Cave Science

The Transactions of the British Cave Research Association

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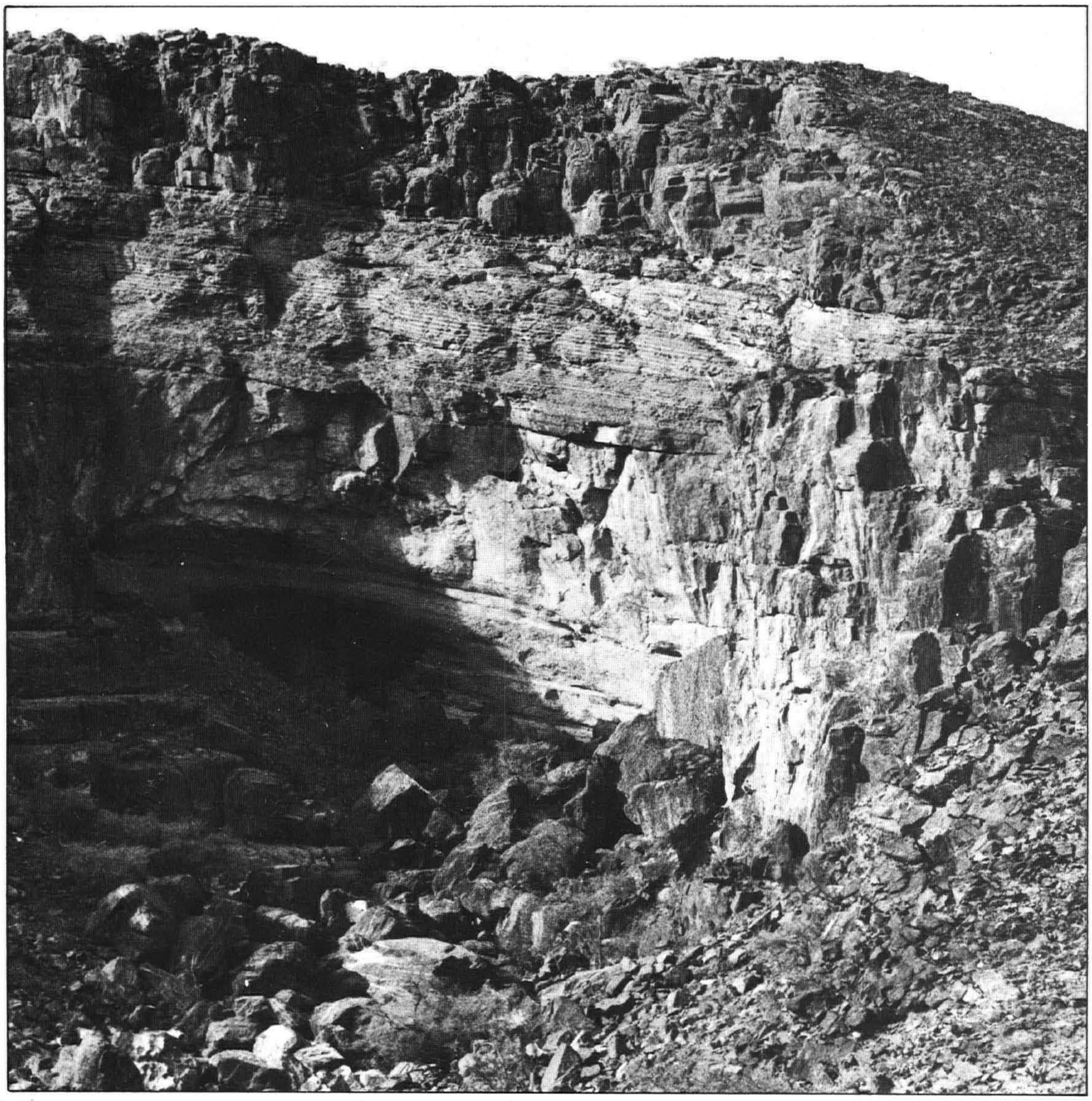

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Karst and Caves in the Jabal Akhdar, Oman

A C WALTHAM, R D BROWN & T C MIDDLETON

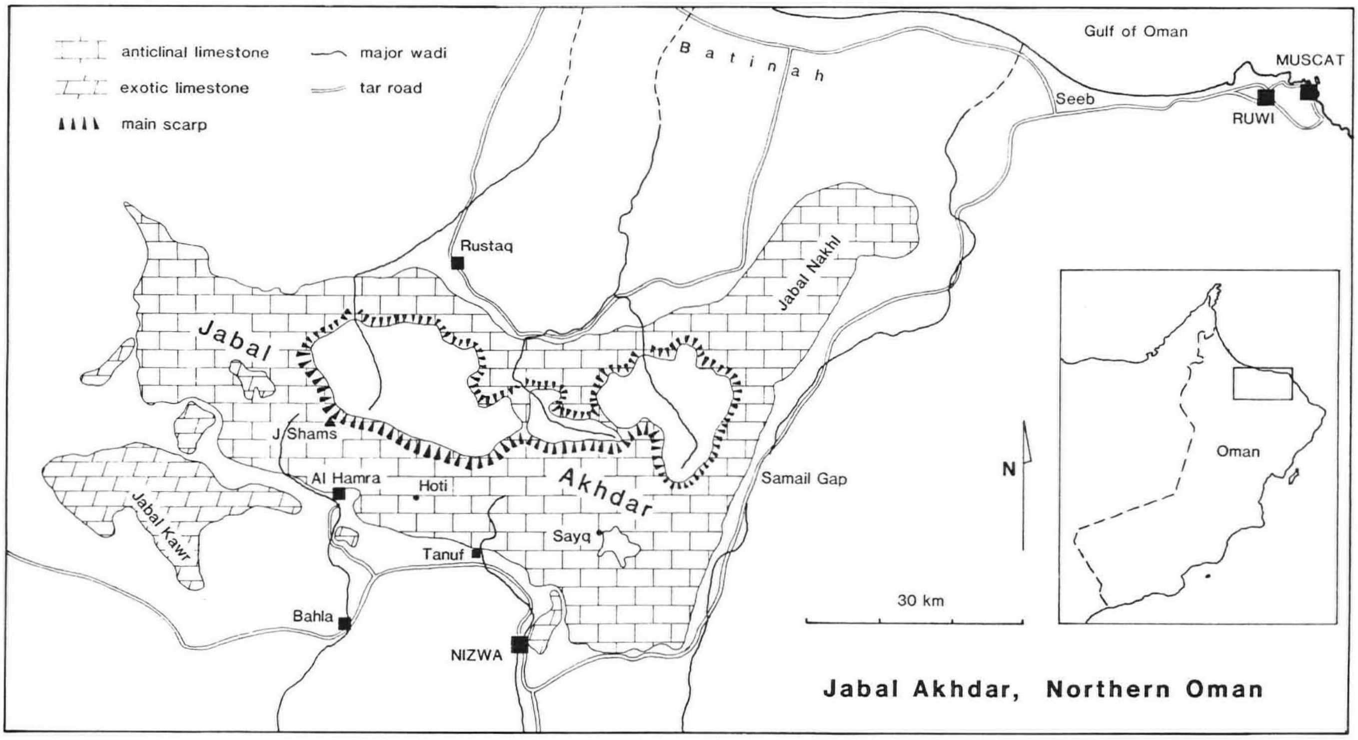
Abstract: The Jabal Akhdar is a spectacular anticlinal mountain range formed in a thick limestone sequence. Karst development is restricted by both the aridity of the modern climate and also the steepness of the surface slopes. The longest of the few caves known is the Hoti system, an underground flood route which provides a fine through trip nearly 5km long.

The Jabal Akhdar rises to over 3000m and forms the highest part of the mountain ranges extending across the northeast side of the Sultanate of Oman. It consists of a large breached anticline of Mesozoic limestones and dolomites. The carbonates form an area roughly 100 km by 20 km; they are surrounded by the outcrop of tectonically overlying thrust sheets of ophiolites and isolated limestone exotics. The anticlinal core is breached and inliers of pre-Permian basement, largely non-carbonate, are exposed; the main limestone outcrops therefore encircle the core inlier with outward facing dip slopes, at dips mostly between 10° and 70°, though with local structural complexities. The Mesozoic carbonate succession is over 2000m thick.

The scenery of the Jabal Akhdar is magnificent, with large rock slabs rising above narrow gorges and canyons. Jabal Akhdar translates as Green Mountain, but this is a misnomer except when compared to the rest of the desert terrain in Oman. Natural vegetation of xerophytic shrubs and trees is only conspicuous along the floors of the major wadis and in the cooler and slightly wetter environment of the upper slopes of Jabal Shams. In stark contrast are the patches of verdant foliage surrounding those villages where ancient adits, called falaj, tap groundwater supplies for the cultivation of dates, limes and other sub-tropical crops. The dominant colour is the dark grey of the bare limestone surfaces.

The Jabal is an arid and harsh environment. It receives less than 200mm of rainfall per year, and much of this falls in very localised, high intensity, summer thunderstorms. Shade temperatures regularly exceed 40°C,and the afternoon sun heats the bare rock to over 75°C, too hot to handle or climb on. Consequently it is surprising to find clusters of stone built huts clinging to the most unlikely sites wherever drinkable water is accessible. The inhabitants of these settlements appear to subsist almost entirely by the husbandry of goats. The restricted economy, rugged lifestyle and cultural isolation of these peoples is quite different from that of the inhabitants of the nearby settlements based on irrigated cultivation. Outside the cultivated areas only the most precipitous slopes are safe from the ravages of the free-ranging goats: in consequence few plants, except the most vicious thorn bushes and the poisonous euphorbias, survive the grazing pressure.

Within the thick carbonate sequence, only the Wasia limestone, at the top of the succession, appears to be significantly cavernous. It is around 300m thick, and is mainly a massive, fine grained, pure limestone, though it does contain thin-bedded and nodular horizons. The Wasia caps the main dip slopes of the Jabal Akhdar anticline, and consequently has relatively large outcrops. Karst is better developed on the southern slopes where dips and surface gradients are lower, together encouraging percolation; surface runoff



dominates processes on the steeper northern slopes. On all slope aspects, the arid climate is a further severe restriction on any approach to karst maturity.

The southern slopes contain the only known caves of any significant size on the Jabal Akhdar. These all lie in the lower dip slopes around Al Hamra and Tanuf. Immediately to the north of the cave sites, the Wasia limestone rises to the crest of the Jabal Shams escarpment, and small caves are known very close to the summit. The intervening outcrop is however broken by faulting and erosion; combined with the less karstic nature of the limestones beneath the Wasia, this places in some doubt the existence of continuous cave development over the 2300m altitude range.

SURFACE KARST

Due to the aridity of the climate, the modern karst of the Jabal Akhdar is immature. Rillenkarren are well developed on some outcrops but are not ubiquitous; though the karren have fine sharp crests, the level of modern activity is unknown, as the rate of destructive mechanical weathering is probably very low. Far more widespread are features which are here described as microkarren. These are grooves approximately one millimetre in width and depth which trend parallel to slope on both plane and rounded limestone surfaces. Individual grooves may show a slightly meandering habit and together they usually form crude networks. Single microkarren grooves are sometimes present in the troughs of rillenkarren. Microkarren are abundant in the Jabal and are not confined to one particular limestone lithology. They do not appear to have been recognized previously and are to be described in greater detail elsewhere (Brown et al, in prep.). Field evidence suggests that they have probably formed by solution on unvegetated limestone surfaces consequent upon rainfall or dew formation.

Dolines and discrete sinkholes are almost non-existent. Open fissures do occur in the outcrops of some of the more massive beds; though they clearly absorb any available water, most are narrow and are choked a few metres down. Hufrah Misfah (see below) is the exception. Springs and resurgences are also rare. Much of the water, which does drain through the cavernous limestone, does not resurge to daylight, but instead drains into the alluvial gravel which floor the main wadis and the plains surrounding the limestone mountains. These gravel aquifers are important water resources and the Jabal Akhdar limestones provide significant hidden recharge. Any springs in these arid mountains are of course exploited by the local people, but any caves that may lie behind them have not necessarily been investigated.

Wadi Hoti, with the rock step above the Hoti Pit entrance

The dominant fluvial landform is the wadi. These entirely subaerial channels are normally dry, but carry spectacularly powerful, short lived, flood flows during storm events. Many smaller wadis, incised from 20 to 100m are oriented straight down the dip slopes. The larger wadis are dendritic, and some, such as Wadi Tanuf, are incised by over 1000m with dramatic and precipitous walls. Numerous cave entrances are visible in the walls of the larger wadis; these invariably fail to live up to expectations, being only rock arches, rock shelters, or passages totally choked with debris still within the daylight zone. Wadi Misfah (see below) is one of the few wadis with a perennial flow; some others had small pools of standing water at the time of survey. Bedrock fissures in the wadi floors appear to act as sinks during periods of flow, but no open cave entrances have yet been found. The blind wadi which drains into the Hoti cave system appears to be unique.

Karst is also developed on limestones other than the Wasia. The Sayq plateau, northeast of Nizwa , is formed on limestones and dolomites lower in the Mesozoic sequence. Here there are extensive tufa beds, as below the village of Al

Limestone slopes above Misfah (all photos by Tony Waltham and Terry Middleton)

Ayn, and also some potential cave sites, but investigation is restricted as the whole area is within a military zone. Outside the Jabal Akhdar anticline, there are mountain blocks composed of exotic limestone which has been emplaced by massive thrust displacements. Some of these west of Al Hamara are over 5km across, with impressive scarp cliffs hundreds of metres high; some small cave resurgences have been reported and also they are commonly fretted by massive karren with solution grooves up to a metre in trough width. Microkarren are seen on the pre-Permain Hajar limestone in the central Jabal inlier; however, there are no signs of caves in the wadis which incise spectacular slot gorges across the Hajar outcrop.

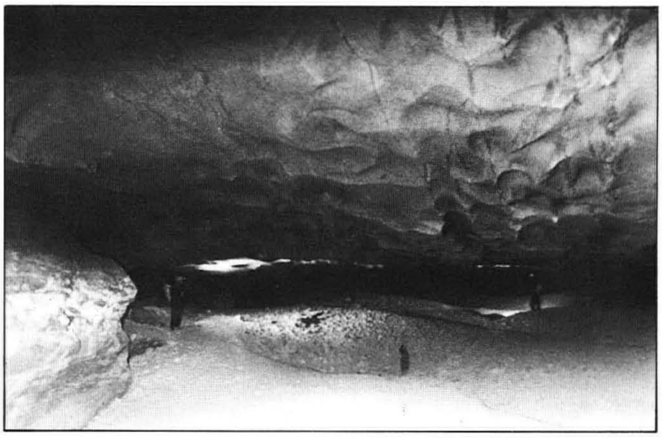
HISTORY OF CAVE EXPLORATION

Local people have explored the easily accessible entrance of any of the caves in the Jabal in their desperate persuit of water supplies. Many of the rock shelters show signs of past habitation, perhaps mostly by transient goatherds; a family still lives in a cave in Wadi Misfah. But there has been very little serious cave exploration, for either sport or science. This is partly because tourists cannot enter Oman, so the only non-Omanis able to explore the caves have been the ex-patriates, mainly American and British, most of whom live in the capital area Muscat and Ruwi. In addition, the high temperatures make walkabout searches for cave entrances rather uncomfortable except in the months of December to March.

The entrances at the top and bottom of the Hoti cave have always been open, but it appears that the first serious explorations were by the Englishman, Doug Green. With men from the Omani army, he made the first through trip in 1977. Since then, most visitors have just gone into the Hoti Cave, with few if any making the through trip from the top. In 1981, the Americans, Don and Cheryl Davison, found the Hufrah Misfah entrance right by the path descending Jabal Shams to Misfah village; they explored down the entrance shafts, but did not push far down the miserable passage below.

In July 1985, the present authors carried out the Jabal Akhdar Project. Working with and for the Public Authority for Water Resources, they explored Hoti Pit and the inner part of Ghubrat Tanuf Cave, pursued Hufrah Misfah a little further and made the first surveys of all these caves. They completed an air photo search for entrances, and walked several wadis and ridges, but without turning up any new caves. The splendid Hoti Cave seems to be unique and the Jabal Akhdar does not hold immediate promise of any more large caves. However new entrances could await discovery by an enthusiastic walker, and some small caves, recorded by the Davisons outside the Al Hamra area, await checking.

Hoti Sink entrance



Main passage inside Hoti Sink

The potential for cave exploration in Oman appears to lie in karst blocks other than the Jabal Akhdar. Unchecked reports tell of cave resurgences in exotic Mesozoic limestones and in the Tertiary limestones, west of Al Hamra and around Ibri. South and southeast of Muscat, there are more karst blocks, with reports of isolated caves in various remote sites. These include the Selma plateau, where the Davisons are currently exploring the deepest caves in Oman. In southern Oman, the Jabal al Qara, immediately inland of Salalan is a limestone range containing some shafts and massive sinkholes over 100m deep; some of these have been descended but they have not been systematically explored.

THE HOTI CAVE SYSTEM

Lying 8 km ESE of Al Hamra, the Hoti Cave System is a major karst conduit within the dip slope of the Wasia limestone. Its top entrance is at the end of a deep, blind, vertical-sided wadi adjacent to the tiny village of Hoti, and its lower exit is a massive cave mouth almost at the foot of the dip slope. The cave contains 4975m of mapped passages, of which 4300m are on the single trunk route from sink to rising, which are 2600m apart in a straight line. The vertical range of the cave is 262m.

Morphology of the cave

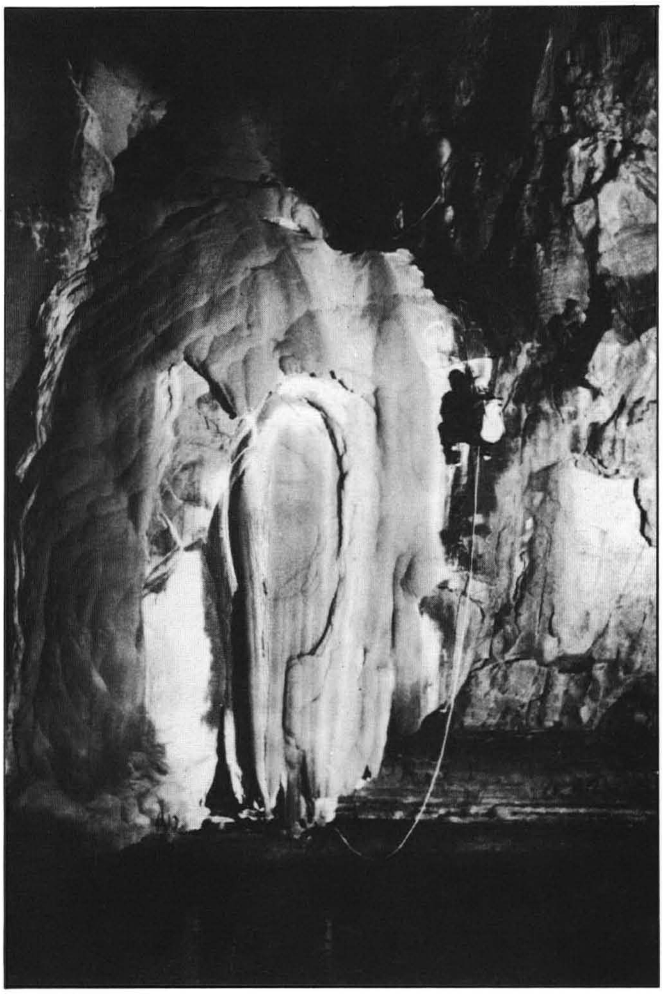
The upper entrance of the system, Hoti Sink (990m a.s.l.) lies at the foot of a 60m high vertical cliff, terminating a boulder strewn wadi. The boulder floor continues unchanged beneath the low entrance arch, into a high chamber, and to the lip of 10m deep holes in bedrock. These holes enter the roof of horizontal passages floored with mud, left by periodic flooding; the gallery extends back beneath the entrance to a mud choke, and also downstream, with no sign of its bedrock floor. After a short descent over breakdown and boulders, there is another horizontal stretch at a level of 33m below the entrance; the passage is over 20m wide, only a few metres high, and has a mud floor due to frequent ponding of flood waters which fill it to the roof.

Blockfall up to 10m in diameter, and water-hammered, rounded boulders up to 5m in diameter, characterise the passage as it steepens into the Wadi Styx; this is a massive tunnel over 25m wide and more than 12m high, with huge piles of angular breakdown sloping down into boulders rounded by flood torrents. The passage is again level through First Lake and Icefloe Lake - the latter named after the spectacular wafer-thin rafts of floating calcite which cover most of its surface. A wide passage then follows down the bedding; it contains some massive gour dams up to 8m high, breached by subsequent scouring. In the wider sections of Cairn Hall and Stump Cavern, limited roof stoping has left low arches spanning breakdown piles. Beyond them, another muddy horizontal section is a site of floodwater ponding at the -122m level.

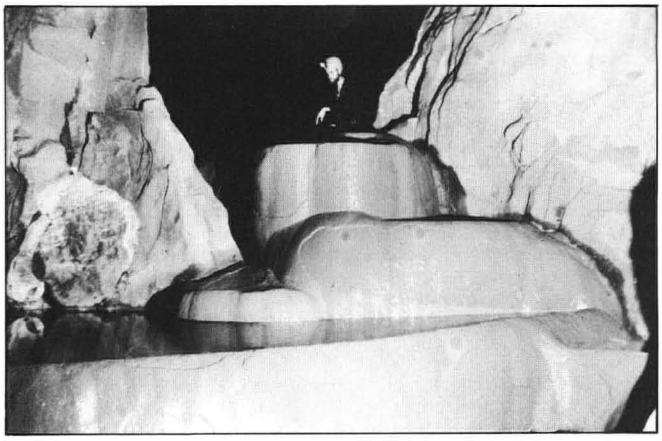
Below that level, the passage develops into a joint-guided rift, over 20m high and mostly just a few metres wide. It descends steeply through the joints, with flowstone shrouded cascades descending into deep lakes. The Warm Inlet has a small permanent stream, but it can be followed up for less than 20m to a constricted sump. Its water is actively depositing calcite, and the next section of passage is splendidly floored with deep clean gour pools separated by barriers of fresh rimstone. The tall rift passage continues in this fine style, though the amount of active flowstone deposition decreases with distance downstream.

The cave again changes character at the Main Lake. This is over 800m long, in a rounded tunnel 10m wide; roof height ranges from 1m to 4m over deep water and a soft sediment floor. The lake ends at a cobble slope over 10m high where floodwaters have banked the rounded cobbles against a zone of blockfall. The lower flood route passes through this blockfall, while a dry high level parallels it to the north until it breaks into Fossil Cavern; this is a segment of ancient conduit totally blocked upstream by massive flowstone deposits.

The downstream tunnel is floored by high boulders, breakdown and massive eroded flowstone, as far as a major boulder pile which rises to the floor at the daylight entrance chamber of Hoti Cave. Beneath the entrance boulder choke, a lower series of rifts and bedding planes reaches standing water at a number of places, and also provides an exit route to the flood rising among the boulders of the wadi floor.



The 13m flowstone cascade in Kahf Hoti



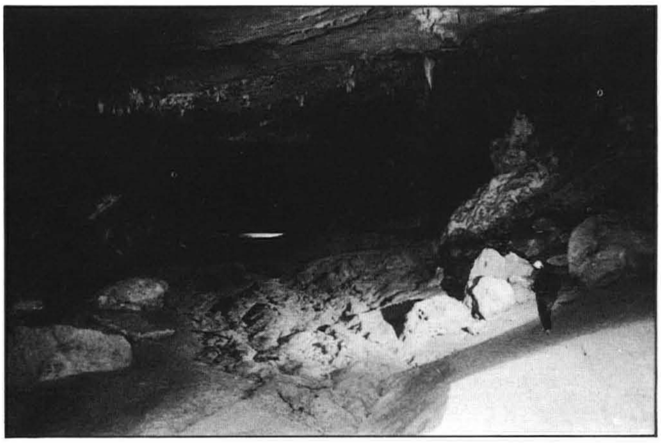
Gours midway through Kahf Hoti

Hoti Pit is an independent cave system with 380m of mapped passages descending 43m. It is entered in the wall of a deep, dry, plunge pool in the wadi floor 400m upstream of Hoti Sink. A 12m shaft drops into a zone of filthy organic mud. The exit passage has a sawtooth profile, down the bedding and up the joints, and is constricted by the sediments dumped by floodwater on the low gradient. Eventually it opens up into Breakdown Cavern, with a roof arched by bedding collapse over a massive blockpile; the far exit is closed by huge banks of laminated clay and silt which reach to the sloping roof. Down through the breakdown, the route of floodwaters is recognised by the rounding of the boulders, and a short spacious passage descends gently to standing water in a fetid sump pool.

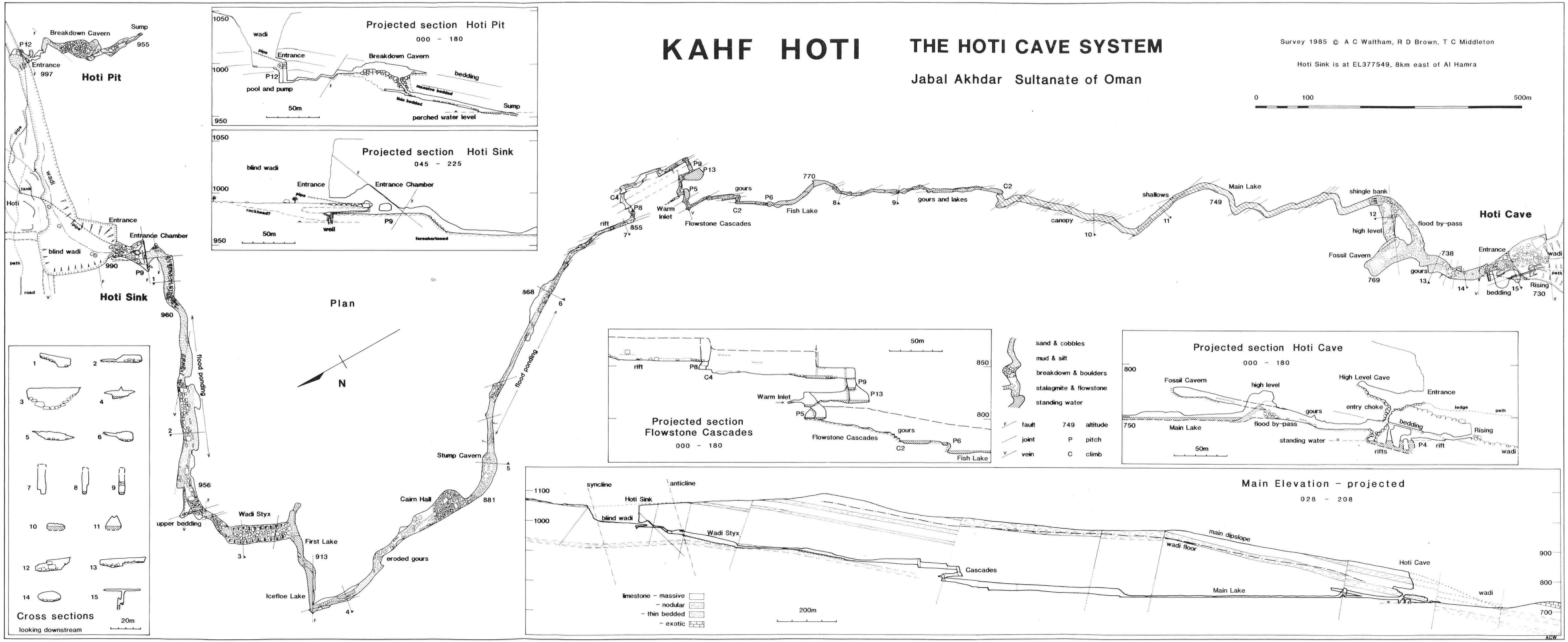
Cave geomorphology

The Hoti cave is a system of considerable age, essentially fossil though still periodically invaded by floodwaters in a regime very different from that in which the cave developed. The wadi feeding Hoti Sink is incised over 50m into the limestone surface, yet the ancient dry valley continuing beyond the sink is a barely recognisable trough.

