emitting diodes) are standard red LED's and show the high or low position of the balance pot. They are designed to 'flip' from one state to the other at the balance point, not to be both on at the same time; The battery voltage is not critical and may be from 3v to 30v (for the given op.amp.) but a 4½v flat torch battery was found to be a very convenient size and shape. It also allows direct soldering to the contacts. A voltage of 6v could be used without any modification, but higher voltages would cause the thermistor to run at several degrees above ambient which is not very desirable. In the above circuit it runs about half a degree above ambient. It is not designed for immersion in mud or water, and it should not be put in direct contact with a thermometer bulb for calibration. Although higher values of bridge resistance would cause the thermistor to run cooler, the effects of op. amp. input current and offset current would begin to become significant, and the given values are about optimum for these two conditions.

The bridge is set up by setting the balance pot. (RV1) to its centre position and putting the thermistor probe in an ambient air temperature of 8°C and adjusting the RV2 pot. to the LED changeover position. The scale, which is not linear, is then calibrated by comparing the readings on the RV1 scale (at the LED changeover position) with a number of known ambient temperatures.

A graph is used to convert the subsequent scale readings to degrees centigrade. As the circuit only takes a few milliamps from the battery, it need not be switched off between readings, but when switched on, the thermistor takes ten seconds or so to reach its stable above-ambient temperature, after which readings may be taken after only a few seconds in each location. The electronic components and battery were mounted in a small plastic box with the switch, LED's and slider of the RV1 balance pot. in the top panel. The thermistor was mounted at the end of a pole 1.2 metres long and connected into the box by twin cable. A wire guard was put around the thermistor for protection and it was free-mounted on its thin wires, uncut, soldered to the cable. If the thermistor wires are shortened or in contact with any part of the 'head' assembly, its settling time will be increased. Being a bridge circuit, readings are not affected by changes in battery voltage, provided it remains high enough for the op. amp. to function.

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