Throughout the cave, roof pockets provide abundant evidence of major early phreatic development. It would appear that the cave was a substantial conduit within the phreas, before any vadose drainage consequent on surface lowering at the foot of the adjacent dipslope. This accounts for both the level stretches within the main conduit, and also the phreatic roof morphology of even the highest rift passages. There are no major canyons, and only minimal signs of vadose erosion; any such features are buried beneath the massive cave fill.



Fossil Cavern in Kahf Hoti


KAHF HOTI
THE HOTI CAVE SYSTEM
Jabal Akhdar Sultanate of Oman
Survey 1985 © A C Waltham, R D Brown, T C Middleton
Hoti Sink is at EL377549, 8km east of Al Hamra
0 100 500m
Projected section Hoti Pit
000 - 180
1050
1000
950
wadi
pipe
Entrance
Breakdown Cavern
bedding
P12
pool and pump
massive bedded
thin bedded
Sump
50m
perched water level
Projected section Hoti Sink
045 - 225
blind wadi
Entrance
Entrance Chamber
rockhead?
well
P9
foreshortened
Breakdown Cavern
Sump
955
P12
Entrance
997
Hoti Pit
pipe
wadi
tank
Hoti
Entrance
Entrance Chamber
blind wadi
990
P9
path
road
Hoti Sink
960
flood ponding
Plan
N
956
upper bedding
Wadi Styx
First Lake
913
Icefloe Lake
eroded gours
Cairn Hall
881
Stump Cavern
868
flood ponding
rift
855
C4
P8
P9
P13
P5
Warm Inlet
Flowstone Cascades
gours
C2
P6
Fish Lake
770
gours and lakes
C2
canopy
shallows
Main Lake
749
shingle bank
Hoti Cave
high level
flood by-pass
Fossil Cavern
769
738
Entrance
wadi
gours
bedding
Rising
730
Cross sections
looking downstream
20m
Projected section
Flowstone Cascades
000 - 180
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P8
C4
P9
P13
Warm Inlet
P5
gours
Flowstone Cascades
C2
P6
Fish Lake
850
800
sand & cobbles
mud & silt
breakdown & boulders
stalagmite & flowstone
standing water
fault
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Projected section Hoti Cave
000 - 180
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Fossil Cavern
high level
High Level Cave
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Main Lake
flood by-pass
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Rising
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P4
rift
rifts
wadi
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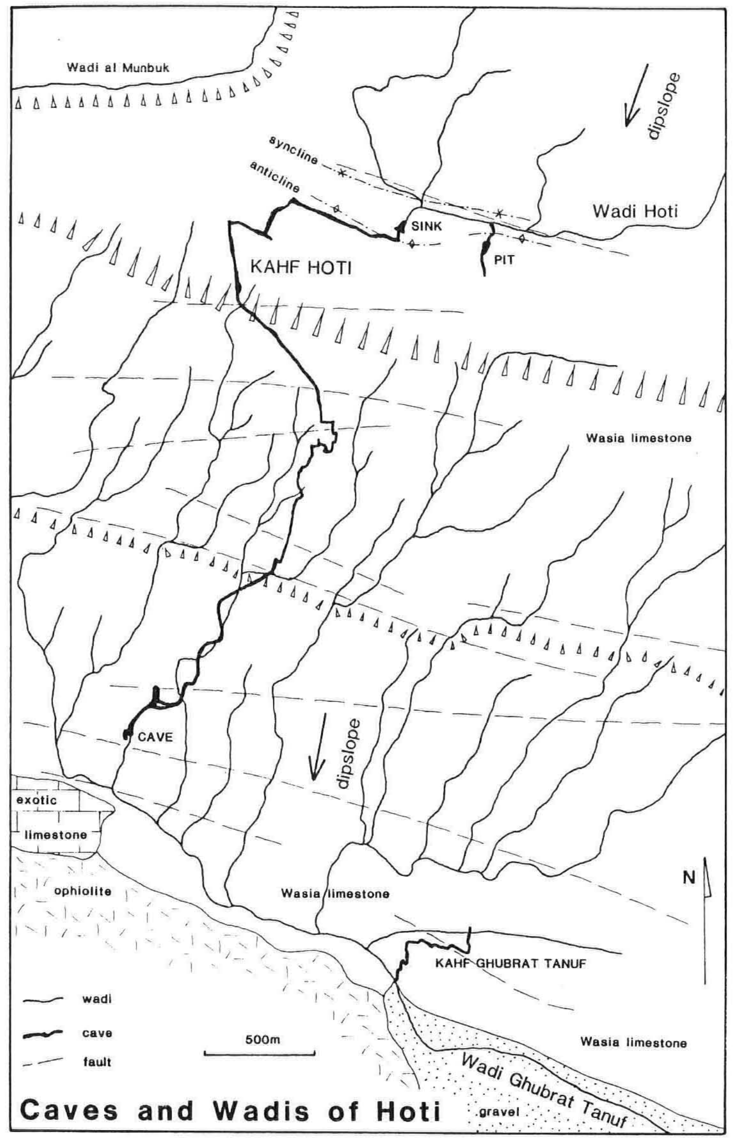
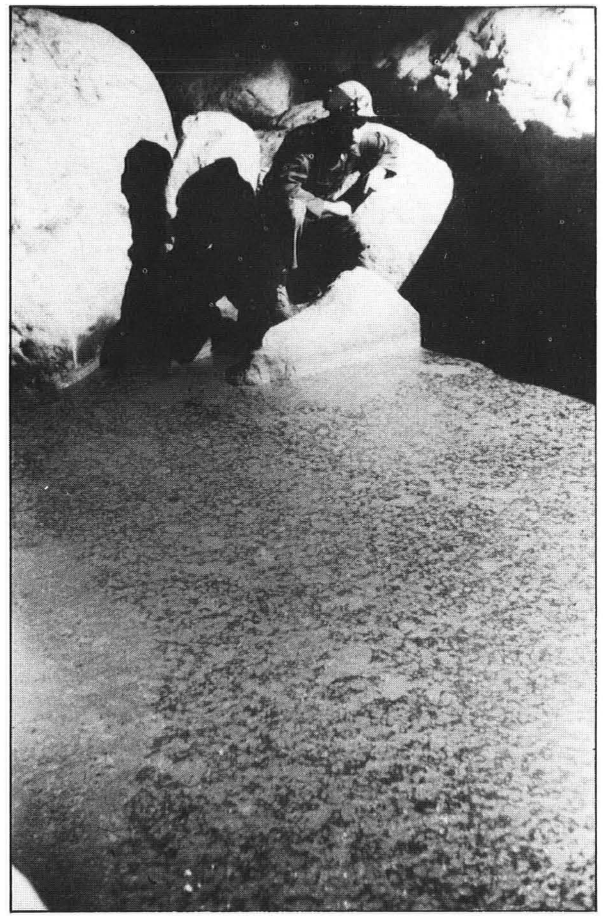
Main Elevation - projected
028 - 208
syncline
anticline
Hoti Sink
blind wadi
Wadi Styx
main dipslope
wadi floor
Cascades
Hoti Cave
Main Lake
wadi
1100
1000
900
800
700
limestone - massive
- nodular
- thin bedded
- exotic
200m
ACW



Caves and Wadis of Hoti



Floating rafts of calcite on Icefloe Lake, Kahf Hoti

An important phase of the cave's history involved massive amounts of deposition. Huge banks of flowstone probably filled the cave to the roof in places; gour dams (rimstone) built up many metres high; thick gravels were cemented by calcite, and false floors now survive at many levels. The age of this phase (or phases) of deposition is as yet undetermined, but it almost certainly relates to climatic variations within the Pleistocene.

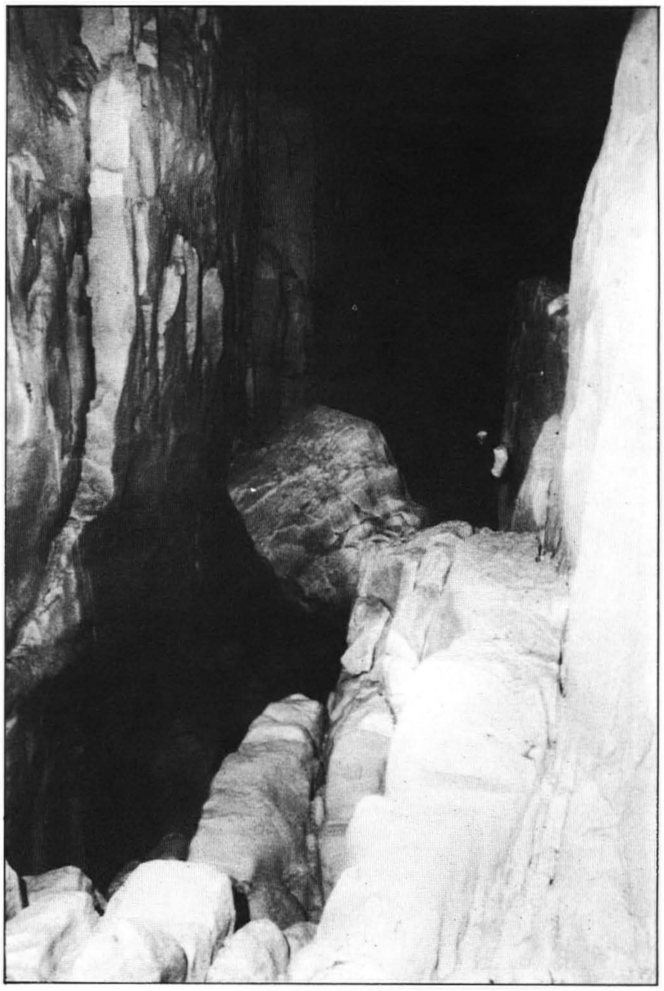
Subsequently major re-excavation has been carried out by sporadic flood flows, and this continues within the present climatic regime. In the steeper sections of the cave, boulders of 20 tonnes and more are transported and rounded; gour dams are completely breached, and moulins over a metre across are cut into flowstone. Waning floodwater leaves extensive mud deposits in the level stretches of passage. Modern solutional activity is limited; flowstone is being deposited by the percolation water from Warm Inlet, all the way down to the Main Lake; abundant calcite rafts are formed on the surface of most pools and lakes whose water is both saturated and evaporating; echinoliths occur at a few sites clear of the main areas of abrasive scour.

The 800m of passage containing the Main Lake cuts across the bedding and reveals only limited control by the major joints. It is difficult to explain its origin as anything other than a shallow phreatic conduit closely controlled by an ancient water table; it lies 40m above the main floor of the adjacent modern wadi. At its top end, the tall, upstream, rift passages terminate abruptly. Downstream of the lake the morphology is complicated by the intersection with the older passage of Fossil Cavern; this is the upper end of a fine phreatic tunnel which probably has a phreatic lift concealed under the boulder piles leading up into the entrance chambers. Upstream of Fossil Cavern, beyond the choke, probably lies the ancient phreatic trunk route which relates to the upper part of the cave and predates the section of passage containing Main Lake; though where this departs from the upper cave is unknown.

The nature of modern phreatic cave development in the Wasia Limestone is indicated by the lowest passages in the Hoti cave. Inclined bedding plane caves are open to heights approaching a metre over wide areas,and are connected by a number of parallel, vertical fissures along the dip joints. Some of these are mapped in the epiphreatic flood zone, and they appear to continue below the base water level.

Hoti Pit is clearly of phreatic origin, with its distinctive sawtooth profiles, though there is limited vadose modification of both the entrance shaft and the lower stream passage. The massive flowstone and thick laminated clastic fill in Breakdown Cavern, together with the subsequent dissection and partial re-excavation, represent further stages in the climatically controlled evolution of the karst.

Main passage inside Hoti Cave

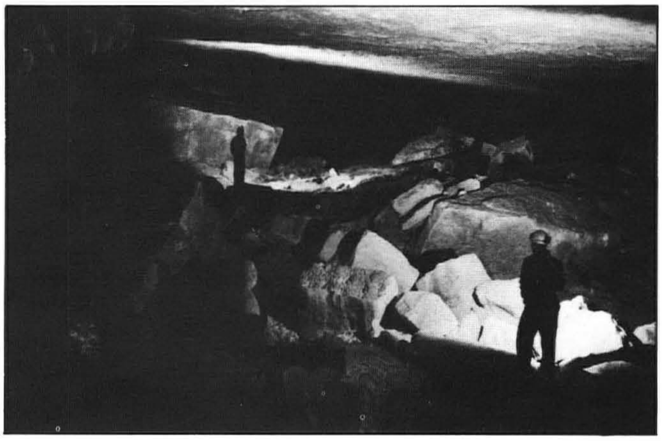


Rift passage above the cascades in Kahf Hoti

Geology of the cave

The entire cave system is formed in the Natih member of the Wasia Group of limestones, and through most of the cave these are dipping between 5° and 15° to the south. Overall there is a crude stratigraphic control on the cave, as the main passage is essentially a downdip conduit. But in detail, the bedding has rather less control; only some sections of passages are primarily on bedding planes - these include much of the upper cave down to the -130m level, Fossil Cavern and the lower entrance passages, and also most of Hoti Pit. Favoured horizons of passage development appear to be massive beds immediately above rather thinner bedded zones; however, this impression may be partly created by any upward passage migration, by stoping and collapse, through the thinner beds until terminated by a stronger roof unit. The cave system is probably confined to a stratigraphic thickness less than 200m, but some fault displacements are unknown. The main passage descends stratigraphically by way of the dip joints, and rises through the succession via either water table levels or joint controlled phreatic lifts.

A critical feature of geological control is the gentle syncline which extends through the Hoti Sink entrance; it is a parasytic fold with an east-west axis breaking the dipping limbs of the Jabal Akhdar anticline. The fold is only about 250m across, with maximum dips on both limbs of around 10°. It appears to be the major feature controlling the location and development of the cave system. The depression created by it on the stratimorphic surface of the mountain dipslope would clearly be a favoured site for sinkhole drainage, with no available exit route for a developing wadi. Either alternatively or additionally, any enhanced fracture opening across the flexure would have encouraged underground drainage. It is perhaps significant that no other comparable synclines, or cave systems, have been recognised on the Wasia outcrops; elsewhere the downdip surface wadis are uninterrupted.



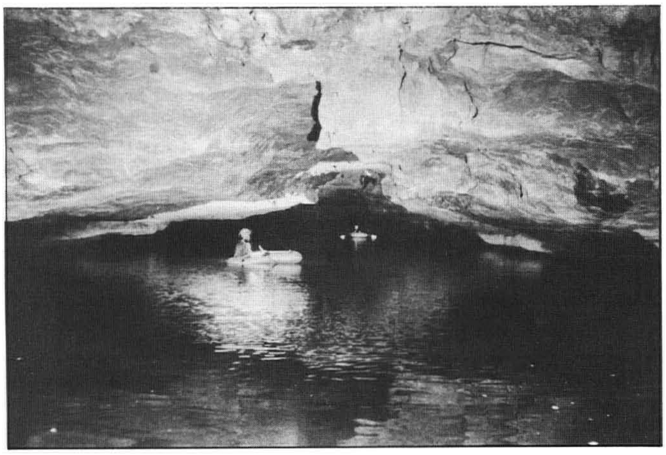
Breakdown passage inside Hoti Cave

Superimposed on the overall dip trend of the cave, there is considerable control of plan detail by both joints and faults. The major control on the cave passages is by the dip joints. Conspicuous joint sets are close to the north-south orientation. The cave map shows how the passages sometimes follows these joints, step obliquely across them or else they completely ignore them,and,as normal in limestone caves,there is little predictable about the pattern. The descending zone midway along the main passage also utilises these north-south joints, but the long fissure between there and the Main Lake is conspicuous in its absence of recognisable fracture control. The main strike fractures are reverse faults with thick veins of crystalline calcite; they have little effect on the cave development except where they have displaced the cave's overall dip trend for short distances near each end of the main passage.

Hydrology of the cave

The wadi which drains into the Hoti Sink has a catchment area of $28km^2$. In normal conditions there is no surface flow; even localised storms of high intensity produce no wadi flow. Clearly though, a major storm event would produce a spectacular flash flood through the cave; this probably occurs on average only once or twice a year. Based on passage size and sediment size transported, the flood flows in the cave may be estimated to exceed 100 m^3/sec.

Percolation flow into the cave is minimal. Warm Inlet, and a few other smaller sources, have



Main Lake in Kahf Hoti

a total base flow of about 2 l/sec. These flows do respond to rain; on a day following a short evening storm, they were observed to have increased by 300%. This response may be rapid, but the water's saturation with calcite suggests a longer fissure residence time. There are no known surface sinks above the cave, and the surface wadis are unbroken; the input is all through narrow fissures.

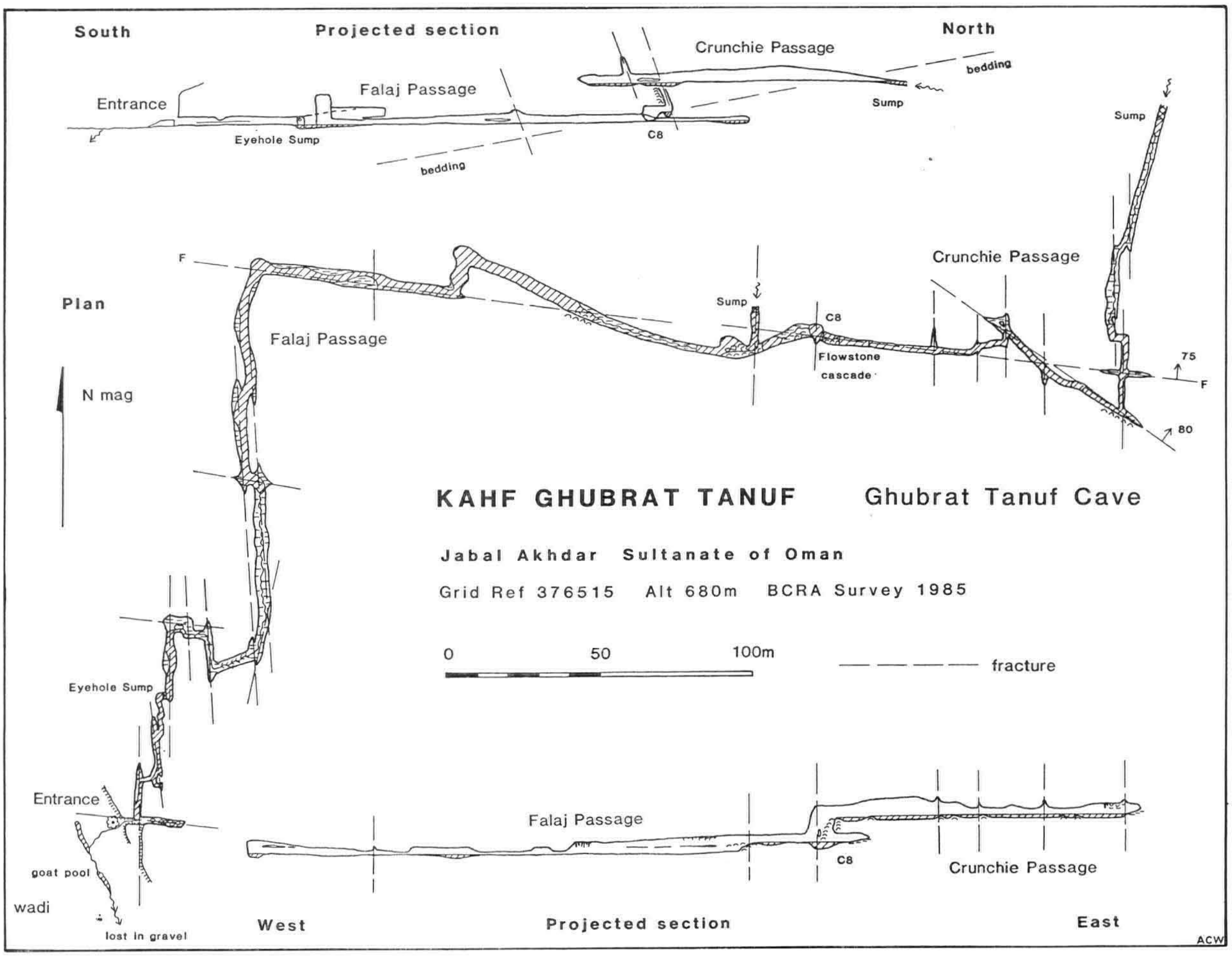
The cave provides storage, of both percolation water and remnant floodwater, in various lakes, which are perched above regional water tables. The largest is the Main Lake with at least 15,000m³ of water standing 22m above water levels in nearby fissures. Water flows continuously through the cave from the Warm Inlet to the Main Lake, out of which it drains through sediment and then down into bedrock fissures. Clastic sediments in the cave act like those in wadis; intersecting flows pass through them, and they provide transient storage. This storage has been exploited by the villagers of Hoti who have dug a well in the blind upstream passage of Hoti Sink; water is pumped from between the boulders and from fissures in the bedrock cave floor, though the yield appears to be small and variable.

Ultimately most cave water drains down to a fissured phreas such as is seen below the lower entrance. There are two exceptions to this general case. Floodwater is lost by discharge from the normally dry resurgence into the surface wadi. Also, water is lost from the cave lakes by evaporation in the conspicuously powerful cave wind; this blows down through the cave every afternoon in response to solar warming of the external air. The extent of the evaporation may be appreciated from the consequent cooling of the cave lake waters; the temperature of the Main Lake is 21°C, while the Warm Inlet, fed from closed fissures with no air circulation, is at 32°C.

KAHF GHUBRAT TANUF

The Ghubrat Tanuf Cave is located on the north side of the long wadi of the same name, adjacent to the roadhead. It is a resurgence with a base flow of around one litre per second; the water flows into shallow pools used by goats and then sinks into the wadi gravel.

The cave passage can be followed for 690m, to an upstream sump 14m above the entrance level. Almost all the passage is joint controlled rift, mostly 1-3m wide and up to 8m high. The floor is completely covered by clastic and calcite sediments. There are some fossil roof levels in sections, while elsewhere the roof descends to low arches with little clearance over pools. Falaj Passage has been entered by local people at some unknown time in the past; they have dug trenches in sediment banks to connect the pools, and in the lower section have built a tiny falaj channel on

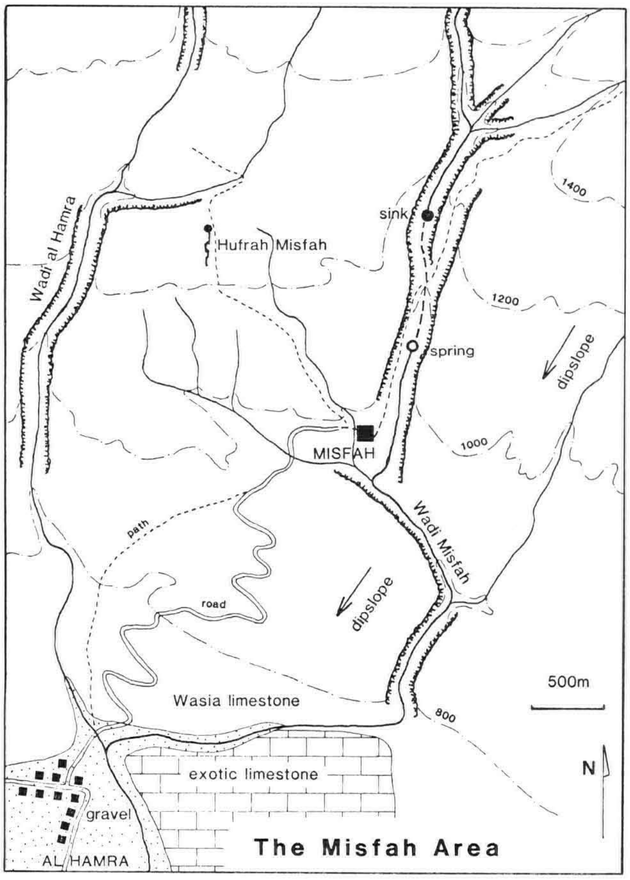


ledges and along the wall. Such effort was presumably expended in some past drought period, but the falaj is now not in use. Above an 8m climbable cascade the passage had received no early visitors; it has a sequence of gour dams (rimstone), with each pool floored by crystalline calcite which crunches underfoot.

All the known passage originated as phreatic rifts. Initially the connected route through these had a far more irregular switchable profile; later development has seen the crests of phreatic loops abandoned, while the troughs have filled with sediment and have had their roofs raised by solution. The subsequent profile is almost graded along each of the two levels. There is no geological cause for the step in the long profile of the cave. The two levels could have originated close to successive water tables; correlation with wadi terraces could substantiate this, but there is no lateral continuation of the upper level, and such an origin would beg the question of when the cave developed. The age of the cave remains unknown.

Joint control on the pattern of development is obvious from the map of the cave. It is indeed a spectacular example of a joint controlled cave, with almost every segment of passage formed along a joint, in some cases regardless of the overall drainage direction. In contrast, the bedding is ignored by the cave passage.

The relatively constant flow through the cave suggests percolation through a fissure zone in the source area upstream of the known cave. The high water temperature, of 32°C, and its saturation with respect to calcite, further indicate a long residence time in a shallow fissure zone within reach of solar heating. The flow may be partly fed by leakage in the bed of the wadi just to the north. Though there is no normal surface flow in this wadi, its sediments contain groundwater, and the cave offers a simple cutoff route inside the substantial westerly deflection of the wadi course.



Misfah village

WADI MISFAH

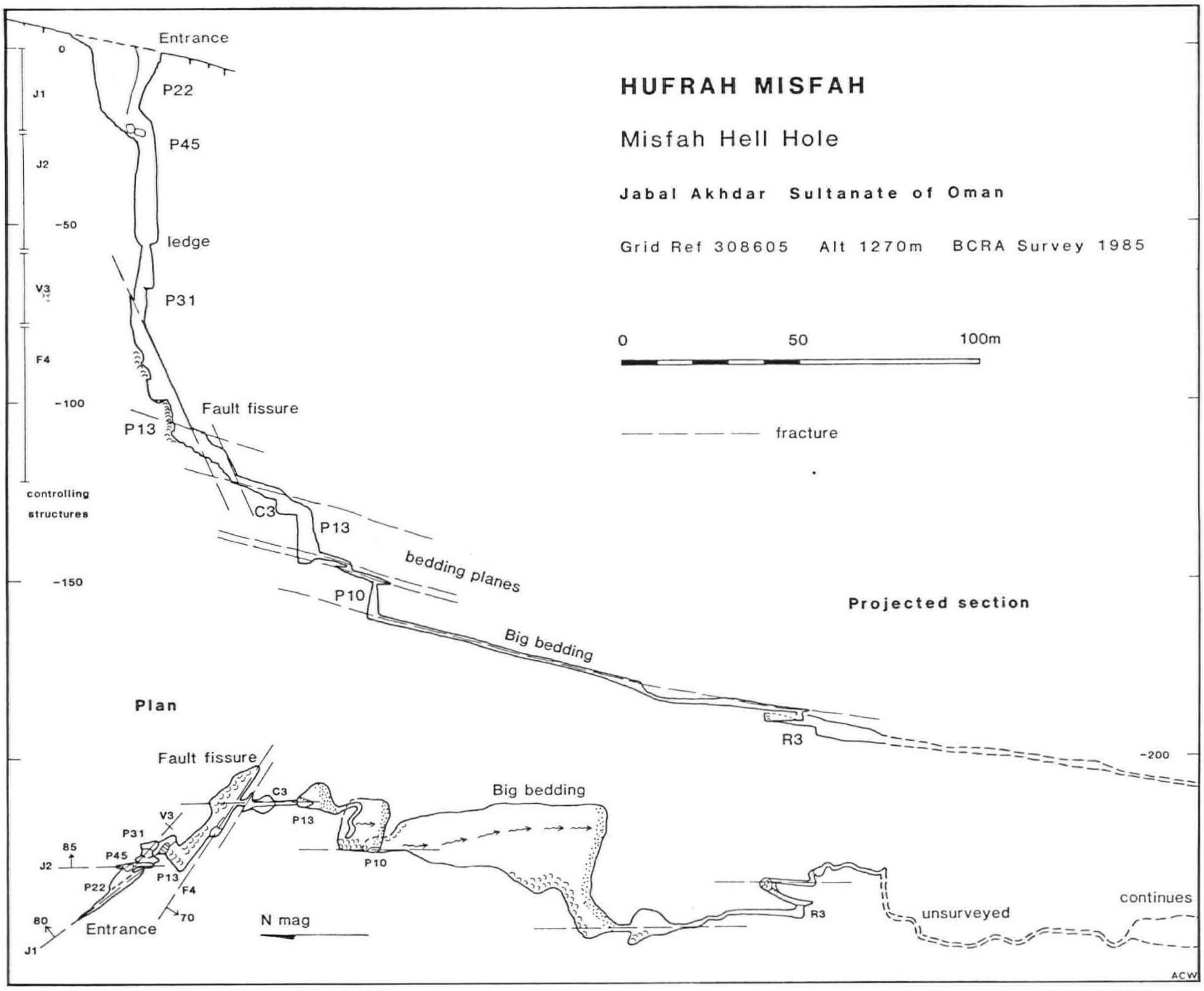
Just north of Al Hamra, Misfah is one of the larger and more accessible Jabal villages. Its survival depends on a major spring in the floor of Wadi Misfah, 700m upstream of the village. The springwater is fed into a falaj with a capacity around 20 l/sec, and this contours the lower wadi to irrigate all the palm terraces and supply the village. The spring emerges between boulders in the wadi floor, with a baseflow of about 10 l/sec of good, clear water. Though there is no adjacent bedrock, the point source suggests that this is a karstic resurgence fed by limestone fissures beneath the wadi fill.

Above the spring the wadi is normally dry, and further up it is incised in the Wasia limestone, in a deep and narrow gorge section. In the higher reaches there is a permanent surface stream, and this sinks underground about 700m up-wadi from the spring. The terminal sink is in a sediment choked pool in the bedrock limestone, and there is clearly also leakage into bedrock fissures in the section of wadi immediately upstream. There is no access to the underground channel. This is almost certainly the same water which emerges at the spring, and the sinking flow is around 75% of the resurgence flow; the additional spring water must originate from leakage further up the wadi and from hillslope infiltration. The cave route for the main water therefore appears to be about 700m in direct length, with a fall of around 80m. In this distance it climbs stratigraphically and passes through a thin bedded unit above the massive bed containing the main sink; the cave is therefore likely to have a saw-tooth profile with sumps and sediment chokes in each downturn. The passage is probably restricted and immature, and floodwaters occupy the surface wadi between sink and rising.

HUFRAH MISFAH

On the dip slopes of the Wasia limestone, either side of Wadi Misfah, the more massive beds contain numerous solutionally opened fissures. Most are choked with debris less than 10m down, but they clearly swallow available surface water. The one fissure which has been explored to greater depths is Hufrah Misfah, also known as the Misfah Hell Hole due to its uncomfortable temperatures. It is a generally small passage system, mapped to a depth of 197m.

The cave starts with a nearly vertical descent of 120m into a large fault fissure. From there its one route continues down a series of rifts and inclined bedding planes. Though some of the bedding passage is very wide, most of it is only about a metre high. It has been mapped to a point 435m from the entrance, and continues in constricted and rather miserable style beyond the patience of both explorers and surveyors. Geomorphologically, it is a simple vadose drain taking the easiest, almost direct, route down through the limestone.



The whole cave exhibits close response to geological structure. The entrance shaft system is down an opened zone of intersecting fractures. In succession, the route follows down two inclined joints, a vertical vein and an inclined fault (all of which are labelled on the cave map), but always stays close to the mutual intersections. From the fault fissure, the drainage has opened a route down a series of bedding planes, following close to the direction of true dip, which ranges 12-18°. The cave steps down the bedding planes by utilising the major dip joints.

There are pools of standing water in the cave, but there is no permanent flow. Rock bruising, due to cobble hammering, indicates the power of flood flows which must occasionally invade the cave; it is a natural storm drain. The catchment area of the cave drainage must be small, probably around 25 ha, but it is unknown in detail; it is determined by the disposition of fissures, especially around the entrance shaft. There is a notable lack of inlets in the cave, and there is no sign of dendritic drainage convergence. The resurgence for the cave is unknown. Though it could drain to the Wadi Misfah spring, there is no apparent reason why it should not maintain its downdip course and ultimately drain through a limestone phreas into the wadi gravels around Al Hamra.

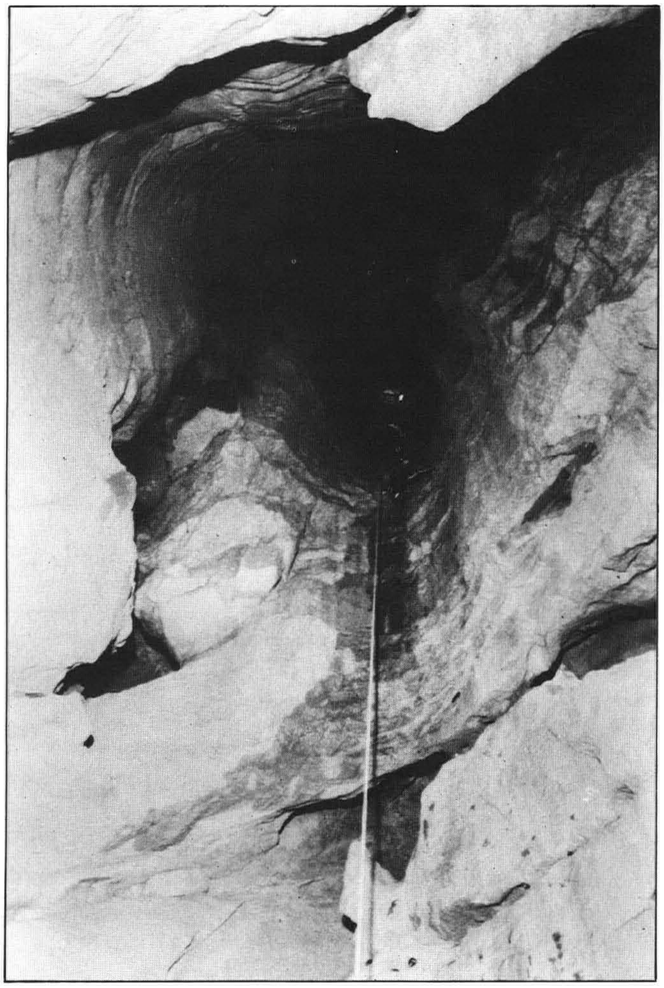
KARST DEVELOPMENT ON THE JABAL AKHDAR

Karst in the Jabal Akhdar is in general poorly developed - largely due to the limitations of climate. The main beds of the Wasia are potentially cavernous limestone, which would support a mature karst in any other environment. Other carbonates on the Jabal, notably the more massive units in the Kahmah and some of the Sayq dolomite, could support karst and contain caves, but on a lesser scale than in the Wasia.

The modern climate is not condusive to solutional activity and karst development. Karst landforms are generally subordinate to surface wadis and stratimorphic slopes. Rainfall is erratic. Major storm events create massive, short-lived, flood flows in the numerous surface wadis; these permit rapid runoff. Only limited infiltration occurs, in both major and minor storm events, and there is then efficient groundwater flow through the fissured limestone.

A critical feature in the Jabal is the fossil karst, dating from ancient wetter climates, probably during the Pleistocene. It includes many cave conduits, which have subsequently been partly or completely filled with clastic and calcite deposits. Where still open, these fossil caves are important modern groundwater routes. They are however few and far between. In the modern environment, most caves are being further filled and not enlarged; modern percolation water is depositing calcite in them, and erosive flood flows stay on the surface as they cannot normally find access to the deeper underground zones.

Overall, wadi drainage on the steep surface slopes is much more important than cave drainage. Caves have few opportunities to develop, and the synclinal location of Hoti Sink appears to be uniquely favourable. Wadi leakage has developed on a visible scale both at Hoti Pit and in Wadi Misfah. No other comparable sites are known, and though they may exist, they are not common; the observed wadis, even in the massive limestone, are notably lacking in sinkhole sites. Less conspicuous fissure sinks may be more widespread, as for example in the potential source area for the Ghubrat Tanuf Cave. Fissure inputs away from the wadis are important sources of percolation



The 45m pitch in Hufrah Misfah

water in the limestone. They are, however, rarely large enough to develop into open caves; Hufrah Misfah demonstrates the form these may take, but its size appears to be anomolous.

CAVE FAUNA

The Jabal Akhdar caves are like any others in a warm climate, in that they contain an extensive fauna which even non-biologists cannot fail to appreciate. Large huntsman spiders and tailless whip-scorpions were seen at a number of sites. Small bat populations occupy all the caves, and the Ghubrat Tanuf Cave contained at least two species of snake. This cave also had wasps' nests inconveniently sited in its narrow entrance, and many rock shelters contain large numbers of hornets' nests, which could be a major hazard at certain times of the year.

The most distinctive fauna are the fish in the Hoti cave. These are eyeless, pale pink in colour, and mostly 3-5 cm in length; they have been identified as Garra barreimiae (Banister and Clark, 1977). Large numbers of them were seen in all the lakes in the lower half of the Hoti cave, but the most remarkable concentrations occur in Fish Lake, just below the bottom pitch. At one point in this lake, hundreds of fish were crowded into a wall notch; there was no apparent reason for this behaviour, though it is possible that a bedrock fissure is yielding a small inflow which is somehow attractive to the fish. Even to the passing geologists, it was a remarkable sight.

ACKNOWLEDGEMENTS

The Jabal Akhdar Project only became a reality when it gained sponsorship from the Public Authority for Water Resources of the Sultanate of Oman. The Project programme was designed to give the team the opportunity to pursue their own karst studies and also to provide PAWR with hydrological data which they sought. Prime acknowledgements is therefore to William W. Doyel, Technical Secretary of PAWR, not only for the Authority's sponsorship, but also for their valuable support. Part of this paper is inlcuded in a research report prepared for PAWR.

The team also gratefully acknowledges Don Davison, John Kay, Dominique Dodge and many others from PAWR, for their hospitality and support in Oman; Brian Clarke of Medinat Qaboos, Ron Franks of Taylor Woodrow and Ali Suliemen for their very generous logistical support in Oman; Rod Dutton of the Centre for Overseas Research and Development at the University of Durham, Nigel Winser of the Royal Geographical Society, Gary Nicholls once of the Imperial College, and Mike Searle of Leicester University, for their time, effort and support in Britain; and the Ghar Parau Foundation, Sports Council, Trent Polytechnic and Sheffield University Department of Geography for financial and material support.

Lastly, the authors acknowledge John Middleton who provided the enthusiasm and motivation behind the whole Project, and was the fourth member of the team until a broken ankle tragically stopped him going to Oman.

REFERENCES

Banister K.E. & Clarke, M.A., 1977, The Freshwater species of fishes of the Arabian peninsula. J. Oman Studies, 1977, 111-154.

Brown R.D., Waltham A.C. & Middleton T.C., in prep., Microkarren in the limestone karst of Oman. Zeit. Geomorph.

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Cave Biology on Tropical Expeditions

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Abstract : Tropical cave biology is still in its infancy - unknown and exciting cave faunas await discovery in suitable habitats throughout the tropics. Expeditions visiting such regions should include caver-biologists capable of reaching the more remote and biologically rewarding deep-cave environments. Inclusion of a sound biological programme can benefit an expedition financially but such programmes should be prepared and executed thoroughly or not at all. Advice is offered on collecting and preserving specimens, recording data, obtaining identifications and writing a report. The need for conservation of cave life and courtesy to the host country is stressed.

INTRODUCTION

In recent years there has been a steady increase in the numbers of British expeditions visiting exotic regions of the world - may to tropical areas whose caves had hardly been explored, such as Papua New Guinea, Borneo, Java and now China. Often cave life of these areas is wholly unknown and sometimes the caves visited are so remote or require so much time and effort to explore that they are destined not to be revisited for many years.

Tropical cave biology is still in its infancy. Until recently, European and American cave biologists believed that creatures in tropical caves were hardly specialized for cave life and that cave-evolved "troglomorphic" animals were only present in significant numbers in caves of temperate latitudes.

The British New Guinea Speleological Expedition of 1975 was among the first of the big British expeditions to the tropics. It was unusual for its time in that it integrated a scientific programme with its sporting objectives, taking some members who performed a dual role as cavers and scientists. These included biologists, of whom the author was one. That expedition produced one outstanding and important biological discovery. Deep in Selminum Tem, the largest cave found by the expedition, Petar Beron and the author found a community of animals which consisted almost entirely of troglomorphic species - i.e. animals which looked and behaved just like the "true" cave species found in temperate caves. This community lived in small, flood-prone passages just above the level of the phreas, where slowly-draining flood waters deposit a harvest of food and where temperature and humidity of the cave air remains very constant. Subsequent visits to the caves of Mulu in Sarawak have revealed different, but equally specialised cave-evolved communities in other sorts of deep-cave habitats (Chapman, 1982). Meanwhile Frank Howarth, as far back as 1973, had begun to uncover yet another specialized cave-evolved community in tropical Hawaiian lava caves (Howarth, 1981).

Individuals of cave-evolved species are occasionally met in cave passages near the surface (e.g. Chapman, 1976:p.193) or are found in patches within the "transition zone" (Chapman, 1982) where the cave climate and food supply are of the "deep cave" type. However, in most large-diameter, dry, or draughty cave passages, or those which contain big populations of bats or swiftlets and lots of guano, there are few, if any, cave-evolved "troglomorphic" species. The larger, guano-rich passages are the very cave habitats which biologists who are non-cavers most often visit, simply because large, open caves are usually well known to local people and are easily entered. It is often only cavers who get into the really remote, small, flood-prone passages where most of the biological excitement lies! Too often on the big foreign expeditions, no-one on the team does any biological work, and an exciting and wholly unknown set of animals escapes notice altogether.

The author predicts with confidence that many tropical areas such as Gunung Sewu in Java and the huge karst areas of Southern China contain rich and complex troglomorphic faunas to match those of New Guinea, Hawaii or Borneo. Their discovery awaits the first biologist-caver who can get down deep into the damp, energy-poor, deep-cave habitats of these regions.

HOW NOT TO DO IT

A half-hearted study is worse than useless. If the biologist does no more than collect a few of the more spectacular cave-evolved animals for return to the U.K., he/she will not be doing any service to cave biology. What is needed in uninvestigated cave regions is detailed, systematic studies of whole cave faunas and their relationship to the cave environment. No cave biologist will be keen to do this when someone else has already "picked the plums" of the cave fauna, leaving only lots of hard work with few exciting discoveries in prospect. Expeditions should by all means record interesting general

The author at work in a tropical cave. Moist sediment banks such as these offer good collecting prospects. Here baited pitfall traps have been installed to catch cave arthropods. An air humidity measurement is in progress. (Photo Jerry Wooldridge).

observations of the cave life (e.g. Stoddard, 1985), but any expedition intent on collecting material should be systematic and thorough, or should leave such work to future investigators.

PRE-EXPEDITION PREPARATION

As with all other aspects of expedition work, successful biological studies are invariably based on sound preparation. The following guidelines are offered:

1. Keep you project to realistic proportions, bearing in mind numbers of personnel and time in the field. Identify the important questions you should investigate and collect relevant published information.
2. At an early stage, seek out and discuss your plans with someone who has done similar work to that which you are planning. It may save you many hours of fruitless effort.
3. Only when you have a clear plan of study, worked out in detail, should you approach funding bodies.
4. Beg or borrow equipment where possible from a university department, The Royal Geographical Society, the BCRA equipment pool, or the manufacturer, but do not rely too much on sophisticated electronic or delicate precision apparatus. Such equipment has a very short working life in a cave!
5. Check whether you need to approach the relevant authorities in the country you intend to visit for a licence to export preserved specimens. In general you will need such permission to export vertebrates, but not cave invertebrates. Detailed information about what permits are required by which countries, and how to apply for them, can be obtained from the World Wildlife Fund, 29 Greville Street, London EC1N 8AX.
6. Think about the volume and weight of equipment/specimens. Take the minimum you will need and always plan to carry any valuable material as accompanied luggage. Freight can be delayed, lost or damaged in transit and should only include insured, replaceable items, never your irreplaceable biological collections.

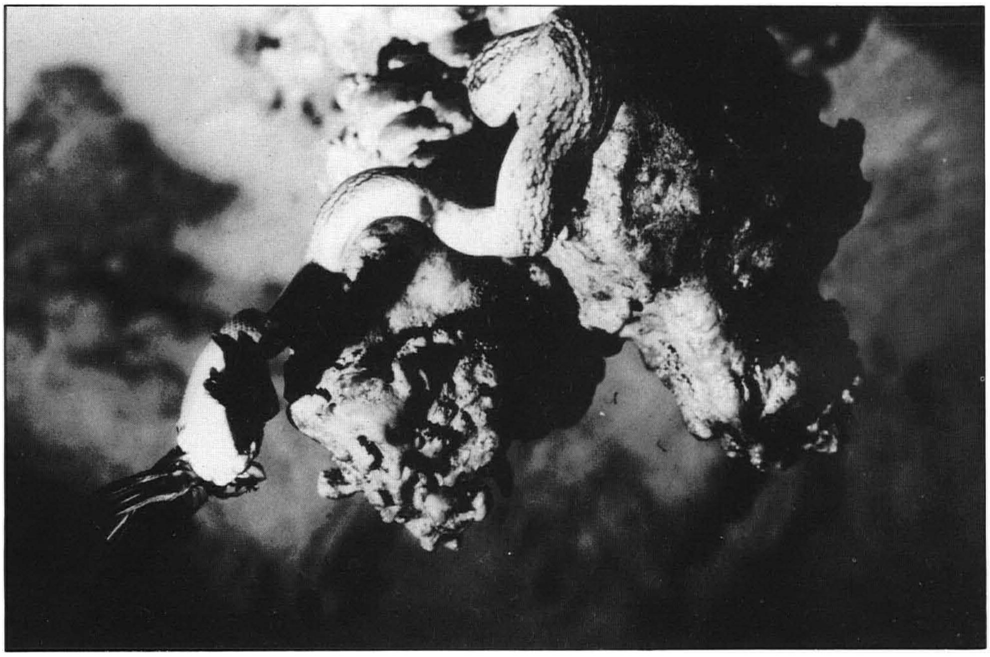
COLLECTING AND THE NEED FOR CONSERVATION

A dead animal is useful only to a specialist who can measure, describe and classify it. If an organism cannot be identified in the field, it may be collected, killed and preserved for later study by a specialist. If the identity of an organism is known and if it can be measured, photographed and described in the field, it should be released unharmed after examination. There is no excuse whatsoever to over-collect rare or unknown animals in caves, nor to mistreat them or damage their living space. Cave animals often have a very low population density and reproduce slowly and so are particularly vulnerable to over-collecting. The techniques involved in capturing cave animals and estimating their populations are much the same as those employed in similar non-cave situations. The reader is advised to consult any competent general text on ecological methods, such as Southwood (1978). A concise, inexpensive guide to biological collecting on expeditions is available from the Royal Geographical Society's Expedition Advisory Centre, 1 Kensington Gore, London SW7 2AR (Hollis et al., 1977).

A dead specimen is useless unless it is accompanied by details of at least where, and preferrably how it lived: its behaviour, food, numbers and habitat characteristics. Always keep a field notebook up to date. It is impossible to record too much information. On-the-spot written observations can often suddenly take on an importance years later which could not be foreseen at the time of writing.

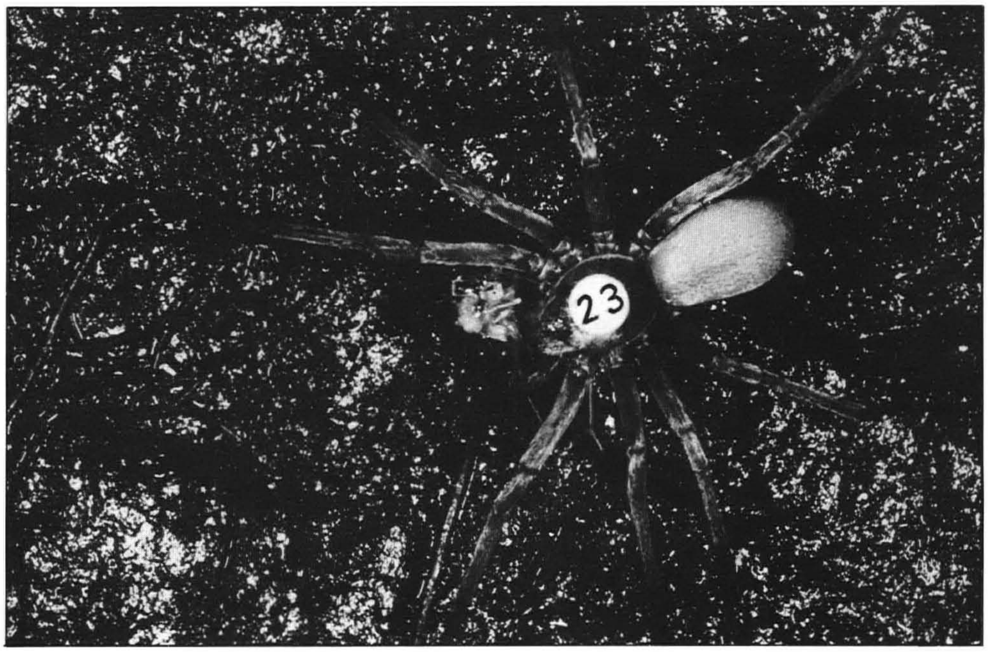
KILLING AND PRESERVING SPECIMENS

Specialists will advise on how best to kill and preserve their particular group of animals. Killing should be done quickly, humanely and without damage to the specimen's tissues. The British Museum (Natural History) publish a series of detailed guidelines under the title "Instructions for Collectors". As a general rule, insects with wings should be dried thoroughly and preserved in air, pinned in boxes, or loose in an airtight container. Steps should be taken to guard dried specimens against attack by fungus and other insects. Everything apart from winged insects may be preserved in a suitable fluid, my preference being 80% ethanol with 5% glycerol added. Some skill is needed to protect all specimens left loose in containers (in air or fluid) against mechanical damage in transit. Choosing a range of suitable-sized containers helps. The specimen should fit snugly, but not tightly into its container. Air bubbles should be excluded from fluid-filled vials and dead space should be filled with soft, non-absorbent padding. Make sure containers do not leak. For small specimens, I favour glass tubes with push-in plastic closures, and I usually double- or treble-pack specimens to prevent messy leaks which can ruin personal luggage. Customs officers can be suspicious of vials of preserved animals. I



Where possible instances of interesting or unusual behaviour should be carefully documented. Here a snake, perched on a stalactite, has caught a cave swiftlet in flight.

Cave animals can be marked to allow the behaviour of an individual to be followed over aperiod of time. This numbered spider is eating a cricket. How long until it will feed again?



usually mark boxed specimens with an ostentatious label to the effect that the package is destined for the British Museum and is not to be opened. Quiet insistence that the package can be x-rayed, but not unpacked, usually works! Finally, always include a detailed, pencil-written label inside each container with each specimen. Soft pencil shows up well after years and does not blur when immersed in preservatives. Labels on the outside of a container are easily lost or erased, and the unlabelled specimen is then virtually useless.

GETTING NAMES FOR YOUR ANIMALS

This is a long-standing problem. There are fewer and fewer specialists in the world working on an ever-increasing mountain of material from the tropics. Some groups of animals, such as spiders and millipedes which are particularly common in tropical caves, are almost impossible to get identified. The collector should be prepared for delays of several years with such material. Other groups, such as mammals, fish, beetles or crustaceans can be done very quickly. There is a need for a register of specialists who are prepared to accept cave material. Exotic material takes time for a specialist to identify and this costs money. If the material belongs to an undescribed species, it will take up more of a specialist's time and so will cost even more to classify and describe accurately for publication. Many institutions will waive the fee which they could justifiably charge for the work involved, in which case it is considered polite to offer them some specimens for their institution's collections even if they do not insist on this.

Many tropical countries have a well-established national collection and do not take kindly to visiting foreigners who make off with valuable biological material and then publish results only in their own country's periodicals, in their own language. If there is a well-curated museum collection in the host country, write and offer them material. Contact any relevant journals published in the host country and offer them an article.

If type specimens of new species have been promised to a specific collection, such as the national collection of the host country, it is important for the sake of future workers to abide by that promise and to make sure that the specialists to whom the material is offered for study will agree in writing to comply with such an instruction. It can be very difficult to recover valuable specimens from a specialist once they are in his/her possession. If possible check on the integrity of the specialist before parting with your collection. The author has learned this lesson the hard way, at the cost of much irreplaceable material!

Some specimens are worth money. They may be offered for sale to a well-off museum, such as the British Museum, to help towards the costs of the expedition. The going rate is what the museum is prepared to offer, so do not rely on selling specimens to pay off the expedition's debts. If it is suspected that excess material has been collected purely for sale, your career as an expedition biologist will be short, and rightly so! Often a deal can be made with a particular institution whereby you agree to collect specific material in return for an up-front payment. This is to be preferred on conservation grounds.

Many specialists prefer to have the fun of collecting their own study material in far off exotic places, and will not accept material from other collectors unless it is particularly interesting. It is therefore worth stressing the features of interest in your material when you first write to the specialist to ask for his/her help.

WRITING A REPORT

British cave biologists are very fortunate in having a regularly-printed, widely circulated vehicle in which to publish expedition scientific reports. This is, of course Cave Science. A preliminary report should be concise, informative and should be prepared as quickly as possible. As a complete description of the fauna often cannot be produced for several years, it may be expedient to make up descriptive names for individual species (e.g. Chapman, 1976) even though these may turn out, with further knowledge to be inaccurate (e.g. Chapman, 1985). Such an exercise is worthwhile if it provides information in a form which is useful to later workers - e.g. the preliminary report of the 1975 British New Guinea Expedition (Chapman, 1976) was frequently referred to by Smith (1980) who conducted a similar study elsewhere in Papua New Guinea with the 1978 Australian Atea expedition.

Copies of expedition reports should always be sent to individuals and institutions who have supported the expedition, and especially to any biological institutions in the host country with whom contact has been made, and who will probably have very little information about their own caves. Apart from being polite, such action is essential to ensure the continued tolerance to, and support of, future visiting expeditions by the host country.

IF YOU DO NOT TAKE A BIOLOGIST

There is life in the caves, even if the expedition has no biologist to point it out. Treat it with respect! The same conservation rules apply in foreign caves as in British caves. All rubbish should be removed from the cave, including spent carbide. Roosting bats or nesting birds must not be disturbed - they may be just as vulnerable as our own dwindling bat populations. In shallow caves, including lava caves, living tree roots may be the sole food source for cave animals - they should be treated as carefully as the most delicate speleothems. Finally, any caver can become aware of the life in the surrounding darkness of the cave. It does not require a head full of Latin names to appreciate the beauty of a perfectly-designed cave animal. Record what you see on film or in writing - you may have been the first person to set eyes on a wholly unknown creature!

REFERENCES

Chapman,P. 1976. Speleobiology. In: Brook,D.B. (ed). The British New Guinea Speleological Expedition of 1975. Trans.Brit.Cave Res. Assoc.3:192-203.

Chapman,P. 1982. The ecology of caves in the Gunung Mulu National Park, Sarawak. Trans.Brit.Cave.Res.Assoc.9:142-162.Chapman,P. 1985. Some biological results of the British New Guinea Speleological Expedition, 1975. Cave Science 12:45-48.

Hollis,D., Jeremy,A.C. and Lincoln,R.J. 1977. Biological collecting for a small expedition. Geographical Journal 143:249-265.

Howarth,F.G. 1981. Non-relictual terrestrial troglobites in the tropical Hawaiian caves. Proc.8th.Intern at Congress Speleol.,USA: 539-541.

Smith,G.B. 1980. Biospeleology. In: Caves and karst of the Muller Range (James,J.M. and Dyson,J.H., eds) 121-129. Speleological Research Council, Sydney, Australia.

Southwood,T.R.E. 1978. Ecological Methods. Chapman and Hall, London.

Stoddard,S. (ed) 1985. Anglo-Australian Speleological Expedition to Java 1984. Cave Science 12:49-60.

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The Blue Holes of Eastern Grand Bahama

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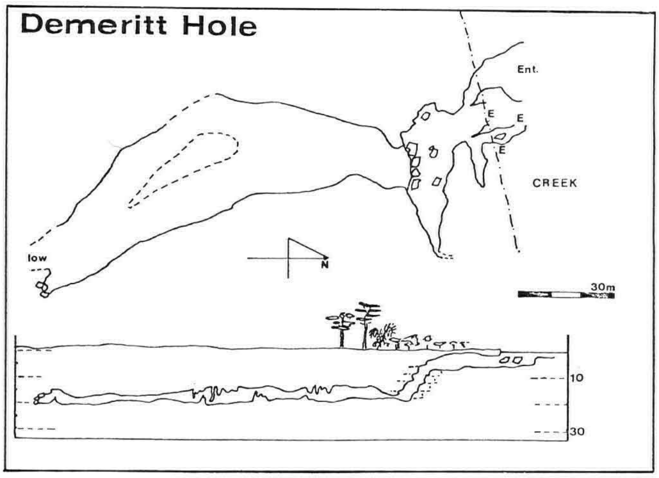
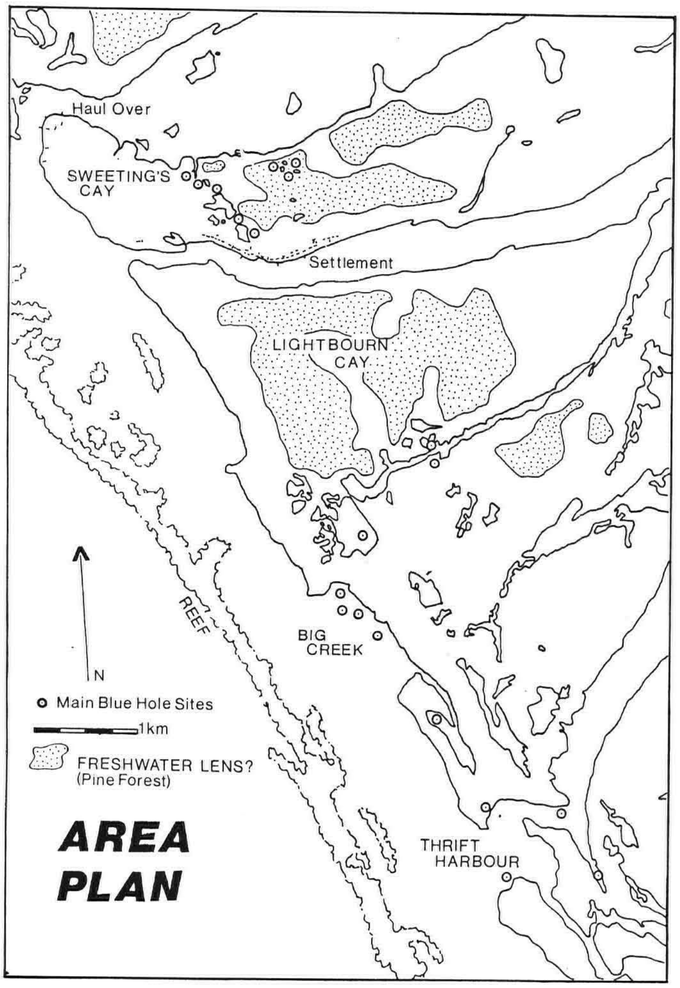
Abstract: The Blue Holes of Eastern Grand Bahama are described, with surveys of the most significant sites, including the major cave complexes of the Zodiac Caverns and Big Creek system.

The Blue Holes visited by the 1983 and 1984 Expeditions were those which could be reasonably reached from the south coast of the island in the time available. It is unlikely that they represent more than the more obvious sites. Other Blue Holes have been identified from the air and many remain unvisited. It is recommended that future expeditions use aerial survey as patterns of cave development become better known. The sites described below are the major sites explored; where other significant sites are known, mention is made.

McLEAN'S TOWN AREA

The Blue Holes in the McLean's Town area divide into three main groups, those in Little Big Water Bush Creek and Big Water Bush Creek behind the township, those offshore on a fracture line inside Sam Laing's Cay, and the Henford Holes, off Crabbing Point, a little to the north of the village.

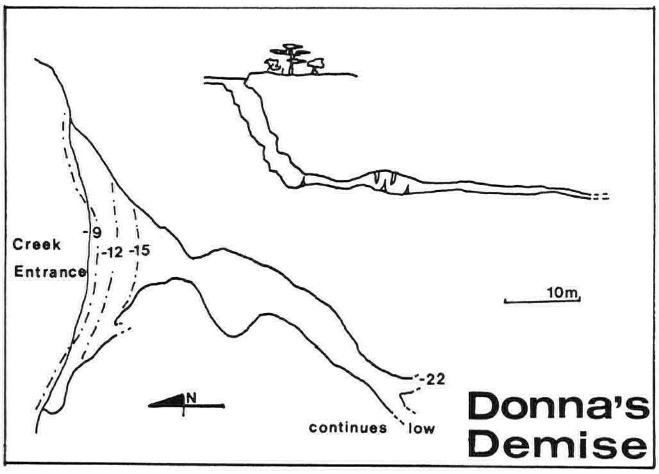




The Creek Holes

Demeritt Hole: (NGR: RV 030514) A cave in the creek immediately north of the village, where a complex entrance leads back beneath the shoreline to a chamber at a depth of -3 to -5 metres. Four separate entrances unite at the edge of the 20m long chamber. A shaft along the southern walls falls past collapse debris to -20m, where a low bedding enters a large, silt-floored passage, well-decorated with speleothems. The cave can be followed past silt-banks and small grottos for 175m to a low wide bedding, where the way on is not obvious. A reasonable current flow was evident in the passage, though not at the entrance.

Donna's Demise: (NGR: RV 033514) The entrance to this Blue Hole is a large aston collapse several hundred metres east of Demerritt Hole, on the south side of Big Water Bush Creek. The 30m long entrance contains a good variety of marine life, but is less exciting underground, leading at -15m to a very silty passage. An initial chamber at -19m contains wide silt-banks with some

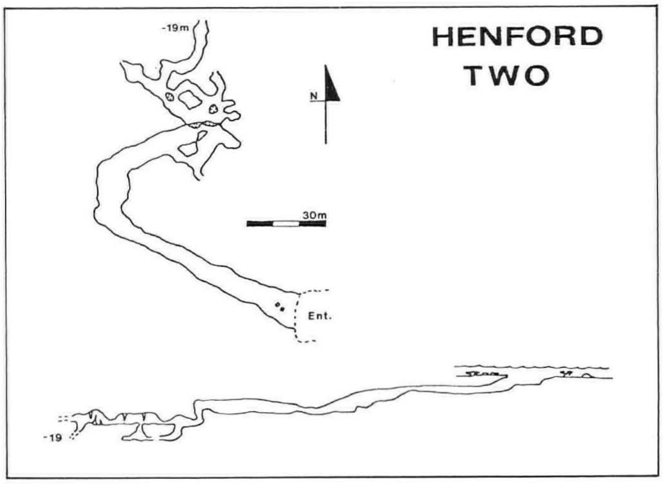


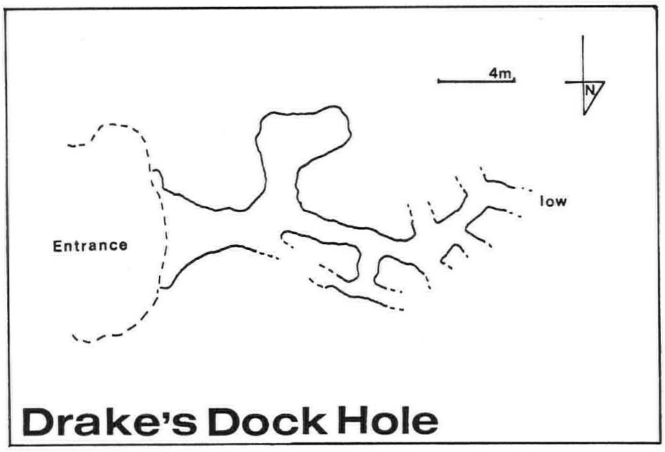
evidence of current patterning, and leads to a low, silt-floored passage which can be followed for 80m before splitting, both ways on becoming too low.

Hole "C": (NGR: RV 033513) Undivided, this small Blue Hole lies in a land-locked and shallow lake between Donna's Demise and the village. The latter cave trends towards this entrance, and the two are probably associated.

There are several undived entrances along both the creeks behind the village, on the farther shores, but a detailed aerial survey would be advised before searching from the ground.

Drakes Dock Hole: (NGR: RV 057056) Total length: 70M. Depth: -15m. This is a large entrance in Rumer's Creek across from Drake's Dock. The entrance is a large semi-circular collapse which slopes down on the eastward side to a wide cavern at -15m. A sizeable passage closes down on the left and a continuation to the right quickly splits into small and constricted solutional bedding caves.





Henford Hole One: (NGR: RV 016510) Total length 300m. Depth 19m. This is the outermost of two ocean Blue Holes 1km west of McLean's Town, near Crabbing Point. The entrance is almost 500m from the shore, and is surrounded by a small coral reef. It descends -10m, where a large horizontal passage leads east. Eighty metres in, shafts in the floor are too tight to descend, but a further shaft at 140m leads to a short length of passage at a depth of 19m. The main passage divides at 180m, and both branches out eventually become too constricted. The water currents are very strong in this cave.

Henford Hole Two: (NGR: RV 016449) Total length: 290m. Depth: -19m. The entrance lies in 3m of water, where a slope leads into the cave at -6m. A descending passage, with dimensions varying from 0.5 to 5m, continues for 130m before descending through a small rift into a series of stalagmite chambers. These soon break up into a maze of smaller tunnels, which become too constricted. The currents at this site are extremely strong.

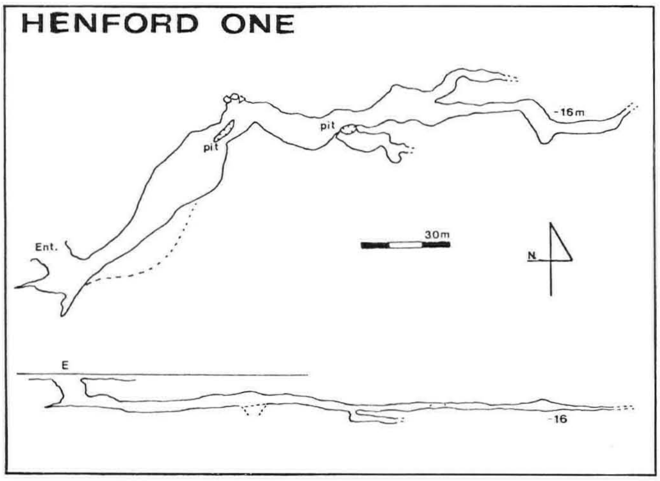
Sam Laing's Cay Blue Holes

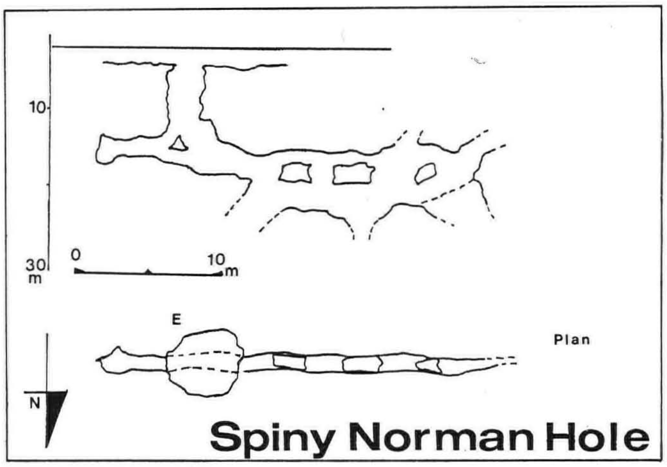
These holes are described from east to west, starting north of the small islet of Sam Laing's Cay, and are a series of Blue Holes running parallel to the coast on a SE-NW line. Exploration shows that the series appeared to deepen to the NW, a depth of 36m being gained in Shell Hole. Of over a dozen entrances, only four lead to caves worthy of description, The remainder, despite food current flow, close down in tight horizontal passages at a common depth of -3m.

SL1. Outboard Hole: (NGR: RV 037506) Length 50m. Depth -36m. A complex opening emitting a strong reversing current. A few metres inside the horizontal entrance passage at -3m, a vertical rift descends, immediately becoming too constricted.

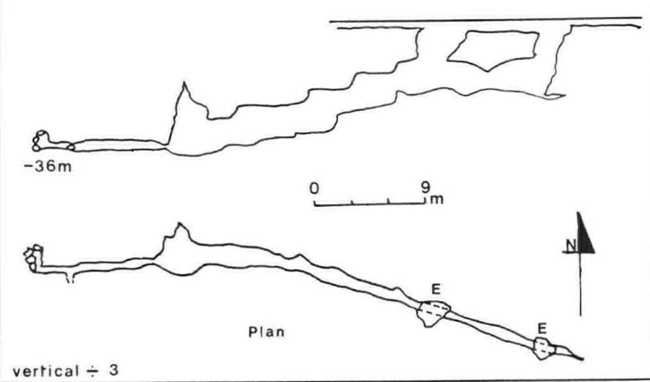
SL2. Sam Laing's Blue Hole: (NGR: RV 040505) Length 30m Depth 20m. This is the longest entrance in the McLean's Town group, a 30m long rift which descends vertically to -18, from where narrow passage can be followed for 20m, past 3 squeezes, before becoming too constricted. Much marine life is present. The large number of cowrie and tulip shells in this and nearby holes is probably related to the surface environment of the caves, which lie in extensive seagrass beds.

SL3. Spiny Norman Hole: (NGR: RV 034507) Length 30m Depth 20m. A circular entrance 3m in diameter narrows quickly, bottoming at -13m. A restriction at this point can be passed to reach several small passages. All become too constricted.





Shell Hole



SL4. Shell Hole: (NGR: RV 033507) Length 50m Depth 36M. The most westerly of the Blue Holes in this series, where twin entrances unite at a depth of -15m in a rift passage. A series of steps down lead to a large passage, which ends in a chamber at -36m. Straight on from this, a smaller rift passage, almost infilled with pebbles and sand, can be followed to the terminal choke.

THE ZODIAC CAVERNS

The Zodiac Caverns were the major discovery of the 1983 Expedition, extended again in 1984. This complex system lies beneath the small island of Sweeting's Cay, forming a fossil hydrological link between the north and south shores of the Cay via three surface lakes. These lie over what must have been an extension of the cave series, before collapse at some time in the past. The average depth of the Caverns is between 15 and 20m, and all the caves contain extensive speleothems. There is a marked thermocline throughout the series, which in 1983 was at -16.5m(±0.5m), and in 1984 at -19m(±0.5m), the water below being markedly cooler (1-2°C) and clearer than above. It is assumed that the current flow (most obvious in Aquarius and Scorpio) is active only at the highest levels.

ZC1. Aquarius: (NGR: 097475) Length 360m. Depth 30m. From little Harbour Creek, a small mangrove creek leads south into the shoreline (Zodiac Creek). Aquarius lies at the end of the first right-hand branch. The entrance is a deep rift, exhibiting aston collapse features, and containing an established marine fauna not normally associated with shallow mangrove creeks. Sponges, corals, fish and crustaceans abound. The entrance is very constricted, and the way down not obvious. At a depth of -15m, a rift on the south side leads to a wide bedding passage, increasing in size to a height of 1.5m and a width of 6m. At 45m from the entrance, a large stalagmite column bisects the passage. At 75m, the passage splits. Left is Pisces Passage, a large, well-decorated passage with an average depth of 20m, and with colder, clearer water than the entrance series. No current flow is evident in this section of cave, and the passage ends 140 m from the entrance in silted alcoves, after passing through several decorated chambers. Ahead at the junction is a low, silt-floored section which emerges after a constricted 10m in Hinchliffe Hall. At a depth of 17m, this chamber is 60m long, over 30m wide, and is on average 4m high. It is profusely decorated with stalactites, stalagmites, columns and smaller dripstone. All of these have been much encrusted with marine fauna, and sponges and polychaete worms can be seen growing upon them. Straight across the chamber, containing south, is a rift series, the Scorpion's Tail, that is gained past a floor-level squeeze under a large block at 180m. At the end of the rift, 240m in, the passage degenerates from dimensions of 2m x 10m to a ridiculous constriction, and soon after splits into tiny phreatic tubes. Holes in the floor along the Scorpion's Tail descend to -30m, but are choked. The east wall of the chamber was not thoroughly investigated and there may be a lead heading towards Gemini. The reversing tidal current is lost at the entrance to Hinchcliffe Hall and may head towards Gemini near this point.

ZC2. Scorpio: (NGR: 094474) Length 100m. Depth 18m. At the head of Zodiac Creek, a complex area of Blue Hole development contains only one cave, Scorpio, at the corner of the final creek junction. The rift entrance bottoms at -3m, and is followed along rift passage for approximately 20m to a depth of -10m. Here the passage enlarges into a low series of stalagmite chambers to a junction at 50m. The left branch soon becomes too low, but the right leads to a wide, sloping chamber with many speleothems, and there is no way on.

ZC3. Gemini: (NGR: RV 098474) Length 450m. Depth 24m. Gemini is a traverse cave, connecting the small lake near Zodiac Creek with the larger Lake 2 to the south. A sizeable entrance in the corner of Lake 3 descends steeply to a junction at -12m. To the left a small, low passage leads after 50m to a well-decorated chamber at a depth of -15m. Right, a very low section soon reaches larger passage, again well-decorated. This narrows at 50m, then opens into the splendid Stalgazer Hall, a chamber 70m long, 20m wide, and on average 3-4 high. This is beautifully decorated with stalagmite, stalactite, columns, flowstone cascades and curtains, occasionally straw stalactites, all unfortunately stained and encrusted with small marine fauna. Two passages lead off on the west side, at depths of 18m and 20m, ending in breakdown and blind chambers. At the far end of Stalgazer Hall, a further junction is met. To the right opens out and then ends on a cross rift after 80m. Left leads to a steep slope and Gemini Two entrance.

ZC4. Pisces (NGR: TE 123466) Length 310m. Depth 30m. The entrance to Pisces lies at the head of the western branch of Lake 2. A very narrow rift descends to a low chamber at -20., floored with fine silt. Across this, a breakdown area has a blind passage at -21m. An opening above the breakdown enters a large chamber, The Crabwalk. The floor rises to a column grotto at a depth of 10m. The chamber carries on for 75m, with a width of 30m and an average height of 2m, across a breakdown floor. Down the south-west wall, speleothem-encrusted breakdowns blocks can be seen jumbled together at a depth of 20m. Beyond, there is a second, smaller chamber and a final rift passage which splits into small phreatic tubes at a depth of 30m.

ZC5. Virgo (NGR: TE 125465) Length 240m. Depth 22m. The entrance lies in the south-east corner of Lake 2, where two openings lead into a narrow descending rift, enlarging to a long, horizontal gallery at -22m. A major junction is reached 50m in at -17m. Right, an upward slope leads into a magnificent decorated chamber, the Red Room. Straight ahead lies another magnificent hall, the White Room, sloping up to a depth of -10m. The formations in this section are pristine, with no encrustations of tannine staining. From the top of the chamber, a low, wide bedding passage leads to an unstable area of fresh breakdown. Left at the main junction leads to a complex series of smaller chambers and passages not fully examined.

Lake 2. A large entrance in the south-west corner was explored to a complete choke after 30m.

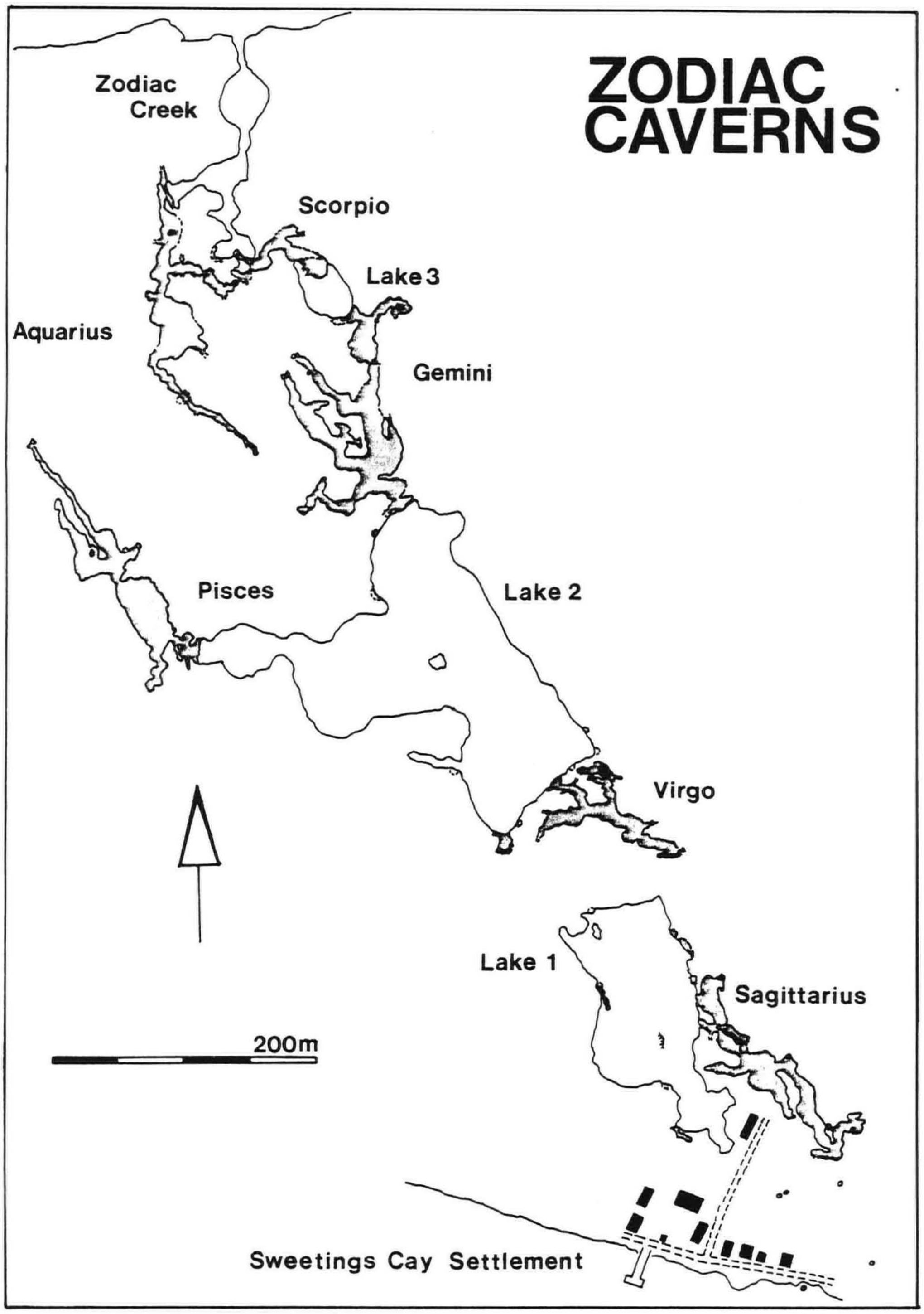
ZC6. Sagittarius (NGR: TE 127463) Length 380m. Depth 22m. The only major cave discovered leading out of Lake 1, the entrance to Sagittarius lies midway up the east shore of the lake. A vertical descent in the larger of the two entrances leads to a large passage at - 10m. Shortly beyond the junction with the other entrance passage, a hole on the left leads to a lower series at -22m. Water in the lower parts of the cave is much clearer and cooler than above, and the speleothems there show less sign of staining or corrosion. The main passage continues above the hole, at a depth of -15m. Left at a second junction leads to a passage well-decorated with speleothems, though some of these have a bizzare and thick encrustation of serpulid worms. A further 60m leads into the Ice Queen's Palace, a glittering cascade of crystal speleothems of every imaginable type. This splendid grotto is the finest in the Zodiac system. Through breakdown blocks at the far side of the chamber, the route continues to a final junction. To the left, the cave ends in two small chambers at -20m. On the right, a steep slope of organic debris ascends through sulphurous water to pass through a thin freshwater lens below the entrance to Sagittarius Three, too blocked to surface in.

A further 110m of dry land divides the end of Sagittarius from the creek. Several rubbish-choked entrances lie en route. There are no other major cave enterable from Lake 1; all the other entrances explored choked in silt and boulders a few metres away from daylight. There may still be unexplored caves in the small, mangrove-enveloped lakes to the west of Lake 1.

Two ocean holes in the creek, near the village pier, were infilled with conch shells following the drowning of a young girl, who was drawn into the cave by the strong inflowing tidal currents. Currents still flow at this site, but the inflow and outflow times at these choked holes appear to co-incide with those at Zodiac creek, suggesting that the flow is from east to west (and vice versa), below the inland itself.

THE LENS CAVES

1km east of Zodiac Creek, where the pine forest almost reaches the shoreline, a series of caves a few hundred metres inland lie underneath a thin freshwater lens. The entrances to each of the caves lie in small surface ponds, surrounded



by a dense growth of deciduous scrub, with many orchids and bromeliads.

Davin's Cavern. (NGR TE 129469) Length 100m. Depth 20m. The entrance lies in the south-west corner of a small lake, approximately 200m inshore from Little Harbour Creek. A descent down the silt-floored entrance slope leads to a well decorated passage, into a chamber, 50m long and 40m wide, with no obvious continuation.

Asgard. (NGR TE 130430) Length 200m. Depth -24m. A larger lake 100m east of Davin's Cavern contains two cave entrances. The entrance on the south side is Asgard, where a steep slope of organic detritus descends through the halocline at -13m to reach a well decorated chamber at 20m. There is no way on at this depth, but above the halocline, a way through speleothems on the west leads to a large passage trending south-west. Most of the cave is effectively a long collapsed chamber, with the floor at -10m. The chamber is well decorated throughout, the density of columns in the upper chamber being staggering, though all those above the halocline are stained with iron deposits precipitated from the freshwater lens. After 120m, an ascent up a collapse bank leads to a small aston chamber at -3m, and there is a lower chamber looping round at -24m.

Lucy's Cave (NGR: TE 130470) Length 300m. The large entrance to Lucy's Cave lies at the far side of the lake from Asgard. A sloping bank of organic detritus leads to a low squeeze over silt banks to gain a small enclosed chamber in clear salt water at -24m, well decorated, but with no apparent continuation. Back at the silt-squeeze, turning left through an even lower squeeze leads after several metres to an enlargement of the passage to more comfortable dimensions. A further 30m of well-decorated passage reaches one of the largest underwater chambers so far discovered in the Bahamas; the Hall of Time is 140m across, 50m wide, and up to 10m high, at a depth between 20 and 30m. The chamber is stunningly decorated, with secondary regrowth apparent on many massive fallen speleothems. Smaller passages to the north and west were not pushed to a conclusion, and neither was a second chamber to the south-east.

BIG CREEK CAVES

A linear group of Blue Holes, developed on a major slump fracture, extend the length of Big Creek, paralleling the coast on a SE-NW alignment. The marine Blue Holes are shown on the map , but the line of openings is known to extend north into a low mangrove/swash area, and south towards Thrift Harbour. Entrances in these two latter areas have not been examined. Not all surface openings in the area have therefore been recorded, nor have all diveable openings been explored. Those which were are described below, together with comments on other inspected entrances. Many of these would bear future examination.

Caves are numbered from north to south, as shown on the map . The shoreline on the map is that at low tide. Star ratings indicate the potential for exploration.

BC 1: Hole below mangrove bush with strong tidal currents. Possible entrance to Great North Road.

BC 2: Rift entrance with strong currents. **

BC 3: Entrance to Great North Road (see BC 8). A constricted descent through jammed boulders on a 45° slope leads at -20m to the main G.N.R. cave passage.

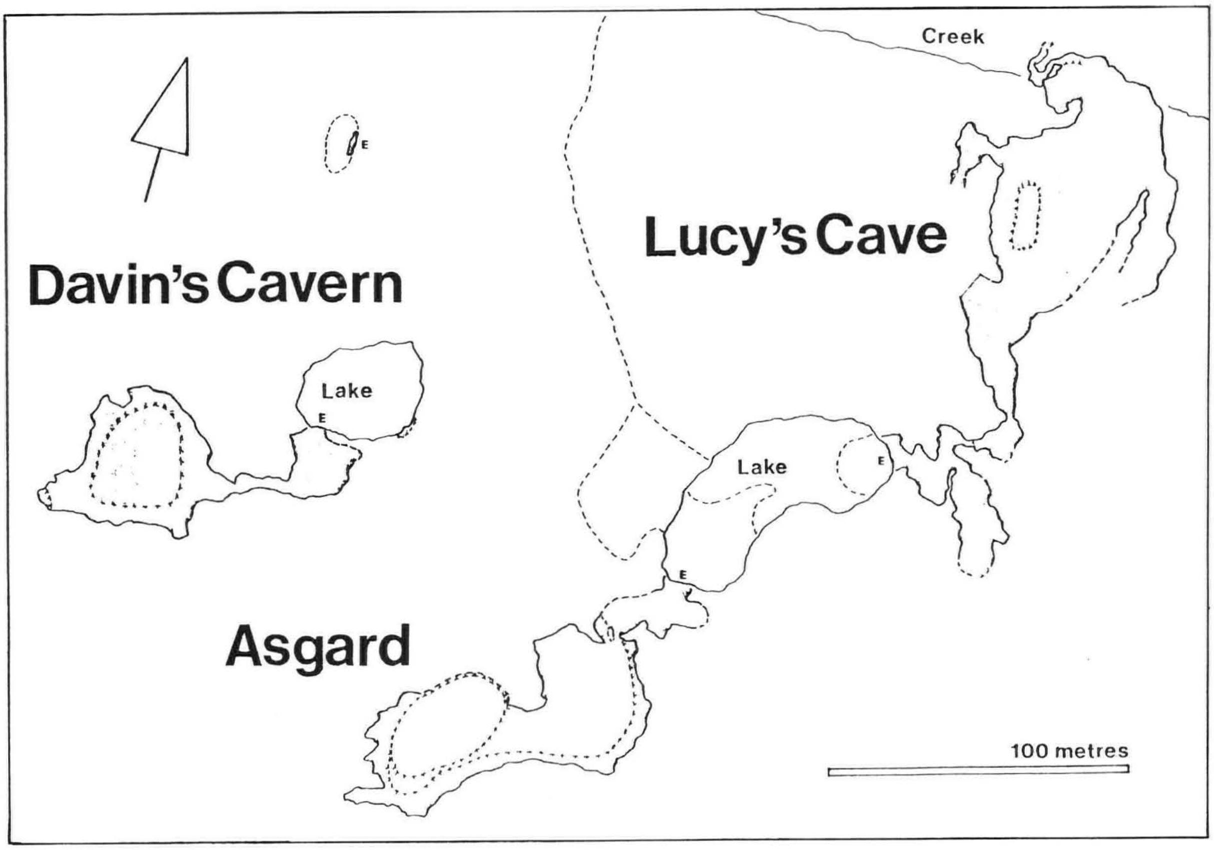
BC 4: Offset from main fracture, in the centre of a small creek. ***

BC 5: Rift entrance 10m long by 1m wide. Probable G.N.R. entrance. ***

BC 6: Small entrance, probably G.N.R. entrance.

BC 7: Offset from main fracture. **

BC 8: The Great North Road. (NGR: TE 134428) Length 270m. Depth 75m. This is the main cave entrance to the deepest cave system so far discovered on Eastern Grand Bahama. The 30m long, 1m wide entrance descends past a series of ledges to -20m, where it opens into a vast passage over 30m high, and 3m wide. The southerly continuation remains unexplored, but is heading towards Lothlorien, 100m away. North-west, at a depth of -40m, the cave continues for 150m



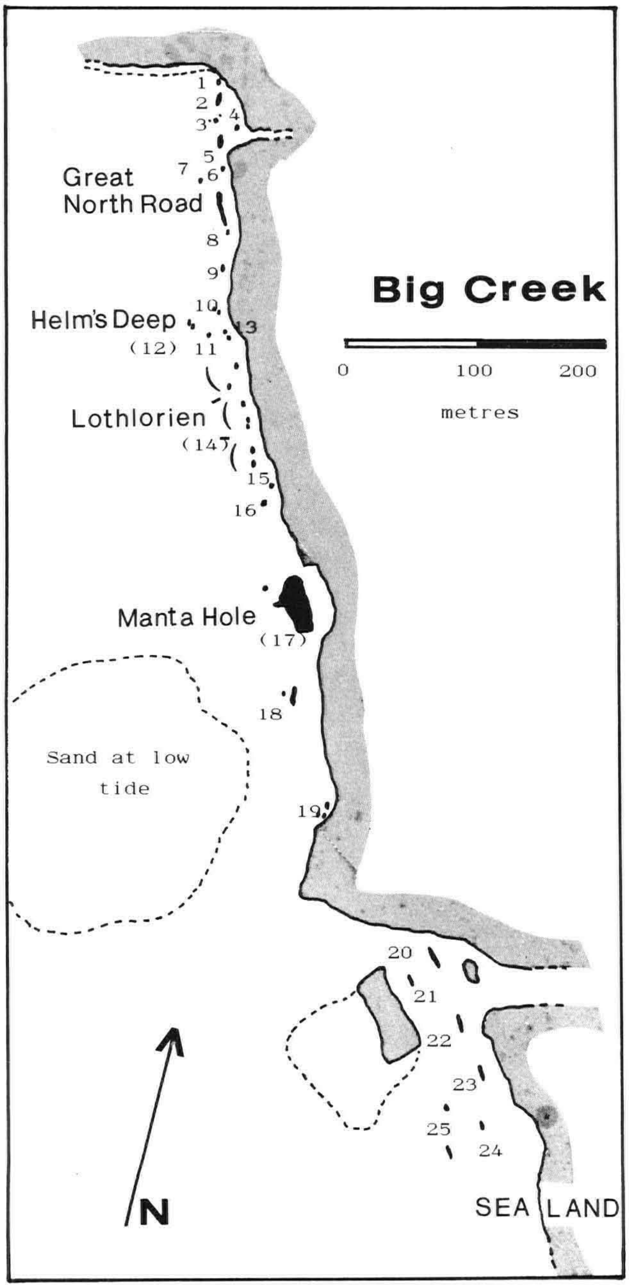
to an obstruction at -38m. Beyond it the way on descends to -60m, below a flat roof. Past the roof, there is an ascent to -48m, and then successive narrowings to a depth of -75m, still in descending cave 3m wide. No floor can been seen to at least -90m in this mammoth fracture cave. The furthest point gained in 1984 was 270m from base, at -75m depth.

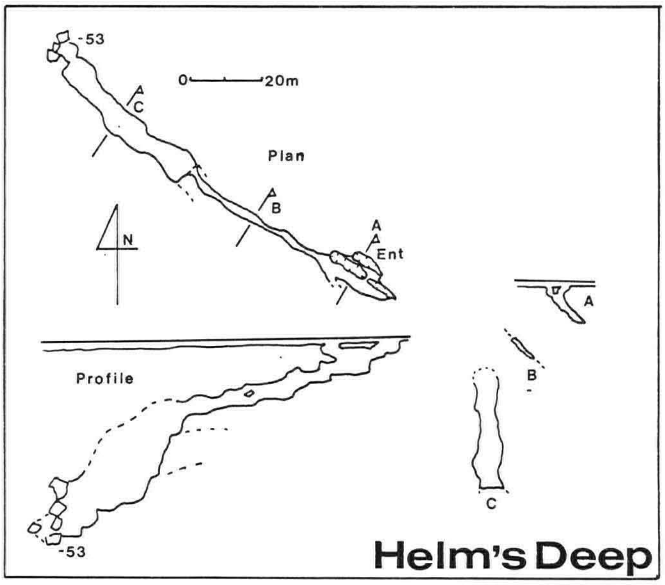
BC 9: Small entrance. **

BC 10: Twin cave openings. **

BC 11: Group of 4 openings. Constricted. **

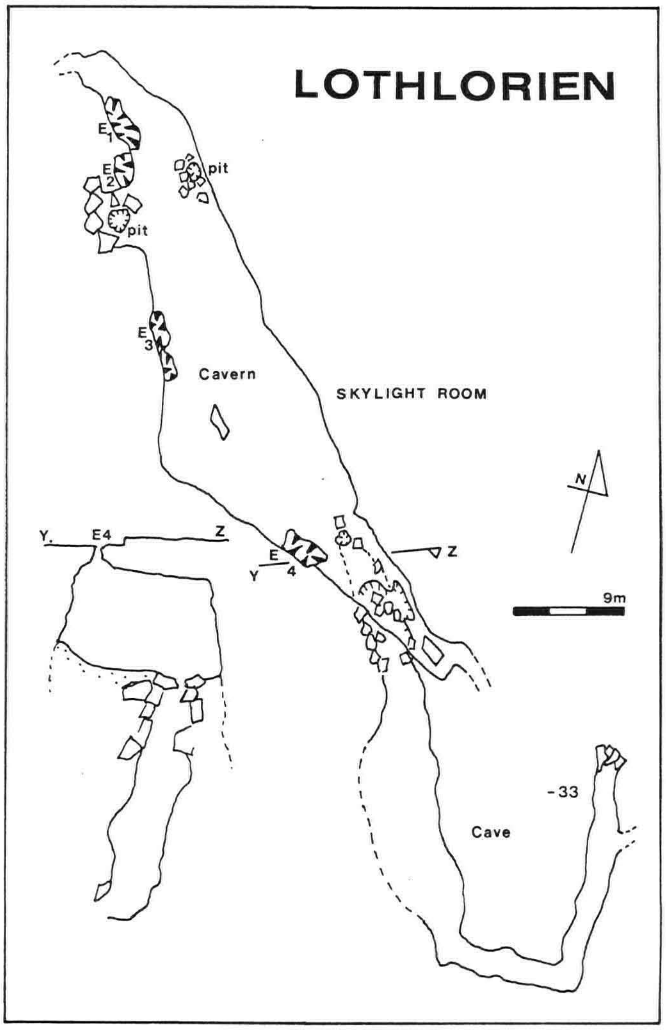
BC 12: Helms Deep (NGR: TE 134427) Length 100m. Depth 53m. 24m seaward from the main fracture line, Helm's Deep's twin entrances unite at -3m. The cave has strong currents, and the constricted nature of the entrance series makes exploration with back-mounted tanks impossible. At -15m in the entrance rift, a rift passage was followed north-west for 50m, slowly getting deeper, into the roof of a much larger passage, 4m across, followed for a further, descending 50m. At -53m, a huge boulder collapse appears to block the way on. A possible south-east continuation below the entrance rift was not examined.

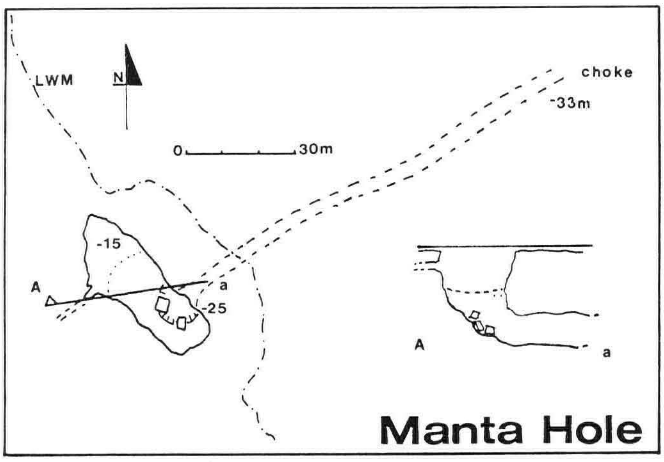




BC 13: A small entrance between BC12 and BC14. *

BC 14: Lothlorien (NGR: TE 135427). Length 150m. Depth 33m. BC14 is the northern of five entrances which unite in this spectacular underwater cavern. Roof depth is -3m, length is 70m, width 20m, and floor depth varies from -15 to 20m. A massive central stalactite dominates the chamber, which is atmospherically lit by daylight streaming from the entrances above. A way down through a boulder pile in the southern





floor drops steeply to 32m. There, the passage splits and both branches are choked.

BC 15: Small opening offset from the main line. **

BC 16: Small opening not considered diveable.

BC 17: Manta Hole. (NGR: TE 136425). Length 175m. Depth 30m. The largest and most obvious Blue Hole in the Big Creek area. The entrance has formed through collapse, is 25m deep at its southern end, and has surface dimensions of 40m by 15m. Passages lead both east and west. The west passage mostly 10m high and 2m wide, has been followed for 175m to a boulder choke. The eastern passage has not been fully explored, but appears to be a constricted rift.

BC 17a:A small opening a few metres seaward of Manta Hole.

BC 18: Narrow, 18m long rift opening. No diving prospects.

BC 19: Three small entrances, with good currents, in the south corner of the main Big Creek bay. ***

BC 20: Rift entrance, 17m long and 0.75m wide. **

BC 21: Opening 3m long, 11m seawards from 20. **

BC 22: Rift opening with weak current. *

BC 23: Rift 10m long. Small Current. *

BC 24: Small unenterable opening, with no obvious current.

BC 25: Small opening offset seawards from BC24. Not diveable.

BC 26: As BC25

BC 27: Small opening with some current flow. *

Inland from Big Creek, and probably associated with the Big Creek caves, are several other Blue Hole sites. The most notable of these end of Lightbourn Creek (NGR: TE 143442), where the tidal flow along the creek from the north shore of the island apparently goes underground, probably to emerge from the Blue Holes at the northern end of Big Creek. Passages in this entrance area have been explored by Dennis Williams and others for an unspecified distance.

Far North Blue Hole. (NGR: TE 1366434). Length 75m. Depth 22m. This small Blue Hole lies below the northernmost of two lakes, in line with the terminal direction of the Great North Road. The cave excurrents when the Big Creek caves incurrent. The entrance passage is small, and leads after 75m to a narrow rift and boulder choke at -22m.

The whole Big Creek-Lightbourn Creek cave complex is one of the most significant systems discovered in the Bahamas and is certainly deserving of further exploration. No other trans-shore system has so far emerged, and the development on deep vertical fractures is of considerable geological interest.

Access can only be gained to the Lightbourn Creek complex during a narrow tidal window, when Lightbourn Creek is deep enough to permit access from the north with a shallow-draught boat. The possibilities of stranding over a full tidal cycle need to be added to the dangers of decompression when considering exploration at this site. The only other access is on foot, over difficult terrain from Big Creek itself.

THRIFT HARBOUR CAVES

Thrift Harbour lies at the south-eastern extreme of Grand Bahama, at the entrance to the creek of the same name. There are four Blue Holes known, although others may exist.

TH 1: (NGR: TE 1500400) A small Blue Hole at the mouth of the bay; it emits a strong excurrent.

TH 2: (NGR: TE 147406) This cave lies in a small embayment on the north-west side of Thrift Harbour. There is reputed to be a descending passage leading to an underwater chamber.

TH 3: (NGR: TE 154406) An undived Blue Hole lies at the entrance to the Creek containing TH4

TH 4: Sandy's Blue Hole. (NGR: TE 157401) This large Blue Hole lies in a small tidal creek separating the bay from St Michael's Cay. The entrance is a classic aston collapse, where an underground chamber has migrated upwards, to create a surface opening. There is a low passage at the base which has been explored for 100m.

THE BLUE HOLES EXPEDITIONS

The 1983 International Cave Diving Expedition, and 1984 British Blue Holes Expedition between them explored over 5km of previously unknown underwater cave passages beneath the East End of Grand Bahama Island.

The 1983 expedition was organised as a joint venture with Bahamian and U.S. cave divers, although in the event the field work centred on the discoveries of the three British divers, who were joined when time allowed by a total of six Bahamian and Florida-based cave divers. The joint work was useful in that it provided a chance for the divers concerned to observe different techniques from either side of the Atlantic, and fostered links between the cave diving countries represented. A total of 21 days were spent in the field, and over 2.5km of cave passage explored in both inland and ocean Blue Holes in 1983. The expedition was based in the village school in McLean's Town. The British team members were financially supported by Wookey Hole Caves Ltd, Rolex UK and the Royal Geographical Society, and the British Sports Council.

In 1984, a five-person British team returned to the same area, with a 4-person film crew, to continue the physical and scientific exploration of the East End caves and make a natural history documentary on the inland and ocean Blue holes for the BBC. These explorations were again supported by the Royal Geographical Society, Sports Council and Ghar Parau Foundation, and were under the Royal Patronage of H.R.H. The Duke of Kent. The expedition was based at Haul Over on Sweeting's Cay, in accommodation provided by John and Eileen Schlanbusch. The team spent 38 days in the field and explored a further 2.5km of caves, making significant biological and geological discoveries in the process. These are outlined in greater detail elsewhere in this report. The filming project was equally successful, and a 25-minute documentary was produced, due for screening in late 1985/86.

ACKNOWLEDGEMENTS

Both expeditions were the result of a considerable amount of work by many people other than the actual Expeidtion members. To all those named below, and to all those who helped in any way, we give our most grateful thanks.

The Expedition Royal Patron, H.R.H. The Duke of Kent, Royal Geographical Society, Ghar Parau Foundation, Wookey

Hole Caves Ltd, Pan-Am Airways, Freeport Harbour Company, Zodiac UK Ltd, Bahamas National Trust, Grand Bahama Rotary Clubs, Princess Hotels Ltd, Underwater Explorers Club, Spirotechnique UK Ltd, Varta UK Ltd, Apeks Marine Ltd, Typhoon UK Ltd, Phoenix Mountaineering Ltd, Honda UK Ltd, James Pearsall Ltd, Camera Care Systems Ltd, Kodak UK Ltd, The Sports Council, Rolex UK Ltd, Arrow Air Ltd, Moonbridge Shippers Ltd, Freeport Power Company, Outboard Services (Freeport) Ltd, Grand Bahamas Minstry of Education, Solomon Bros. (Freeport) Ltd, Deep Water Cay Ltd, Institute of Oceangraphic Sciences, GUL Wetsuits Ltd, SOS UK Ltd, Wemlor Marine Ltd, 3M Thinsulate Division, Sea and Sea Ltd, U.M.E.l. Ltd, CPL Bristol Ltd, and Fuji UK Ltd.

In the Bahamas: John Hincliffe, Dennis Williams, Jill Yager, Jack Hayward, Jack Worsfold, John and Eileen Schlanbusch, Jack Rogers, John and Mary Brooks, David and Michael Pincus, Colin Rose, Martin Gaucci, Doug Silvera, Theo and Alex Galanopoulis, Godfrey Waugh, Ben Russell, Nick van Beurden, George and Donna Hume, and the people of Sweeting's Cay and MacLean's Town.

In Britain: Frank MacBratney, Tony Boycott, George Warner, Sir John Rawlins, Bernard Parker, Pat Cronin, Phil Chapman, Peter Smart, David and Jenny George, Tony Colwell, Richard Brock, Daniel Plummer and the late Oliver Lloyd.

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APPENDIX 1 TEAM MEMBERS

1983: Robert Palmer, Dennis Williams (Co-Leaders), Rob Parker (UK), Julian Walker (UK), Gene Melton (USA), George Hume (Canada/Bahamas), Dr Anitra Thorhaug (USA), George Thompson (USA) Jeff Bozanic. (USA)

1984: Rob Palmer, Rob Parker, Julian Walker, Sarah Cunliffe (biologist), Lucy Heath (geologist). Film crew: Peter Scoones, Leo Dickinson (cameramen), Mandy Dickinson, Georgette Douwma.

APPENDIX 2 TRANSPORT

In 1983, the British team flew out under sponsorship from Arrow Air. Freight was shipped by Moonbridge Shippers Ltd from London to Freeport, Grand Bahama, and driven there to the East End by truck provided by Dennis Williams, Bahamian-based Co-Leader of the Expedition. Transport in the field was by a 6-metre Zodiac GR.MK4, with a 35hp Johnson engine (the former on loan from Zodiac UK, the latter from Outboard Services Ltd of Freeport). This proved entirely adequate for the shallow seas and reefs, and for accessing sites up shallow inland tidal creeks. On occasion, for the most inaccessible sites, diving equipment was carried on foot over the difficult limestone bush terrain.

In 1984, the British Expedition was greatly assisted by Pan Am Airways in transporting both personnel and filming equipment to the United States. Trans-Atlantic freighting of equipment was again provided by Moonbridge Shippers Ltd, to and from Freeport. Freeport Harbour Authority and Freeport Power Company provided transport of personnel and equipment to East End, and travel in the field was again Zodiac GR MJ4, and a small 3m whaler on loan from John Schlanbusch. Aerial reconnaissance was provided by Dennis Williams and Jack Rogers.

In 1983, fuel was ferried in from Freeport, but this was obtained locally on Sweeting's Cay in 1984. The slightly-higher local price was more than offset by the logistical problems of Freeport supply. Drinking water on both expeditions was obtained from public standpipes in MacLean's Town; Sweeting's Cay water is brackish, and not fit for consumption. Little food other than fish and some fruit was available locally, and most supplies were brought in from Freeport at regular intervals.

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The Effect of Anchialine Factors and Fracture Control on Cave Development below Eastern Grand Bahama

R J PALMER and L M HEATH

Abstract: Cave development beneath eastern Grand Bahama is closely related to the vertical position of a Ghyben-Hertzberg freshwater lens, development being additionally enhanced where major fracture zones exist parallel to the south edge of the Little Bahama Bank. Horizontal devlopment occurs during periods of eustatic stability, and vertical development during periods of eustatic fluctuation. Collapse within the caves is progressive, encouraged by solutional acitvity at the mixing zone and enhanced by the removal of buoyant support of the rock during periods of eustatic exposure.

British cave divers have investigated underwater caves (Blue Holes) below the eastern end of Grand Bahama during two expeditions in 1983 and 1984. The area studied extended from Crabbing Point to Thrift Harbour on the south-western coastline, to a maximum inland extend of 2 km from the shore. A total of 92 cave openings were examined during these two field periods (Palmer, this volume) and of these 16 lead to cave systems over 100 m in length. Over 5 km of cave passages were explored by expedition members over the two periods,

Grand Bahama lies on the Little Bahama Bank. Like the majority of Bahamian islands, it is formed from consolidated calcarenite dunes on the windward side, backed by low-lying oolitic limestones and calcareous muds. Unlike most other Bahamian islands, where dune ridges are on the eastern coasts, the Grand Bahama dunes have built up along the the south shore of the island, and are orientated east-west. The original Pleistocene dunes have greatly eroded, and the highest point on the island is only 22 m above current sea-level. Most of the dune rock has an average elevation of less then 10 m. Later Holocene aeolianites, often unconsolidated, fringe the southern shore. Sea caves in the Lucayan National Park at Gold Rock Creek provide evidence for high eustatic sea-levels at approximately while submerged dune ridges and wave-cut platforms overlain by secondary reef growth can be observed in the Peterson Cay Land and Sea Park, suggestive of a standstill of sea level 2 to 3 metres below the present. This lower stance may have a significant relationship to the development of anchialine (lens-based) caves on the island.

On Grand Bahama, the development of caves has been observed to relate to both the vertical position of fossil and current freshwater lenses and the occurrence of slump fractures which parallel the New Providence Channel on the south side of the island (Williams 1978; Palmer 1984). The island contains what is currently the most extensive underwater cave system in the world, the 10 km long Lucayan Caverns at Gold Creek. Similar anchialine systems have been discovered both in the nearby Owl-Hole/Mermaid's Lair systems and the more distant Zodiac Caverns at the eastern end of the island. These extensive horizontal networks have developed at the base of ancient Pleistocene freshwater lenses in the manner described by Palmer and Williams (1984) and Back, Hanshaw and Van Driel (1984), at a time when eustatic sea-levels were lower than today, though perhaps by only 2 or 3 m. Speleothems formed during periods of sub-aerial exposure in the Lucayan Caverns during low eustatic sea-stances have been dated at around 60-70,000 years B.P., suggesting this date as the minimum possible age for caves. The modern halocline is evident only in the very highest regions of the caves, in areas associated with present-day secondary solution or collapse of existing passage roof, the latter presumably enhances by solutional activity at the overlapping halocline.

At the eastern end of the island, anchialine and fracture-controlled caves are closely associated. Where major slump fractures open to the surface at MacLean's Town (Shell Hole, etc) and Big Creek (Great North Road, Helm's Deep, etc.), mixing zone activity at the base of ancient lenses has preferentially enlarged these pre-existing weaknesses through solution and associated wall-collapse. This has been encouraged by the removal of the dissolved limestone by tidally-related marine currents which flow below the halocline (Williams, 1979). It appears that the primary level of cave development in eastern Grand Bahama has been at a depth of approximately -20 to -30 m, depending on the

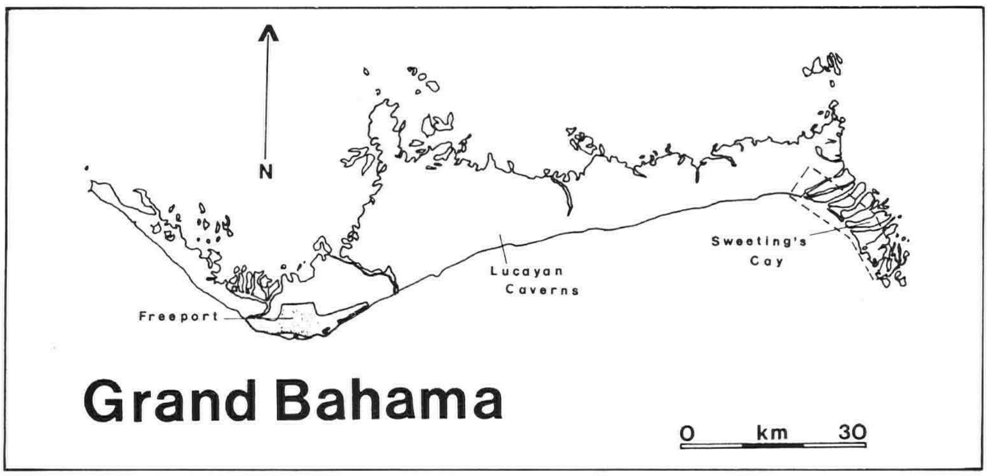


Figure 1

position of the cave relative to the curvature of the lens base. Caves nearer the platform edge are shallower than those further inland (the Henford Holes, 0.5 km offshore from Crabbing Point are 15 to 19 m deep, whilst Lucy's Cave in the centre of Sweeting's Cay has solutional features at -30 m). In Big Creek, the primary development level appears to have been around -20/25 m. The presence of large solutional passages below the common roof depth of -20/25 m in these Big Creek fracture caves, which extend to depths in excess of 75 m, is in accordance with the eustatic fall in sea-level (and corresponding downward movement of the freshwater lens) during the late Pleistocene, which reached its maximum depression of approximately 120 m between 15-18,000 years B.P. We can presume the fracture caves, therefore, to have a potential depth of at least 120 m, plus the depth of the freshwater lens at that time. The lack of large solutional passage above the -20 m mark is the result of the rapid rise in sea-level at the end of the Pleistocene, the freshwater lens rising too quickly for large passages to form. The main fracture caves of eastern Grand Bahama currently have no lens above them, and most lie offshore in shallow marine bays. There may be a relationship between the formation of these bays and the presence of the caves, as suggested by Back, Hanshaw and Van Driel in 1984, from studies of similar features on the Yucatan Peninsula of Mexico.

Rock walls in the fracture caves are typically planar, though highly-corroded by marine organisms (polychaetes, sponges, bivalves, etc.) which have obscured much solutional evidence. The occurrence of massive boulder piles across the deeper parts of all these caves is indicative of wall collapse infilling the lower parts of the fractures. Sand and skeletal debris is transported for considerable distances into the caves by the tidal currents and current-patterning has been observed over 150 m from the entrances to Manta Hole and Great North Road. Entrances to such caves form where the fissure extends to the surface and has been enlarged by a maximum of biological corrosion and marine abrasion, or by collapse of the overlying rock.

Slump fracture caves are distinctive in that they are vertical, deep, and contain little horizontal development other than along the line of the fracture itself. The main fractures can be seen from the air; they are curvilinear, often complex, and may extend for several kilometres. They are intersected by major joints at approximately right angles and large passages taking strong marine currents have been occasionally explored along these joints (Great North Road, Manta Hole) away from the main slump fractures, but exhibiting the same deep vertical morphology. A network of such fissures may form the dominant control in the presumed underground hydrological connection between the Big Creek fracture caves and a major Blue Hole complex at the south-west end of Lightbourn Creek, where the

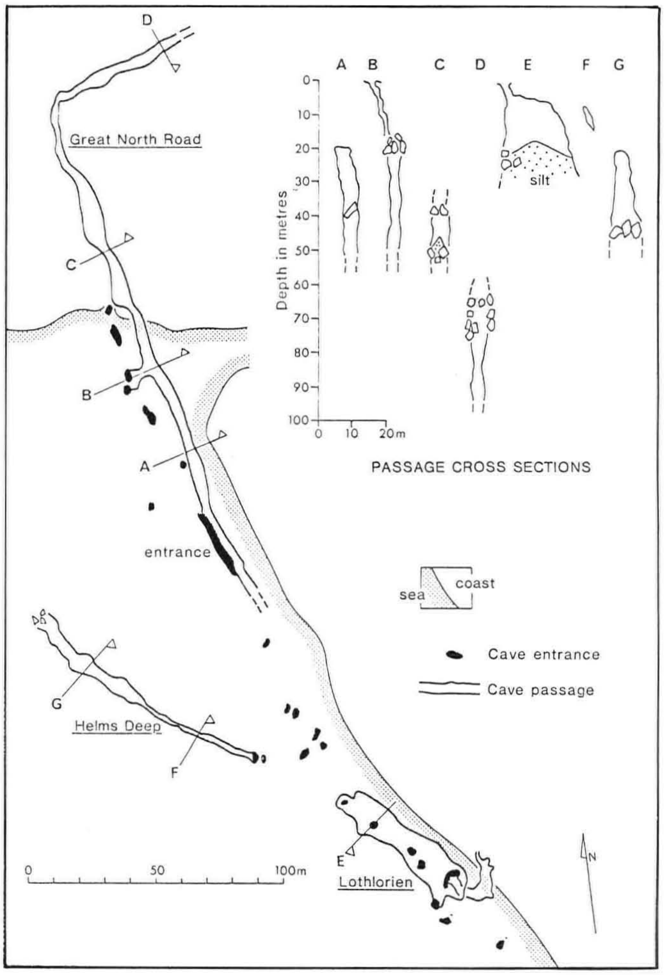
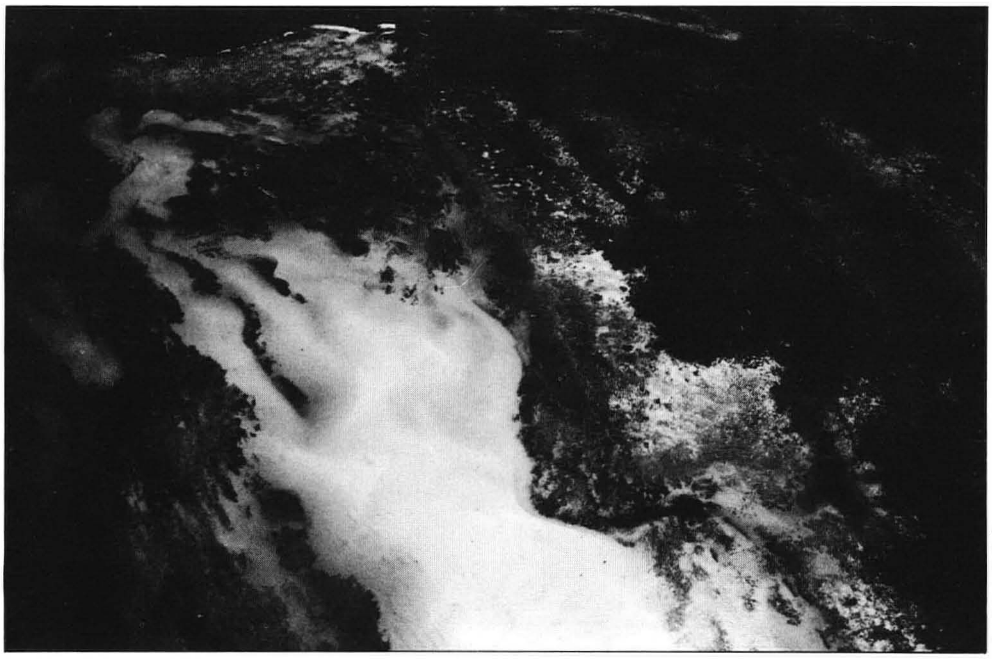


Figure 2. Cave passages below northern Big Creek.



Aerial view of Big Creek, looking north. Manta Hole is in the centre of the photograph, and the fracture governing cave development beneath Big Creek can be seen above and below the Manta entrance.

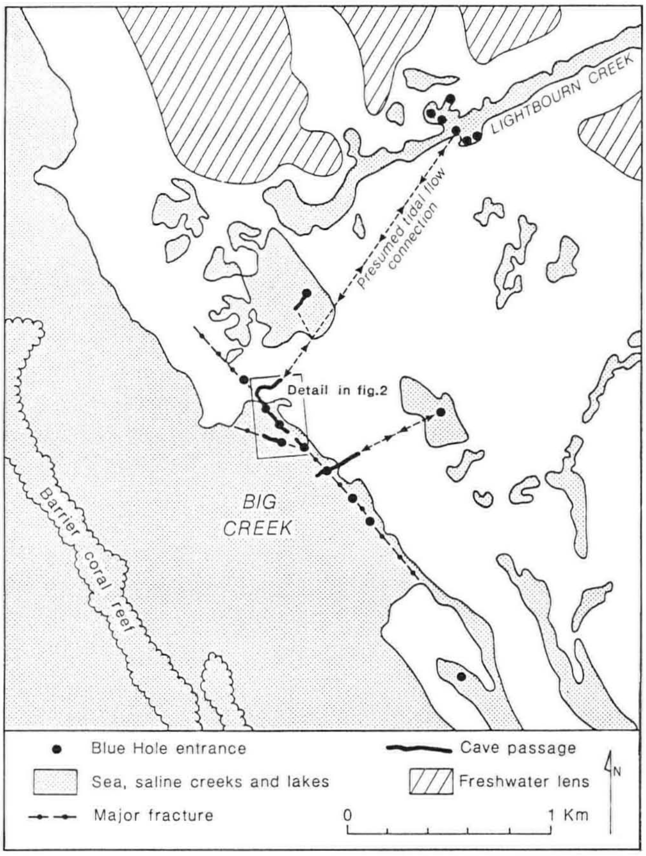
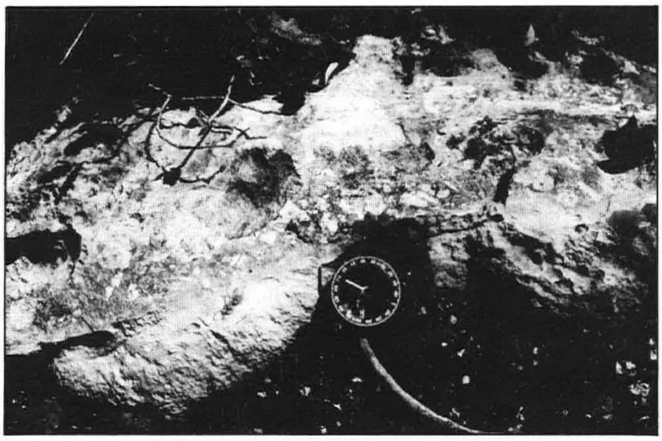


Figure 3. Area plan of Big Creek/Lightbourn Cay, showing orientation of Blue Holes on major fracture line in Big Creek, together with presumed underground tidal flow connection with Lightbourn Cay Blue Hole complex.

major north-shore tidal creek ends abruptly and the flow goes underground (Fig 3.).

Fractures traced on the surface at Big Creek and Sweeting's Cay exhibited both solutional enlargement and secondary infill, usually a pink micritic matrix (Heath and Palmer, this volume). Some contain angular fragments of limestone within this matrix, (Plate 2) and as there is no evidence of displacement along the inland fractures, this infill is not considered to be a fault breccia. The evidence suggests that these features can be considered Neptunian dykes, i.e. fractures infilled with penecontemporaneous sediments, including reworked limestone as sharp as fragments which have undergone little transport or erosion. There is some evidence for separate phases of fracture widening in the form of zoned infill.



Fracture infilled with a pink micritic matrix, containing angular fragments of limestone.

Further inland from the platform edge and the slump fractures, the influence of the mixing zone becomes more significant, and the caves correspondingly more complex. Although many of the main cave passages are still orientated on, or bounded by, major joint or fissure lines, these fissures are linked horizontally at distinct depths by phreatic mazes of horizontal lens-base passage, as shown in Pisces (Fig 4), in the Zodiac Cavern System. Here, two major parallel fissures are linked by large phreatic chambers. The main of phreatic development in the Zodiac Caverns has been between -20 and -24 m, with phreatic enlargement of fractures extending upward to -12 m and downward to -30 m. The -20/25 m level can be assumed to represent the position of the mixing zone at the base of the freshwater lens during the formative period of the caves. A fall in present-day sea level of between 2 and 4 metres would be enough to create such a lens. The present-day freshwater lens of Sweeting's Cay is much reduced, and is heavily contaminated by saline intermixture and organic material in solution. It can be seen to a depth of -12 m in the caves of the Asgard System, 1 km to the north-east of the Zodiac Caverns. Fluctuating sea-levels since the formation of the caves have been exposed them to sub-aerial conditions and, during suitable climatic conditions, extensive speleothem deposits have developed throughout the caves. Sections through speleothems collected for dating purposes have shown that there has been more than one inundation/exposure cycle during their development, with the presence of layers of salt water corrosion or freshwater tannine staining in the cross-section.

Collapse of wall and roof material has occurred throughout the Zodiac system. Primary collapse seems to have occurred in response to solutional weakening of roof and wall rock under the original phreatic conditions, such collapse debris being typically clean blocks which exhibit solutional fretting on all surfaces, and visible only in the deeper phreatic passages of the inland caves.

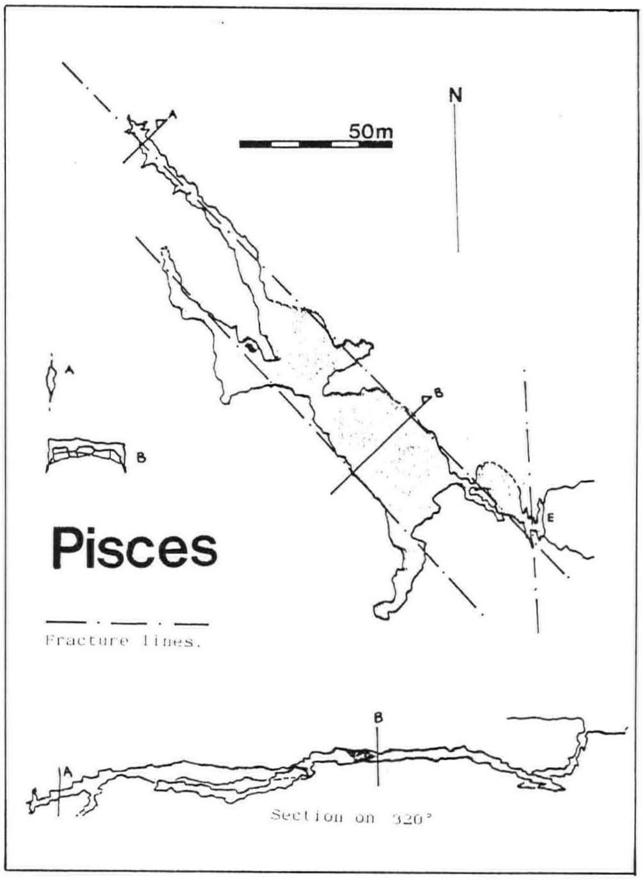


Figure 4

The removal of buoyant support from the roofs of the caves during periods of eustatic exposure has encouraged secondary collapse (aston collapse) of the overlying rock into the caves beneath, and this has been particularly extensive where the horizontal phreatic development has been bounded on all sides by major vertical fissures (eg. Section B in Fig 4, where collapse reaches to within 10m of the surface). Such collapse material is typically composed of large flat slabs of roof-rock, exhibiting little if any solutional fretting. In extreme cases, such collapse has been responsible for the creation of surface depressions, such as the shallow but extensive lakes behind the settlement of Sweeting's Cay, associated with the Zodiac Caverns. The full extend of the Zodiac System is now obscured by the huge collapse zones which have created the lakes, beneath which the greater part of the original cave network must have lain. Entry to the inland caves is sometimes possible where such collapse exists, and routes may be explored down the sides of the collapse debris into the continuation of the caves beneath. We can presume that there must be many solutional cave networks beneath the Bahamas which remain inaccessible to exploration through the lack of such collapse entrances.

Mixing zone solution below the freshwater lens has been responsible for the creation of massive voids below Sweeting's Cay. The largest so far explored, the Hall of Time in Lucy's Cave in the Asgard System, has dimensions of 140 m in length, 50 m in width and 10 m in height at a maximum depth of -30 m. Elsewhere in Asgard, upward migration of the cave through aston collapse has reached -3 m without final collapse of the overlying rock. The presence of extensive speleothem development in both these chambers, and on the collapse debris of all the entrance slopes to the inland caves, suggests that no major collapse has occurred since the last major rise in sea-level some 10-15,000 years B.P.

MORPHOLOGY OF THE ZODIAC CAVERNS

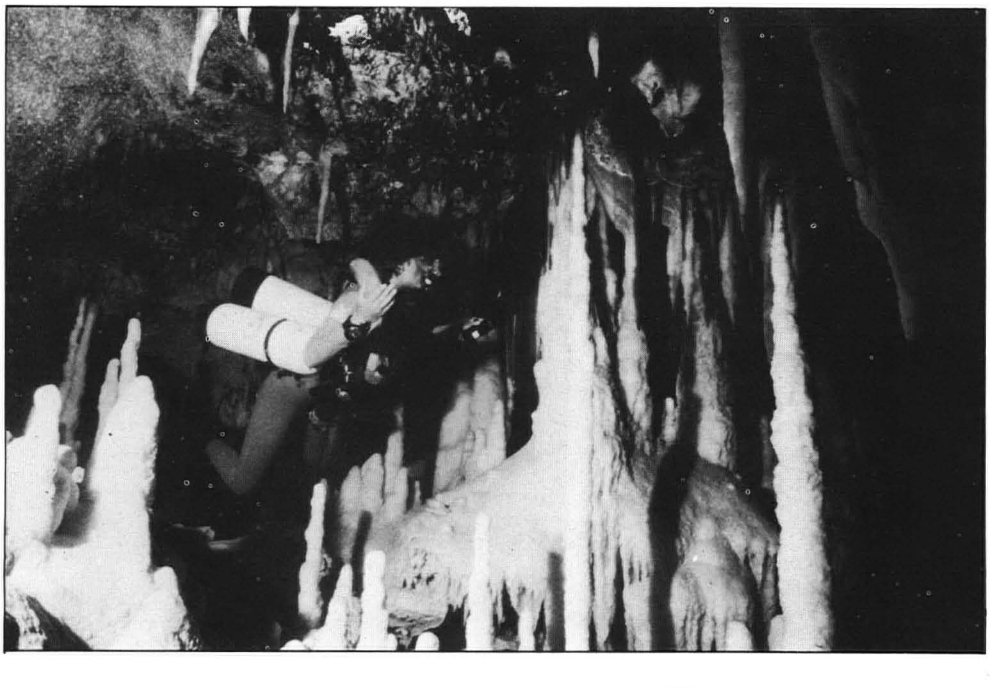
Aquarius extends from the base of the aston collapse forming the end of the Zodiac Creek. The entrance passage to the cave is orientated along a major fracture which is also responsible for the entrance to Pisces Cave. The passage shape is obscured by sediment, but appears to be solutional in origin, unmodified by collapse, with walls and roof scoured and corroded by organic growth (sponges, hydroids, etc.) and tidal flow. Pisces Passage in Aquarius is largely sediment-free and is a remnant of the original -20/22 m solutional development level. Collapsed blocks exhibit solutional fretting on all surfaces, and the walls are pitted by solutional corrosion. Hinchcliffe Hall, the largest chamber in the cave, owes its morphology to extensive roof collapse between vertical fractures during a low sea-level stillstand. Speleothem deposits on top of the large slabs of collapse debris are extensive and there appears to have been no additional collapse since the last eustatic rise. The deep passage that leads south from the chamber has formed by solutional enlargement of a major fissure at an obtuse angle to the entrance fissure. The fissure forming the final Aquarius passage also controls one of the deep solutional passage in Gemini. The main enlargement of the fissure in Aquarius is between -18 and 24 m, but narrow shafts in the floor descend to depths in excess of -30 m. Collapsed fragments of wall exhibit fretting on all surfaces, as do the walls themselves. The rock in this section is clean, white, and extremely friable. The passage ends in small solutional tubes along the main fissure line.

Scorpio, entered from the Zodiac Creek aston collapse, appears to be the original continuation of Pisces Passage in Aquarius, linking it with Gemini before the major collapse event which formed Zodiac Creek and Lake Three. It now consists essentially of a single sediment-floored horizontal chamber, blocked by banks of sediment and collapse at each end.

Gemini is in essence a single long chamber between two associated fractures, floored by secondary roof collapse, but with deeper side passages at the old solutional level. The shallow passages have clean, speleothem-covered walls with little solutional pitting, whereas the deep solutional passages, despite a similar speleothem coating, have walls which are fretted and friable. The cave ends at the massive collapse which now forms the base of Lake Two.

Pisces contains some of the most dramatic collapse, its two chambers having formed between two major fissures. Extensive roof collapse has floored the chambers with massive bedding slabs. Speleothem deposits on top of these are small and poorly-developed and it seems reasonable to assume that this collapse was one of the last major events before the final, post-glacial eustatic rise. The deep solutional fissures at the end are similar to the final passage in Aquarius, extending to -30 m in places, with white, very corroded rock.

Virgo at the opposite end of the lake to Pisces and Gemini, has also been much modified by collapse. The original solutional level is only



Extensive speleothem deposits in Sagittarius Cave

The entrance series of Lucy's Cave with a fine group of stalagmites, and roof scallop marks providing evidence of phreatic solutional development.

visible at the entrance to the cave, where the walls exhibit solutional fretting and scalloping. The rest of the cave is formed by a series of inclined collapse chambers, well-decorated with speleothems in their upper levels. The passages to the east of the entrance lead to a series of extremely loose fissure-orientated passages. A small passage at -12 m at the southern end of the cave may have collapsed since the last rise in sea-level. The rock now flooring the passage is clean and fretted, with no sediment or speleothems.

Sagittarius, the only major cave to lead from Lake One, has largely escaped the destruction of the other Zodiac Caverns. It seems to lie just outside the main fracture zone, and as a result the original deep solutional passages can be observed clearly,. Away from the organic sediments of the entrance series, the cave is effectively a series of solutional chambers which lie at the primary -20/22 m level. The floor is often obscured by large limestone blocks with solutional fretting on all surfaces. Some of these blocks also host speleothem deposits which, due to their current erratic angle, have obviously developed before the blocks fell from their original positions. It appears therefore, that at least some of the primary collapse either occurred during the first stage of eustatic exposure, or that it occurred during a second inundation/solutional phase of development.

The Asgard System is characterised by the presence of a shallow freshwater lens, which is evident throughout the three caves associated with the system by its tannine colouration, the result of a high organic input from the overlying pine forest. Though much of Asgard is greatly modified by major roof collapse, its deeper regions below -20 m are typical of the deep Zodiac development. Speleothems are unusually dense in the upper collapse zone, despite the minimal rock overburden.

Davin's Cavern is similar to Asgard in most respects, save for the lack of a deep solutional zone beyond the collapse area. The entire original solutional chamber appears to be in the process of migrating to the surface through roof collapse.

Lucy's Cave is perhaps the most enigmatic. It exhibits solutional fretting and passage development to -30 m, and contains the largest single void so far discovered on Grand Bahama (The Hall of Time), Its walls display well-defined phreatic scalloping, its speleothems suggest two discrete development stages separated by a major collapse event (and possibly also by eustatic inundation and retreat), and there are narrow clean bands on stalagmites at around -26/27 m. These might suggest the presence of a stable, but tidal, lake in the chamber at some time in the past, or alternatively, they might mark the level of a former halocline.

The Zodiac Caverns appear to have developed along a line of fracturing parallel to that of the marine slump-fracture caves, but approximately 2 km further inshore. Whether this secondary fracture zone is related to the slump-faulting, or whether both sets of fracturing (and Bank platform edge) relate to a pre-existing joint network, is unresolved. Such a joint network might, as suggested by Newell and Rigby (1957), be orientated in response to the original underlying topography beneath the Bahama Banks themselves. If so, such an explanation would go far towards solving the peculiar orientation of many Blue Holes on major fracture lines on Grand Bahama and elsewhere in the islands.

The secondary Zodiac Caverns fracture zone can be traced south-east through the Lightbourn Cay Blue Hole complex, and a further series of shallow inland lakes on Lightbourn Cay and Gainum's Cay. This suggests the possible presence of other, as yet unexplored, caves beneath eastern Grand Bahama, which may cast further light on the complex history of cave development on the island.

REFERENCES

Back W., Hanshaw B.B. and Van Driel J.N., 1984. Role of groundwater in shaping the eastern coastline of the Yucatan Peninsula, Mexico.From: Groundwater as a Geomorphic Agent (ed R.G. La Fleur) Allen and Unwin, London pp. 281-293.

Heath L.M. and Palmer R.J., 1985 (this volume) Hydrogeological observations on the karst of Eastern Grand Bahama. Cave Science Vol 12, No 3.

Newell N.D. and Rigby J.K., 1975. Geological Studies on the Great Bahama Bank. Soc. Econ. Palaeontologists and Mineralogists Special Pubn. 5, pp. 51-72.

Palmer R.J., 1983. Report of the 1983 International Cave Diving Expedition. Privately published.

Palmer R.J. and Williams D.W., 1984. Cave Development under Andros Island, Bahamas. Cave Science, 11, 50-52 Vol 11.

Palmer R.J., 1985 (this volume). The Blue Holes of eastern Grand Bahama. Cave Science Vol 12, No 3.

Williams D.W., 1978. Nature's Reversing Syphons. Bahamas Naturalist, Winter 1978. pp. 6-8.

Williams D.W., 1979. Cave Diving in the Bahamas. Paper presented at 1979 Convention of Nat. Speleo. Soc.

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Hydrological Observations on the Karst of Eastern Grand Bahama

Lucy M HEATH and Robert J PALMER

Abstract: Studies made on the 1984 Zodiac Project established the existence of a freshwater lens on the island of Sweeting's Cay, Grand Bahama. The paper examines the methods used to identify the lens, and examines the hydrological and structural controls on the anchialine and marine caves (Blue Holes) associated with the area.

The aim of the hydro-geological programme on the 1984 Zodiac project was to establish the existence of a freshwater lens of Sweeting's Cay and the position of major thermoclines within this lens and associated cavern waters. It was also intended to relate the surface structure of Bahamian limestone in the area to the alignment of cave passages.

The area of study covered the Zodiac Cavern and Asgard System of Sweeting's Cay and the Big Creek coastal zone approximately 4 km further south-east, on Lightbourn and Gainum's Cays.

METHODS OF STUDY

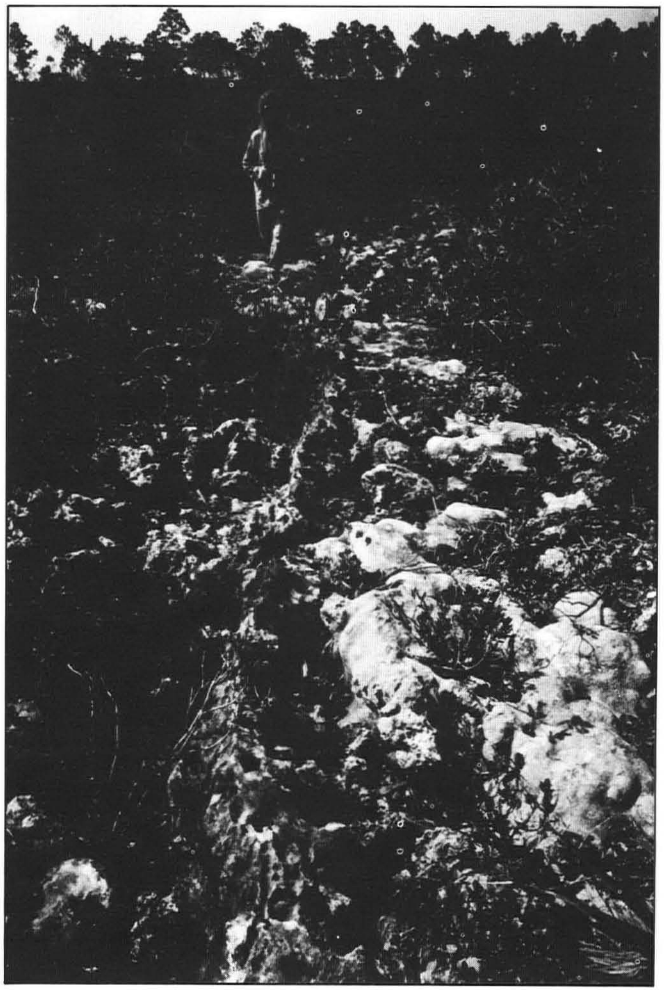
Salinity: Open water was measured directly to a depth of 1.10 m, using a WTW-LF91 conductivity meter (ie. to the length of the probe and cable supplied). Below this, and inside the caves, water samples were taken using a plastic screw-top bottle, air-filled at the surface and opened at the sampling point. The bottles were held in front of the diver and inverted. Salinity was measured using the meter as soon as the sample was brought to the surface. Salinities were not found to alter if the sample was left over a 24 hour period. The most precise measurements are those taken to a depth of -1.10 m. Below this, the measurements represent at best a 10cm layer.

Depth: This was measured with depth gauges read to 0.5 m, and the different gauges were not accurately calibrated. However, measurements repeated within 1-2 days at the same locality were within ±5% of the original reading. The most representative measurements were those taken on initial visits or after a long "rest-period" for the cave.

Temperature: open water was measured directly to a depth of -1.10 m using the temperature scale on the WTW-LF91 meter. Some lake temperatures below this depth were sampled by bottles and taken directly to the surface. This had to be done quickly, as surface temperatures were considerably higher than water temperatures, and this method was therefore inappropriate for cave waters. In the caves, a standard thermometer was used, which had been calibrated with the conductivity meter and could be read to 0.5°C. It was left for 2 minutes at each site to reach equilibrium. Unfortunately both thermometers were lost during the expedition and so only limited temperature data is available.

Tides: Tide tables were obtained for Freeport and these appeared to be approximately 1 hour in advance of Haul Over, at Sweeting's Cay, although weather variables and the effect of the tidal discharge from Little Harbour Creek have not been calculated. The tidal range at Haul Over was approximately 1 m, at Little Harbour Creek north of the Asgard System it was approximately 0.4 m, and over the same tidal cycle in Asgard Lake it was 0.28 m. It is suggested that future researchers use remote sensing recorders for more precise measurements over a longer time scale.

Placement of limestone tablets: A total of 45 bags containing limestone tablets, precisely weighed to the nearest 0.01 mg, were placed in the Zodiac Caverns/Asgard System where there were found to be significant variations in temperature, salinity or physical parameters (eg. down the side of aston collapses at cave entrances). Each bag contained a cylindrical marble control tablet and square piece of Bahamian limestone. The tablets will be left in place for two or more years to establish current solutional or accretional rates within the existing cave passages.



Karst surface above Pisces Cave, with protruding vein. (Photo L. Heath).

STRUCTURAL GEOLOGY

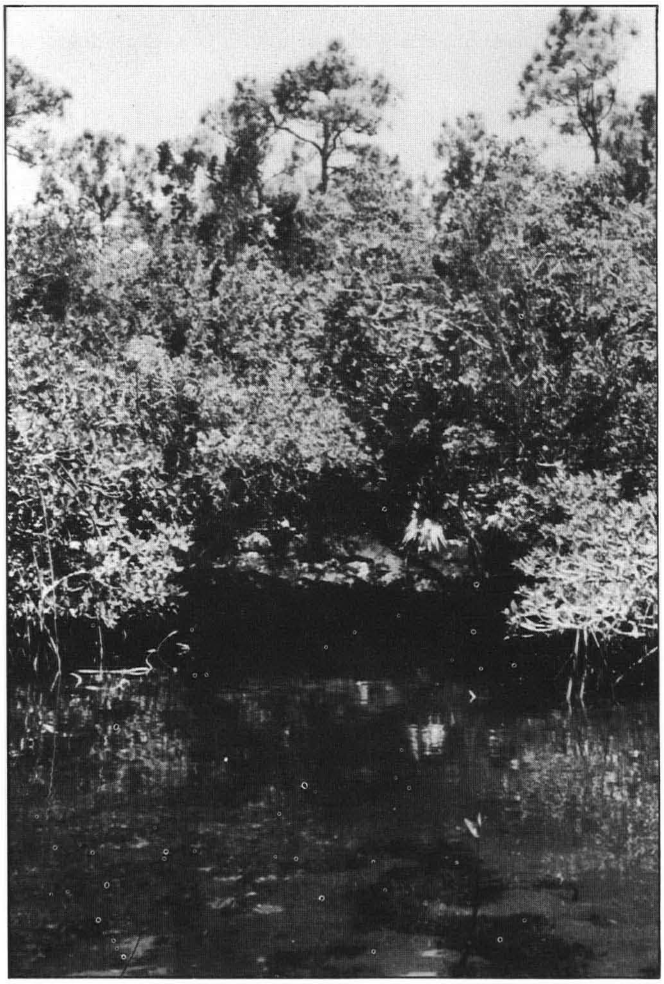
A number of long fractures cross the limestone. They appear to be vertical, but there are limited exposed sections where it is possible to confirm this. The fractures are up to 30 cm wide at the surface, although where cave passages intersects them below to the surface they can be much wider, due to secondary enlargement by solution collapse. Some are eroded out, but others contain a pink micritic matrix and protrude from the surrounding limestone surface.

Fractures often run parallel to the edge of lakes (eg. the southern end of Lake 2, and the south-east bank of Lake 1 on Sweeting's Cay). Others parallel the entrance channel of Zodiac Creek. Two main orientations predominate, one at approximately 150°, and the other at approximately 060°, the former being parallel to both the dominant cave direction and the ocean drop-off. Fractures are unpredictable, and they tend to curve, alter direction suddenly, and divide into two.

HYDROGEOLOGY

The Big Creek Blue Holes follow a NNW/SSE orientation, which can be traced inland to some outstanding fractures with orientations of 166°, 154°. 159°. 154° and 171°. These bypass an area of raised coral reef. There is no current freshwater influence on these caves, which appear to be hydrologically linked to Blue Holes inland in lakes to the north-east, and at the south-west end of Lightbourn Creek. The land surface is of very low-lying calcrete, intensely corroded, with overlying mangrove vegetation, fronted along the foreshore with raised fossil reef terraces and heavily eroded eolian dunes.

In the Zodiac Caves, the waters of Scorpio and Aquarius are completely saline, never becoming shallow enough to reach any thin lens which may exist above them. There is some evidence for an extremely thin lens above Aquarius in the form of a thin soil cover and a vegetation other than mangrove. Both Scorpio and Aquarius run under a fretted limestone pavement which, above Scorpio, is flooded at high spring tides. The lack of established soils and vegetation above the two caves may be due to the enhanced water flow through the caves and the overlying rock; both caves are open to direct tidally induced current flow via their creek entrances. Vegetation is sparse above both Gemini and Pisces, possibly indicative of a very thin lens above both caves. Lake 3 is very shallow, averaging 0.5 m in depth, and despite a high surface temperature is comparatively fresh. At the end of June 1985, the



Entrance to Asgard Cave in an outcrop of limestone beside the tannine stained lake water. (Photo R. Palmer).

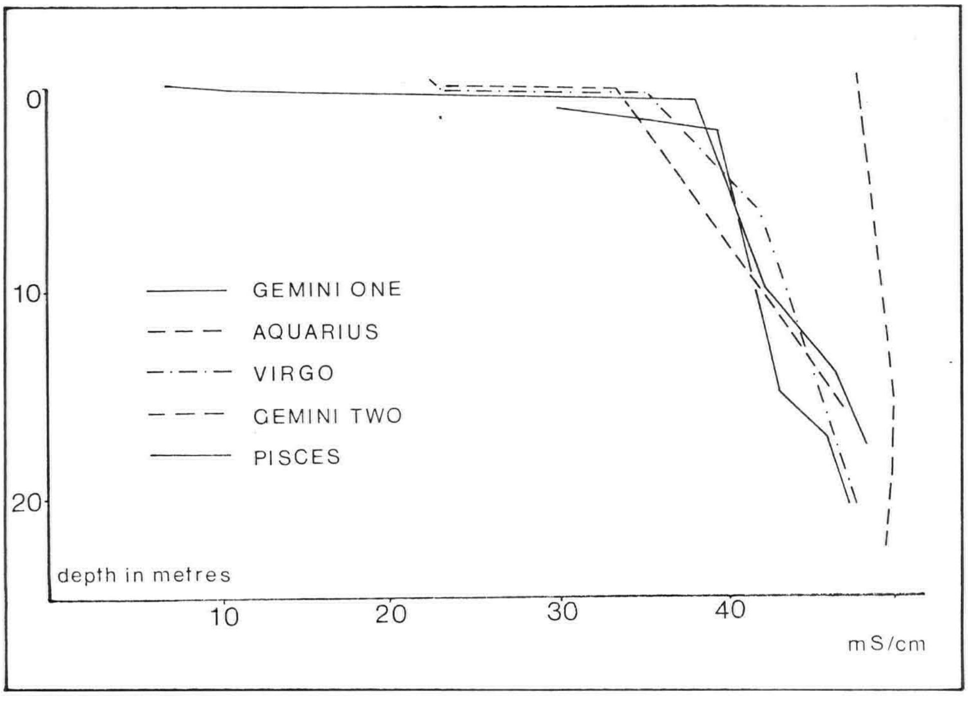
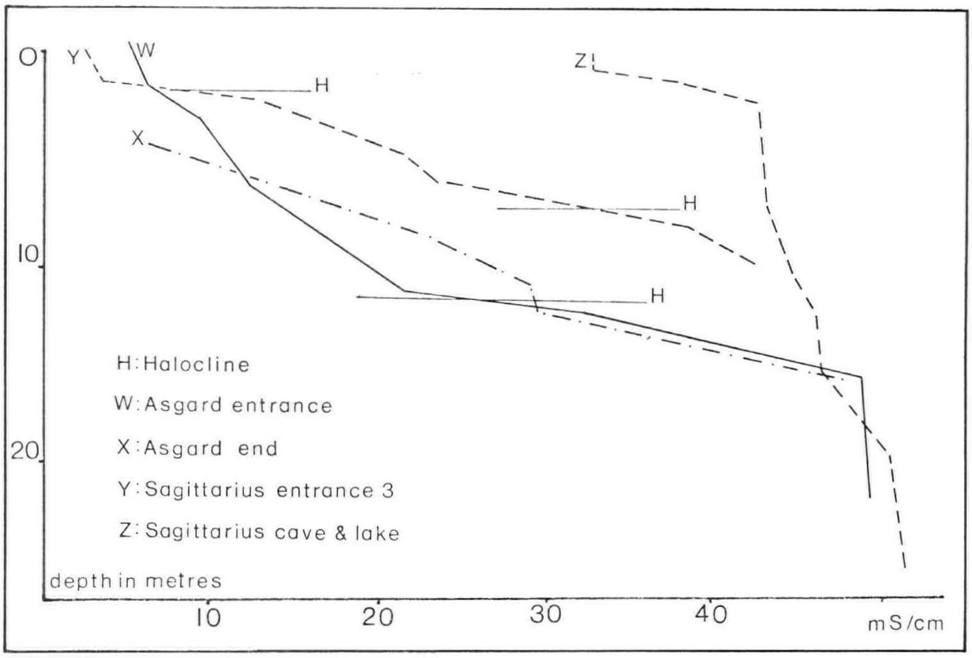


Figure 1 Comparative conductivity with respect to depth in Zodiac Caverns waters.

Figure 2 A comparison of conductivity of Sagittarius and Asgard cave waters.



upper water was almost potable (ie. 7.28- 10.70 mS/cm in the top 25 cm, increasing rapidly to 31.1 mS/cm at -1.10 m). By late July, the salinity had greatly increased, apparently in response to reduced rainfall. A similar pattern occurs in both Lakes 1 and 2, indicating a response to direct rainfall and through the surrounding thin freshwater lens. Evidence for a thicker lens on the north side of the Zodiac System is scanty, and is suggested only by the presence of pine forest and the diluted lake readings.

The lake entrances to Pisces, Gemini, Virgo and Sagittarius have upper salinities and temperatures similar to the rest of their associated lakes (Fig 1). Unlike marine Blue Holes, there is a little "suck and blow" effect to disturb the upper water layers, but lake levels respond to tides with apparently little or no time lag. Thermoclines were found in the lakes, suggesting vertical stability, (eg. Lake 2 on 5th July 1985, where temperature increased to a depth of 85 cm, and then decreased again with depth). The upper water surface is cooled by contact with the colder air above, and wind movement over the surface circulates the upper layers.

Salinities within the above four caves increase rapidly with depth (Fig 1), coming to equilibrium with marine and creek salinity by approximately -15 m. There is some evidence to suggest that the major common thermocline at -16 m (1983) and -19 m (1984) may be associated with a final increase in salinity though it may represent the boundary between the mobile sub-island tidal flow and the underlying deep static salt water phreas.

The exception to this rule in the Zodiac System is the third entrance to Sagittarius, where the cave cuts vertically through a thin freshwater lens, with haloclines between 1 and 2 m and again between 7 and 8 m. The entrance is surrounded by lush vegetation, including epiphytes. Vegetation evidence suggests that this established lens extends over both Virgo and Sagittarius.

The Pine forest thickens to the east and is perhaps densest in the region of the Asgard System. The two small lakes which contain the entrances to Davin's, Asgard and Lucy's Caves are surrounded by thick circles of broadleaved scrub containing orchids and bromeliads. Salinities in both lakes are very low, Asgard Lake especially so (Fig 2) and despite the tannine staining in the water (the result of decaying organic material) Asgard and Lucy's Cave are relatively fresh to a depth of 6 m. A distinct halocline is evident at a common depth of 12 m throughout the three caves, above which the water is fresh/brackish and tannine stained throughout. Below the halocline, the water suddenly becomes crystal clear (visibility exceeds 50 m), as it is at depth in all the inland caves.

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The Flora and Fauna of Sagittarius, an Anchialine Cave and Lake in Grand Bahama

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Abstract: An unusual habitat with an extensive and bizarre growth of serpulid worms and a free-swimming troglobitic crustacean community has been discovered in an inland, anchialine, Pleistocene cave beneath the island of Sweeting's Cay, Grand Bahama. The cave system and it adjoining lake are isolated from the open sea, yet the lake is tidally-influenced and is typified by a prolific population of green algae, coelenterates (including representatives of the Scyphozoa and Zoantharia), gastropods and bivalve molluscs. Potential mechanisms by which the lake became colonised, the nature of the cave community and how nutrients enter the cave system are discussed.

INTRODUCTION

The life existing in oceanic Bahamian Blue Holes has been observed by Dill (1977), Gascoyne et al (1979) and Warner and Moore (1984). However, few observations have been made concerning the life associations found in these inland anchialine caves, that is caves influenced by both salt and fresh water (Iliffe 1980; Yager 1981). The 1983 International Cave Diving Expedition, under the leadership of Robert Palmer and Dennis Williams, was mounted to explore caves seen from a light aircraft over eastern Grand Bahama in the wake of the 1982 Cave Diving Expedition to Andros. These inland caves, specifically those referred to as the Zodiac Caverns (Palmer 1985) proved to be so fascinating that they inspired further study. This paper presents the results of a preliminary biological survey, and the characteristics of a highly unusual habitat, the anchialine Sagittarius Cave and its associated lake. A fauna list is given in Table 1 and a diagramatic section shows the environmental relationships (Fig. 1).

Sagittarius Cave and Lake lie 200 m north of Sweeting's Cay Settlement on the island of Grand Bahama (26°37'N, 77°53'W). The lake is 500 m from the nearest marine influence and occupies an area of roughly 10,500m², with an average depth of 4 m. The lake bottom comprises limestone, which in some areas is covered by a thin layer of course, shelly sand and organic debris. The surrounding terrain consists of exposed and fretted limestone, colonised by sparse scrub to the north, south and west, and by pine forest to the east. The entrance to the cave is located on the east side of the lake and its presence is indicated by bare limestone on the otherwise mangrove-fringed bank. The entrance shaft is 1.5 m wide and 4 m long, and lies at a depth of 2 m at high water; it drops vertically for 12 m, narrowing to just sufficient size for a diver to enter the cave. At -12 m, the cave becomes horizontal, widens, and gradually deepens to a maximum -22 m. The cave extends through some 400 m of passages under the island of Sweeting's Cay in a south-easterly direction. Exploration of the lake and cave by expedition member Rob Parker in 1983 indicated no enterable caves or major surface routes connecting either the cave or lake to the sea.

THE FLORA AND FAUNA

The lake

The lake is characterised by a prolific growth of green algae (Chlorophyceae) covering the lake bottom, an abundant population of herbivorous gastropod molluscs and the presence of scyphozoan, aubogoan and zoantherian coelenterates. The high salinity and temperature of the lakes ensures that only euryhaline/eurythermal stress-tolerant organisms are present. The flora and fauna of the lake is typical of shallow, tropical, mangrove swamp waters. The isolated nature of the lake enables prolific growth to occur, as the lake escapes both

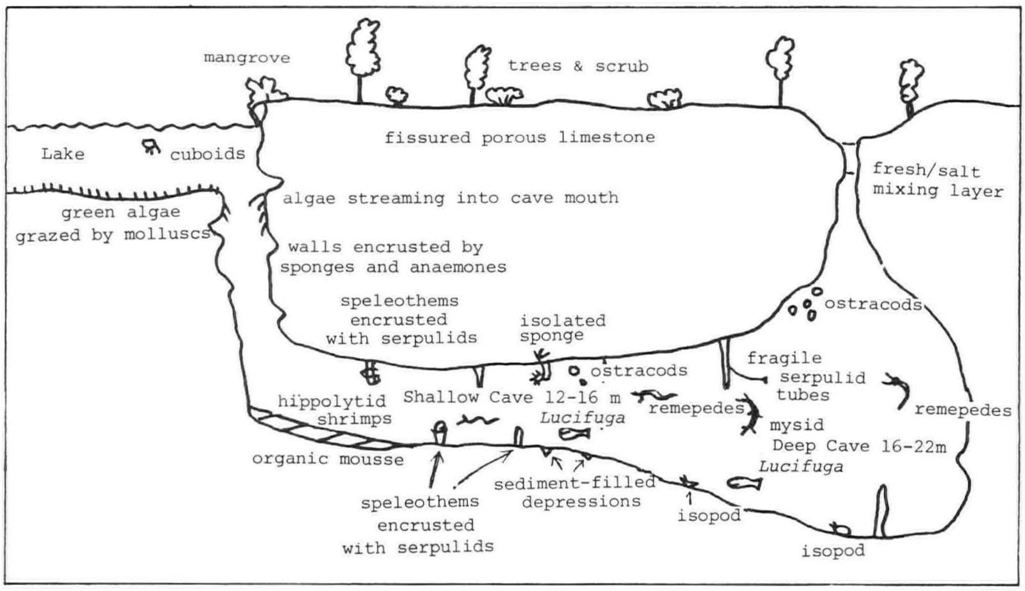
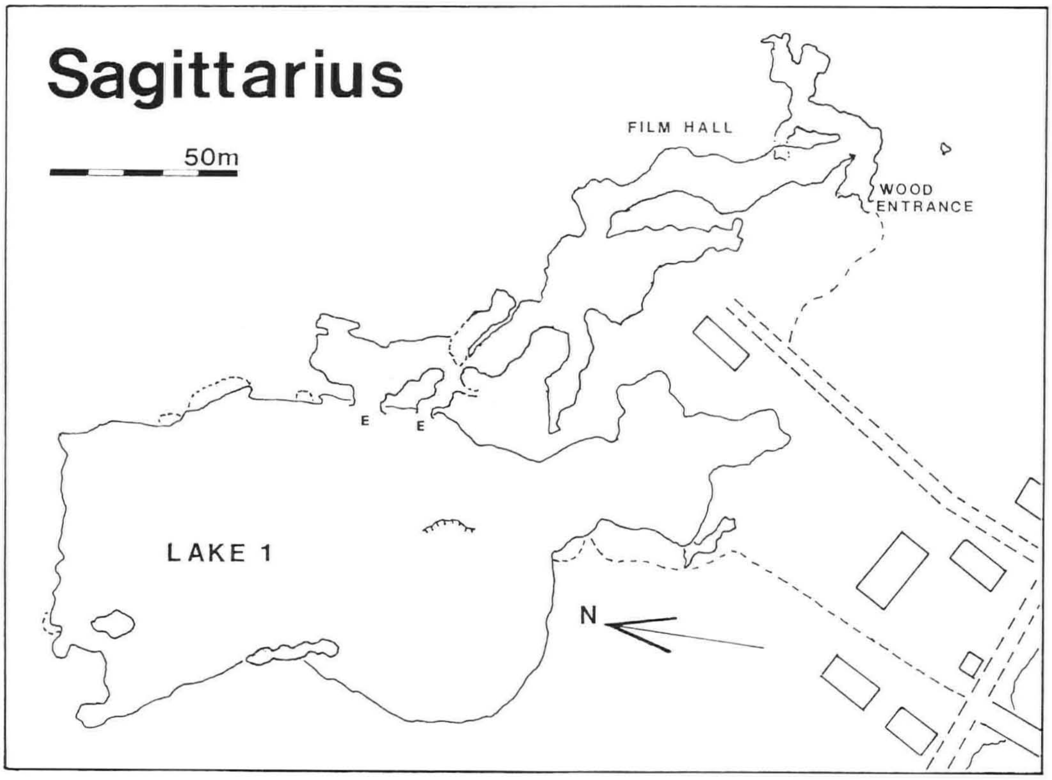


Figure 1. Diagrammatic section of environments in Sagittarius Cave

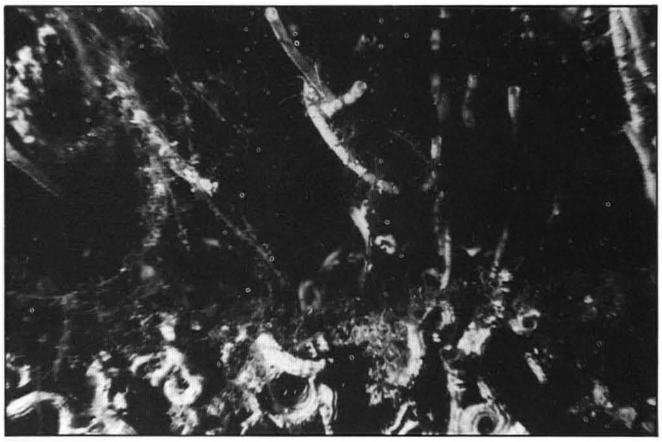


the grazing action of many marine animals (urchins, parrot-fish, etc.) and the strong, scouring action of the tides in the marine creeks to the north and south of Sweeting's Cay (4-5 knots on spring tides).

Dominant algae present are representatives of the families Dascycladaceae and Cauterpaceae, namely Batophora oerstedii, Dascycladus vermicularis, Caulerpa sertulariodes, plus the more sporadic presence of Acetabularia crenulata and the Codiacean, Penicillius capitatus. Grazing the algae, the cerithids, Cerithededa costata, Cerithium mucsarum, and Cerithium eburneum were commonly observed. The carnivorous ophistobranch bullomorph, Haminoea elegans and the marginellid, Marginella apicina were also present, feeding on the numerous polychaete worms available. Attached to the algae and mangrove roots, the bivalve mussel, Brachidontes exustus was frequent. In the sandy/organic sediments, the venerids Anomolocardia auberiana, the corbiculid, Polymesoda maritima and the tellenid, Tellina mera were also present. A grey, felt-like sponge (Halicona sp?) was occasionally observed, attached primarily to the walls of the lake below ELWS (extreme low-water spring tide). Presumably, in the lake proper, the rapid growth of the algae soon smothers the slow-growing sponges. Coelenterates present included the scyphozoan, Cassiopea xamachana; attached to the algae, the worm-like actinarian, Phyllactis conchilega and the occasional corallimorpharian, (unidentified) with clubbed, translucent tentacles. In the open water, shoals of the non-stinging cubomedusae, Tripedalia cystophora were observed (previously recorded from mangrove swamps in Jamaica, the Phillipines and Japan). An abundant population of polychaete worms, including the fire-worm, Hermodice carunculata was present. On the calcified stipe of penicillus capitatus, the serpulid Spirorbis sp. was occasionally present. The parchment cases of a sabellied worm were also found, though no living specimens were observed. Of interest was the presence of acorn worms (hemichordates, class Enteropneusta). These were sighted on two occasions, but unfortunately their soft, slimy bodies broke easily on handling and no satisfactory specimen was collected. Fish present included shoals of the mosquito fish, Gambusua manni, and the occasional pipe-fish.

The entrance shaft

Algae as described in the lake section were also present at the cave mouth. An unidentified mat-like algae growth(?) (possibly fungal or cyanophyte) was also observed, dangling into the cave mouth. The vertical (-2 m to -12 m), narrowing nature of the shaft (width 4 m to 0.5 m), rapid reduction of available light, and the smothering, blanketing effect of organic matter falling into the shaft caused a rapid decrease in biomass and diversity. At a depth of -5 m (3 m into the shaft), the high density algal growth was replaced by the occasional Batophora oerstedi) and Acetabularia crenulata. With the reduction of algae, the sponges became more visible, and more abundant with depth. Seven species were collected, the most common being a grey felt-like sponge (Halicona sp.) also found in the lake. Another species of similar morphology had two distinctly coloured body-tissues, grey and pink. A grey tubular species with one terminal osculym was occasionally present, as was a fawn "knitting" sponge, a cream, knobbly globose species (Timea sp?) and the golf-ball growth of a tehyid-like species (Cinachyra sp?). Coelenterates present again included Phyllactis conchilega, Phyllactis flosculifera the unidentified corallimorphian,



Serpulid tubes encrusting the walls of Sagittarius entrance, with thread-like Bryozoans Amathia vidovici attached.

Table 1 Sagittarius lake and cave species list.

CRUSTACEA
OSTRACODA
Deeveyne sp 4
Speleocia sp 4

REMEPEDIA
Speleonectes lucayensis Yager 4

MYSIDACEA
Stygiomysis holthuisi Gordon 4

ISOPODA
Bahalana geracei Carpenter 4

NATANTIA
Barbouria antiguensis Chase 3

MOLLUSCA
GASTROPODA
Cerithedea costata do Costa 1, 2
Cerithium muscarum Say 1, 2
Cerithium ebuuuurneum Bruguiere 1, 2
Haminoea elegans Gray 1
Marginella apicina Menke 1

BIVALVIA
Brachidontes exustus Linne 1
Anomolocardia auberiana Orbigny 1, 2
Polymesoda maritima Orbigny 1, 2
Tellina mera Say 1, 2

BRYOZOA
OPHIUROIDEA
Amathia vidovici Heller 3, 4

ECHINODERMATA
Amphiodra sp 2, 3

HEMICHORDATA
Enteropneust sp 1

TUNICATA
Stetla 2

ALGAE
CHLOROHYCEAE
Batophora oerstedi (Agardh) 1, 2
Dascycladus vermicularis (Scopoli) 1, 2
Caulerpa sertulariodes (Gmetin) 1, 2
Acetabularia crenulata (Lamoroux) 1, 2
Penicillus capitatus Lamark 1, 2

RHODOPHYCEAE
Lithothamnium-like sp 2

PORIFERA
Haliclona sp ? 1, 2
Timea sp ? 2
Cinachyra sp ? 2, 4
grey tubular sp 2
fawn knitting sp 2

COELENTERATA
SCYPHOZOA
Cassiopea xamachana Bigelow 1

CUBOZOA
Tripedalia cystophora (Conant) 1

ZOANTHARIA
Aiptasia pallida Verrill 2
Phyllactis flosculifera Leseur 2
Phyllactis conchilega Duchassaing & Michelotti 1
Corallimorpharian sp 2

ANNELIDA
Hermodice carunculata (Pallas) 1

SERPULIDAE
Spirorbis sp 1
Filograna sp 2
Vermiliopsis glandigera infundibulum group 2, 3, 4

PISCES
Lucifuga speleotes Cohen 4
Gambusia manni 1
Syngus sp 1
crevice dwelling goby 2

Location key: 1 = lake; 2 = entrance shaft; 3 = shaft bottom; 4 = cave.

which was commonly attached to exposed rock surfaces, and a pale anemone, Aiptasia pallidia. Errant polychaetes were as those found in the lake; however of interest was the appearance of dense growths of serpulid worm tubes belonging to the Vermiliopsis glandigera infundibulum group, which is currently under review by Dr H.A.ten Hove. Dense encrustations occurred, particularly under overhangs in the entrance shaft. Two species were present, one a thick-walled species incapable of forming a perfect exoskeleton cylinder, with striations running down its tube and a fluted-trumpet-like lip, the other (which was only occasionally present) being a perfect spiral tube without a fluted lip. Their biomass increased with depth in many areas to the exclusion of all other species present. Serpulids began to appear at a depth of -4 m, (the depth at which algae became only occasional). At this -4 m depth, an encrusting red algae (Rhodophyceae) was observed on the light-facing side of the serpulids. The fine, delicate tubes of a Filograna-like serpulid were also occasionally present. Cerithid gastropods (as described in the lake section) were present where algal matter was available for them to graze. Most common however were venerid bivalves, which were found in the organic material that collected in cracks and crevices. Brittle stars, family Amphiuridae (Amphiodra sp?) were occasionally seen, as was the tunicate, family Steylidae (Steyla sp?). Hidden in crevices and well-camouflaged, a somewhat ghoulish-looking and unidentified fish (possibly a goby?) proved common.

The shaft bottom

At a depth of 12 m, the vertical shaft opened into a horizontal passageway, where a drop in temperature was immediately noticed. At the bottom of the shaft lay a fine, organic "mousse" in areas up to 0.5 m deep and which extended horizontally for approximately 20 m into the cave. Living on this mousse was a prolific population of bright orange hippolytid shrimps, Barbouria antiguensis (see appendix 1.). Numerous empty venerid shells were lying on the mousse, presumably having fallen down the shaft and died. The presence of the mousse indicated the isolated nature of this part of the cave system and the negligible presence of current flow; the mousse preserved "foot-prints" of the shrimps and, where the divers disturbed and broke up the mousse, it remained as it had been disturbed. Sections of mousse revealed well-defined stratification. Occasional brittle stars (Amphiodra sp.) and the hippolytid shrimps were the only errant species observed at the bottom of the shaft. Dominant sessile species were the two serpulid species of the Vermiliopsis glandigera infundubulum group. Others included a thread-like bryozoan, Amathia vidovici attached to the serpulid cases; the occasional presence of the felt-like sponge (Halicona sp?) and the tethyd-like sponge (Cinachyra sp?).

Barbouria antiguensis (cubensis?) in the Sagittarius entrance sediments. Photo: R. Palmer.

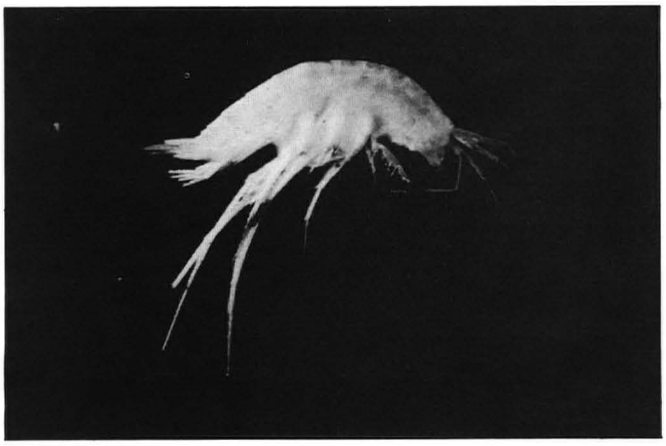
The cave

Sagittarius Cave extends horizontally for approximately 400 m. It broadly forms a series of chambers which gradually deepen with increasing penetration (0 - 100 m penetration, approximate depth 16 m; 100+ m penetration approximate depth 20-22 m). In the 0 - 100 m zone, both thick and thin-walled serpulid species heavily encrusted the walls, roof and speleothem formations. In the 0 - 100 m zone, rock formations and serpulids were discoloured a mottled, rich-brown tannine colour. Organic matter was present in cracks and depressions, but was not a continuous covering, as in the entrance zone. Beyond 100 m, the serpulid distribution was strange; only the thin walled species was observed. This was present in some chambers, absent in others. Throughout the cave, the serpulids were generally found in the upper zone and roof of the passage. Beyond 100 m, growth forms were bizarre, in many instances composed of a perfect spiral which then produced a long, unsupported (i.e. not cemented to a rock formation) calcareous tube, the operculum end orientating towards the centre of the cave passage. In many instances, these errant tubes were observed to grow to lengths in excess of 0.5 m, and were white in colour. The only other sessile species observed in the cave was the isolated occurrence of a single tethyd-like sponge (Cinachyra sp?) observed 60 m into the cave, attached to a stalagmite in mid-passage. The strand-like bryozoan Amathia vidovici was also occasionally present, attached to serpulids (perhaps capitalising on the feeding currents created by the filtering activities of the serpulid tentacle crown?), but was not seen past 100 m.

Of particular interest in the cave was a bizarre community of free-swimming, blind, cave-adapted (troglobitic) crustaceans. These included representatives of the recently-described sub-class Remipedia (Yager 1981), namely Speleonectes lucayensis (Yager) and a possible two new species (description in progress, Jill Yager) thermosbanaceans (possibly a new genus, description in progress by Jill Yager); the mysid, Stygiomysis holthuisi; ostracods, Deeveynes sp. and speleocia sp, (both possibly new species), and the Cirolanid isopod Bahalana geracei, which was more commonly observed on the cave floor than free-swimming. At least one cave-fish, the ophidioid, Lucifuga speleotes was seen on each dive. When disturbed, one individual was consistently seen to return to one particular crack in the cave. The first species were observed at a depth of -18 m, 60 m from the cave entrance (the limit of the twilight zone?).

DISCUSSION

Isolated marine lakes have been defined as anchialine (Iliffe 1981), that is "having no surface connection with the open sea, but which nevertheless contain salt or brackish water, the level of which fluctuates with the tides".



The Mysid Stygiomysis holthuisi. Photo: S.Cunliffe.

Clearly, however tenuous, there is a connection between Sagittarius and the open sea, as the lake is tidal. So how was the lake colonised? It would seem that there are four potential mechanisms:

1. The introduction of species is facilitated by horizontal, tidally-induced current flow into the lake made possible by the porous, fissured nature of the limestone. This "fissure current flow" in effect constitutes a potential dispersal mechanism for algal spores and larval forms to populate the lake. Colonisation would therefore be an active and continuous process.

2. Colonisation occurs during catastrophic events - on average, the Bahama Islands lie 2.5 m above sea-level and are therefore in extreme circumstances (ie storm surges, hurricanes) susceptible to flooding. Clearly this could make a major sporadic contribution to the colonisation of the lake.

3. Vectors such as birds provide accidental transport. Although the numbers of individuals transported and able to colonise by this means is doubtless low, it is nevertheless a well-documented means of transfer (Segerstales 1954; Geelack 1977).

4. The Bahamas have undergone recent periods of long-term inundation. Fairbridge (1961) and others have postulated that high sea-level stands have occurred in response to glacio-eustacy within the last 6,000 years, the mean sea-level rising by as much as 2-3 m. This is further supported by Lind (1969) from studies on Cat Island. Much of the Bahamas would then have been periodically flooded. Clearly this would then be an important means of colonisation.

The species present in the lake were, overall, typical of those to be found in the nearby, shallow, sheltered coastal and creek waters; of interest was the presence in the lakes of the cubomedusan, Tripedalia cystophora, which was not observed in the open water. Those species present reflected their ability to cope with environmental extremes (temperature, salinity, etc), the isolated nature of the lake enabling prolific growth to occur.

The distinct character of the cave fauna is principally the result of long-term isolation and lack of illumination. The absence of light excludes the fast-growing space competitors, so the ceiling, walls and overhangs of caves are well-suited to colonisation by filter-feeders, providing them with a substrate where they do not get buried by sediment. Vasseur (1974) in his studies of an open-ended tunnel found that only a limited number of sessile groups are able to adapt successfully to growth in complete darkness. However, in Sagittarius, the only sessile organisms to colonise the cave successfully were the serpulid worms of the Vermiliopsis glandigera infundibulum group. Why the serpulids are so successful is unknown. Possibly the serpulid trochophores are capable of swimming far greater distances without the assistance of a current than, say, the sponge larvae present. Water circulation in the cave must be sufficient to remove metabolic wastes and ensure replenishment of food supplies, so the serpulids must be able to adjust more readily and successfully than other potential troglophiles to the completely dark, cryptic, "still-water" conditions present in Sagittarius.

The absence of spatial competitors and the minimal water disturbance has enabled the serpulids over a maximum of 10,000 years (the time in which rising seas at the end of the Pleistocene glaciations will have re-inundated the caves) to colonise Sagittarius very successfully. Dense growths of serpulids were observed to encrust the speleothems in the cave. Heavily encrusted broken stalactites were also present on the cave floor, the serpulids' weight presumably being sufficient to break off stalactite formations. In other instances, the serpulids had aggregated to form "pseudostalactites" - a term introduced by MacIntyre and Videtich (1979), meaning "bearing a superficial resemblance to a stalactite, but which is entirely marine in origin, and projects from the ceiling of the cave".

The distribution and morphology of the serpulids was observed to change with increasing penetration into the cave. Beyond 100 m, the "errant" tubes of the thin-walled species were seen. This may well be a response to the reduced intra-specific competition occurring in this part of the cave, as it was in slightly shallower 0-100 m section of the cave that the dense aggregations and pseudostalactites were observed. These somewhat abberant forms may even represent a response to the increasingly cryptic nature of the cave, perhaps even constituting a long-term adaptive response such that the deep cave serpulids may in time develop troglobitic characteristics themselves. Certainly the tubes were so long, delicate and fragile that it is inconceivable they could survive under more 'normal' circumstances.

The number of serpulids actually alive in the cave at any given time is thought to be only a limited percentage (probably less than 10%): few worm tubes collected were actually occupied and their tentacle crowns were rarely observed. Obviously this gives no idea of numbers, as they were extremely sensitive to water disturbance by divers. MacIntyre et al (1984) suggest that only about 1% of the surface serpulid tubes collected in Belize are colonised by live serpulids. As the serpulids were observed to the very end of the explored cave and their abundance decreased with increasing penetration, it seems likely that the serpulid population is initially the result of colonisation of the cave entrance, but thereafter the cave colonisation represents local recruitments.

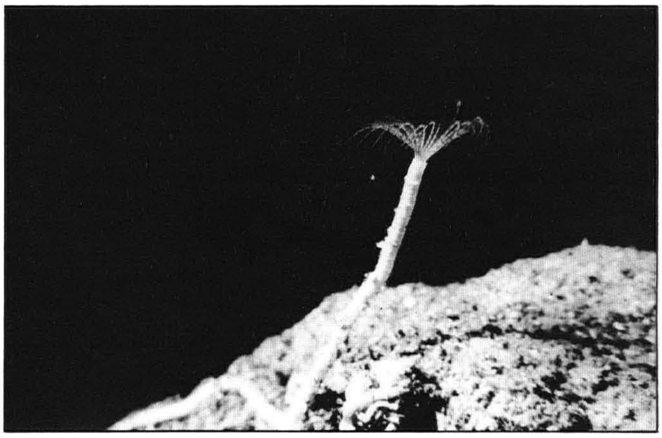
The tubes were generally observed to orientate their operculum towards the passage centre. This is believed to be an orientation response to food, which would be filtered from the cave water. It is postulated that the cave ecosystem may have three means by which nutrients are acquired:

1. The slow percolation of surface organic matter into the cave (aided by the flushing action of meteoric waters) is an important primary nutrient input for the cave community.

2. Tidally-induced, horizontal fissure current flow (as described in mechanisms of lake colonisation) will bring nutrients into the cave. These subterranean currents will also draw organic matter falling into the entrance further into the cave, although the distance that nutrients may travel by this means may be limited.

3. Where the freshwater interfaces with the underlying saline water (the mixing zone or "halocline"), there exists a chemically and biologically active layer, where breakdown of detrital matter from sources 1 and 2 (above) occurs. This zone is found at a depth between -3 and -8 m in the third (forest) entrance to Sagittarius and is presumed to overlie the entire extent of the cave in the flooded fissure network between the passages and the surface. Numerous sulphur-reducing bacteria are postulated to be present, as observed at other Bahamian cave sites (Palmer: in prep.) These may make an important contribution to the energetics of the cave ecosystem (R Palmer pers.comm).

To give support to the above, with regard to (1), organic surface downput was particularly noticeable in the nearby cave system, Asgard. Here, a dense pine forest covered the surface above the cave, organic matter was physically seen to enter the freshwater lens found in the cave via cracks in the roof, and the cave fauna below the lens was typified by a particularly abundant and diverse community of crustaceans (number of individuals present in certain areas were approximately $10/m^3$, whereas in Sagittarius 1-2 individuals/m^3 were exceptional). However, no serpulids were present in Asgard, presumably because the cave is more isolated from marine influence than Sagittarius, and so the crustacean abundance may in part reflect a reduced competition for food.

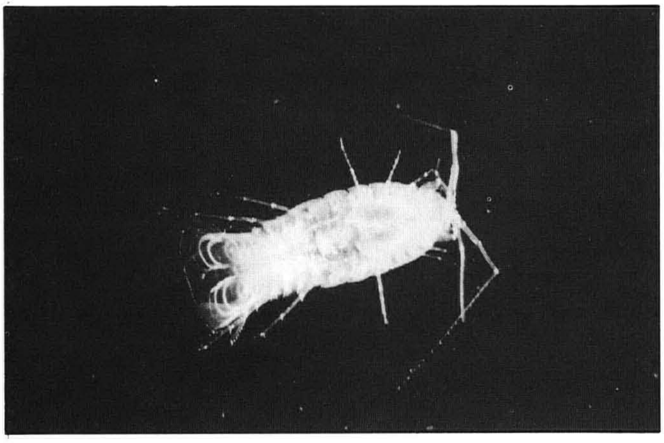


Serpulid worm, feeding in cave passage, showing long "errant" tube development. Photo: R. Palmer.

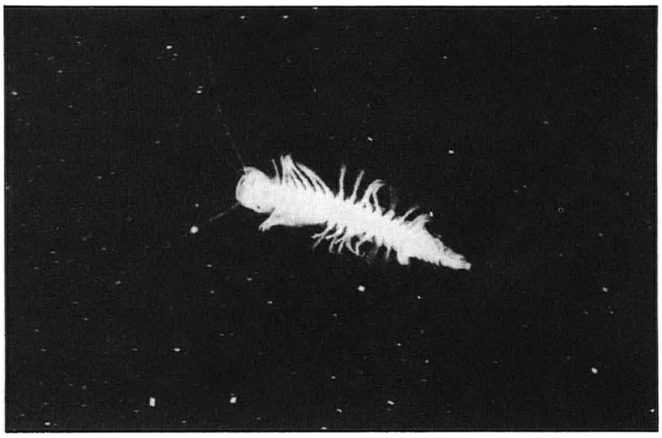
With regard to proposal (2), no current was physically detected in Sagittarius by the divers. The organic mousse at the base of the entrance shaft indicates the isolated nature of the cave, but nevertheless algae at the head of the entrance shaft were observed on occasion to stream downwards towards the cave interior. Professor Thorhaug (1983) comments "the large macroalgal populations penetrating into the cavern parts of the caves must be important producers for cave carbon cycles". As the tannine coloured section of the cave extends for some 100 m from the entrance (the shallower zone), perhaps this represents the limit of the lake influence? Future current studies may give validity to this theory.

To give support to the more controversial proposal (3), particularly as at this stage we have no bacterial results to back up the theory, I refer to the observations made by Rob Palmer in the third entrance to Sagittarius, in mid-forest, and in Asgard, where pale, strand-like bacterial forms were observed in the distinctive mixing zone between fresh and saline waters. Bacterial masses have been observed at considerable distances (up to 100 m) horizontally into the dark zone of the anchialine caves on other Bahamian islands (Palmer. in prep.). As so little is known about these deep cave systems, all possibilities should be considered. For future visits, the study of the micro-biology and the micro-zooplankton could well prove informative.

The existing serpulid population can only have colonised the cave within the past 10,000 years. The crustacean community likely represents a very much older introduction. That "the marine caves have served as faunal refuges over long periods of time", as suggested by Hart et al (1985) in their excellent paper, is obviously relevant to the Bahamian caves. Further, the suggestion that some troglobitic species may have deep-sea origins (Hart et al, 1985) is lent further credence by the presence of Bahalana geracei in Sagittarius. This cirolanid isopod was formerly only known from San Salvador Island, Bahamas, and is a benthic species whose range is thus increased by 450 km. The two islands from which it has now been reported are separated by ocean waters 600 m deep. The suggestion by Hart et al (1985) that "species or species-groups could form a continuum, reaching from the caves of one island into the deep waters via the natural crevices amongst rocks, and so on up the slopes of other islands or sub-continental masses" is certainly supported on a local level by our observations of fauna in seven anchialine caves on Sweeting's Cay, unconnected save for hostile surface waters or fissure porosity. What has been noticeable in all the inland caves explored is the remarkable overall similarity of the mobile crustacean communities so far discovered. The certainty is that with improving techniques of collection and distance and depth penetration, there will be much still to discover. All of this



The Cirolanid Isopod Bahalana geracei. Photo: s. Cunliffe.

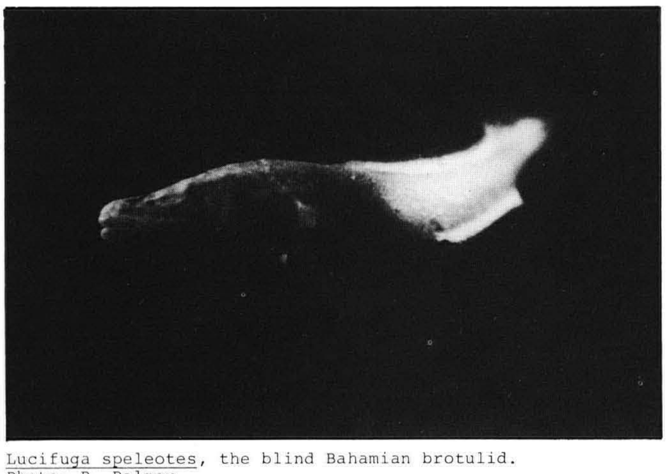


Remipede: unidentified species from Sagittarius.

lends peripheral support to Hart et al's concept of the caves as refuges sheltering their occupants (accidental or otherwise) from historical environmental extremes, particularly of the Pleistocence. The fissures provide suitable habitats and escape routes into which the cave fauna could migrate during long-term periods of sea-level and climatic fluctuation. The fissures were also perhaps the original means of entry to the cave systems, either for deep-sea Crustacea or surface-dwelling crevicular forms ("crevicular" - Hart et al: aquatic habitats formed by crevices in and among rocks, as well as describing the organism that lives in the habitat. For further biogeographical deliberation, the reader is directed to Hart et al (1985) and Iliffe et al (1983) as comprehensive papers on the subject).

The specimens we have so far collected from the caves have all tended to be free-swimming. A future potentially rich area of research may well be the fissures and cracks in the caves (and devising successful means of sampling them!). Effecting study in these caves is not, however, the easiest of biological tasks. We were privileged to be able to observe the cave fauna in situ, but the actual in-cave time available for such observations was obviously limited. It is interesting to consider the possible structure of the communities so far observed in the Sweeting's Cay anchialine caves, with specific reference to Sagittarius. The following is, however, no more than speculative at this stage.

At the top of the food chain, the cave fish Lucifuga speleotes is thought to be a major predator of the crustaceans. No more than two such fish were ever seen in Sagittarius on any one dive. One of these was consistently observed to return to the same crevice in the cave floor, suggesting that Lucifuga may well be territorial. It seems unlikely that Sagittarius could support many more individuals of the size of L. speleotes (up to 15 cm).



Lucifuga speleotes, the blind Bahamian brotulid. Photo: R. Palmer.

Second in importance to Lucifuga as a carnivore, the Remipedia were relatively common in Sagittarius. As already mentioned, these are fast-swimming and may even be capable of envenomating their prey (Yager pers,comm.). The remipedes were probably feeding on the small ostracods, thermosbanaceans and other minute zooplankton species (using a fine net, Dennis Williams collected harpacticoid copepods from Sagittarius). Remipedes may even tackle the larger cirolanid isopods (up to 1.25 cm) and amphipods (up to 2 cm).

The mysids are probably omnivorous. The cirolanid isopods were seen swimming only twice, the remaining time being spent on the cave floor. They are primarily benthonic, and omnivorous (probably due to their poor swimming abilities), but most commonly feed on detritus. Ostracods were occasionally seen dragging tiny pieces of organic, root-like matter around in mid-water, and they, together with the thermosbanaceans, are likely to be detritivores.

The thermosbanaceans were more readily observed in Asgard Cave, and near the third entrance to Sagittarius. They may be extremely euryhaline and temperature tolerant, and have been observed by R. Palmer to make vertical migrations (albeit limited) into the mixing zone, presumably in search of food. No other crustacean species was observed to do this (with the exception of the Bahadzia shrimps).

None of the specimens collected was observed to be in a reproductively active state. Seasonal changes in water temperature and the relative abundance of surface material available to cave fauna (possibly related to seasonal fluctuations in meteoric input) may well dictate a breeding season. If this is so, it might be reasonable to expect a breeding season in the wetter months, when food would be more abundant. However, specimens have been collected throughout the year by Yager and Williams and no reproductively active forms have yet been discovered. The cave environment has many parallels with that of the deep sea. Rokop (1977) studied deep-sea amphipods and isopods collected from depths of -450 to -1300 m over a period of a year and found that there were no signs of seasonal peaks in their reproduction. Further, approximately 40% of the deep-sea populations were always reproductively fertile. So why no actively reproductive specimens have so far been found in caves is a mystery. Carpenter (in press) sheds some light on this enigma by commenting "while over 50 specimens of troglobitic cirolanid isopods from the Bahamas have been collected and observed since 1978 during the summer and winter months, neither young nor females bearing eggs have been found. Two females developed oocytes when weekend laboratory temperatures periodically dropped to approximately 16°C". So perhaps the reproductive biology of the cave crustaceans is indeed temperature and therefore seasonally or depth dependant. Physiological experimentation in this area would clearly be most illuminating.

This perhaps highlights just how little we do know about this fascinating and much under-studied environment. It is pertinent to conclude this paper on a rather more definite point. Much physical damage has already been done to underwater cave systems - Grand Bahama's spectacular Lucayan Caverns are but one for example. The anchialine cave ecosystem is a fragile environment, reliant in part on organic input from the land surface above to sustain a nutrient level sufficient to maintain life. Any land management programmes in the future where areas of known subterranean beauty and rarity occur should therefore bear in mind that deforestation (removal of nutrients), water pollution (addition of fertilizers, pesticides, bleaching, dumping of refuse, etc) could easily destroy a rare, fragile and important habitat from which man has much to learn.

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REFERENCES

Carpenter. J. Troglobitic Marine Cirolanid Isopods from Grand Bahama Island, Bahamas In press. Northern Kentucky University.

Dill. R.F. 1977. The Blue Holes - Geologically significant submerged sinkholes and caves off British Honduras and Andros, Bahama Islands Proc. 3rd Int. Coral Reef Symp. pp 237-242.

Fairbridge R.W. 1961 Eustatic Changes in Sea Level. In Physics and Chemistry of the Earth. Vol 4 (Ahrens L., Press F. and Rankama K. eds) New York, Pergammon Press pp 99-185.

Gascoyne M., Benjamin G.J., Schwartz H.P., Ford D.C. 1970. Sea-level lowering during the Illonoian Glaciation: Evidence from a Bahama Blue Hole. Science Vol 205, pp 805-808.

Gerlack S.A. 1977. Means of Meiofauna Dispersal Mikrofauna des Meeresbodens, 61, pp 89-103.

Hart C.W., Manning R.B., Iliffe T.M. 1985. The Fauna of Atlantic Marine Caves: Evidence of dispersal by sea floor spreading, whilst maintaining ties to deep waters Proc. Biol. Soc. Wash. Vol 98, (1), pp 228-292.

Iliffe T.M., Hart C., Manning R. 1983. Biogeography of the Caves of Bermuda. Nature, Vol 302, No. 5904, pp 141-142.

Iliffe T.M., Sket B. 1980. Cave Fauna of Bermuda Int. Rev der Gerammten Hydrobiologie Vol 85, (6), pp 871-882.

Lind A.O. 1979. Coastal Landforms of Cat Island, Bahamas Dept. Geog. Res. Paper No 122, University of Chicago.

MacIntyre I.G., Vedetich P.E. 1979. Pseudostalactites from a submarine cave near Columbus Cay, Belize - evidence of extensive submarine lithification Soc. Econ. Palaentologists & Minerologists, April 1-4, 1979. p145.

MacIntyre I.G., Rutzler K., Norris J., Faychild K. 1984. A submarine cave near Columbus Cay, Belize: a bizarre cryptic habitat. Smithsonian contributions to Marine Science, No 12, pp 127-141.

Manning R.B., Hart C. 1984. The status of the Hippolytid shrimp, genera Barbouria & Ligur (Crustacean: Decapod) - a re-evaluation. Proc. Bio. Soc. Wash. Vol 97, pp 655-665.

Palmer R.J. 1985. The Blue Holes of Eastern Grand Bahama Cave Science Vol 12, No 3.

Palmer R.J. (in prep). The Blue Holes of Cat Island. A description of the morphology and biology of seven underwater caves.

Rokop F.J. 1977. Patterns of reproduction in the deep sea crustaceans: a re-evaluation Deep Sea Res. Vol 24, (7), pp 683-692.

Segerstrale S.G. 1954. The freshwater amphipod Gammerus pulex and Gammerus lacrustis in Denmark: a contribution to the late and post-glacial immigration history of the aquatic fauna of Northern Europe. Soc. Sci. Fennica Comm. Biol. Vol 11, pp 1-92.

Thorhaug A. 1983 Pers comm. Investigation of the macro-algal growth of 17 ocean holes and 6 inland lakes, Grand Bahama Florida International University.

Vasseur P. 1974. The overhangs, tunnels and dark reef galleries of Tuleur (Madagascar) and their sessile invertebrate communities. Proc. 2nd Coral Reef Symp. Vol 2, (Cameron A.M. ed) pp 143-159.

Warner G.F., Moore C.A.M. 1984. Ecological studies in the Marine Blue Holes of Andros Island, Bahamas Trans. Brit. Cave Res. Vol 11, pp 30-44.

Yager J. 1981. Remipedia, a new class of Crustacea from a marine cave in the Bahamas J. Crust. Biol. Vol 1, (3), pp 328-333.

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APPENDIX

Manning and Hart (1984) described the Hippolytid shrimp, Barbouria, as possessing two species, one from anchialine waters, Barbouria cubensis (Von Martens). and the other Barbouria antiguensis (Chase) from marine sub-tidal habitats (now assigned to a new genus, Janicea). The shrimp from Sagittarius Cave has been identified as B. antiguensis (Chase). However, according to Manning and Hart its distribution is Western Atlantic, Antigua and Bermuda, whereas B. cubensis (Von Martens) is known from Cuba, Turks and Caicos, Bahamas, Cayman Brac and Bermuda. At the time of going to press, the author is unsure whether confusion in identification has arisen, or whether Janicea antiguensis (Chase) is also to be found in anchialine waters in the Bahamas, and its range thus extended.