Cave Science

The Transactions of the British Cave Research Association

BCRA

Volume 9 Number 1 February 1982

A North Yorkshire Windypit

BRITISH CAVE RESEARCH ASSOCIATION

NOTES FOR CONTRIBUTORS

Articles for publication in the Transactions may cover any aspect of speleology and related sciences, such as geology, geomorphology, hydrology, chemistry, physics, archeology and biology. Articles on technical matters such as caving techniques, equipment, diving, surveying, photography and documentation are also accepted for publication as well as expedition reports, historical and biographical studies.

These notes are intended to help authors to prepare their material in the most advantageous way so as to expedite publication and to reduce both their own and editorial labour. It saves a lot of time if the rules below are followed. All material should be presented in as close a format as possible to that of the Transactions. Text should be typed double-spaced on one side of the paper only. If typing is impractical, clear neat handwriting is essential. Subheadings, sectional titles etc., within an article should follow as far as possible the system used in the Transactions. In any case, they should be clearly marked, and a system of primary, secondary and tertiary subheadings, if used, should be clearly indicated and double-checked before submission.

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Acknowledgments: anyone who has given a grant or helped with the investigation, or the preparation of the article, should be acknowledged briefly. Contributors in Universities and other institutions are reminded that grants towards the cost of publication may be available and they should make appropriate enquiries as early as possible. Expedition budgets should include an element to help publication, and the editor should be informed at the time of submission.

Illustrations: line diagrams and drawings must be in BLACK ink on either clean white paper or card, or on tracing paper or such materials as kodatrace. Anaemic grey ink and pencil will not reproduce! Illustrations should be designed to make maximum use of page space. If photo-reduction is contemplated all lines and letters must be large and thick enough to allow for their reduction. Letters must be done by stencil, letraset or similar methods, not handwritten. Diagrams should be numbered in sequence, Fig. 1, Fig. 2, etc., and referred to in the appropriate place in the text by inserting (Fig.1) etc., in brackets. Captions should be typed on a separate sheet if they are not an inherent part of the diagram.

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Speleological expeditions have a moral obligation to produce reports (contractural in the cases of recipients of awards from the Ghar Parau Foundation). These should be concise and cover the results of the expedition as soon as possible after the return from overseas, so that later expeditions are informed for their planning. Personal anecdotes should be kept to a minimum, but useful advice such as location of food supplies, medical services etc., should be included.

Authors may order reprints of their contribution for their own private use. The order must be notified to the editor at the time of submission. Orders after publication cannot be accepted.

If you have any problems regarding your material, please consult the editor in advance of submission. (Dr. T.D. Ford, Geology Department, University of Leicester, Leicester LE1 7RH. Phone 0533-554455 ext. 121 or 0533-715265).

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Cover: A North Yorkshire Windypit: photo by Ian Davinson

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CAVE SCIENCE

By decision of the Council of the British Cave Research Association the Transactions is re-named CAVE SCIENCE from this issue onwards. It will, however, retain the secondary title of Transactions of the British Cave Research Association and the volume numbering will continue unbroken. References in future citations should continue to include Trans. Brit. Cave Res. Assoc. as heretofore. Although bearing the name CAVE SCIENCE, the Transactions is not a direct continuation of the defunct journal of that name published by the British Speleological Association, which merged with the Cave Research Group of Great Britain in 1974. The volume numbering of the present CAVE SCIENCE neither continues the old series, nor does it overlap.

The editorial policy regarding the contents of CAVE SCIENCE remains unchanged.

ERRATA

In Transactions BCRA Volume 8, no. 3, in the contribution on Geochemical Controls on the composition of Limestone Groundwater by Christopher and Wilcock page 135, Abstract para 4, line 2 should read "(high relative entropy)"; page 143, the first two lines should read:

calcium, bicarbonate and ionic ratio; high relative entropy, potassium, sulphate and Pco_2. They are also undersaturated to calcite.

MULU

It is regretted that the scientific reports on the Mulu expeditions which it was hoped would appear in Transactions, Volume 9, no. 1, have been delayed and will be published later.

Transactions British Cave Research Association. Vol.9, no.1, pp.1-14, February, 1982.

THE WINDYPITS IN DUNCOMBE PARK, HELMSLEY, NORTH YORKSHIRE

R. G. Cooper, P.F. Ryder and K.R. Solman

ABSTRACT

The three windypits in Duncombe Park are described, and new surveys of them are presented. Buckland's Windypit is both longer and more complex than hitherto suspected. Antofts Windypit contains evidence of at least two phases of fissure widening. A new series of fissures is described in Slip Gill Windypit.

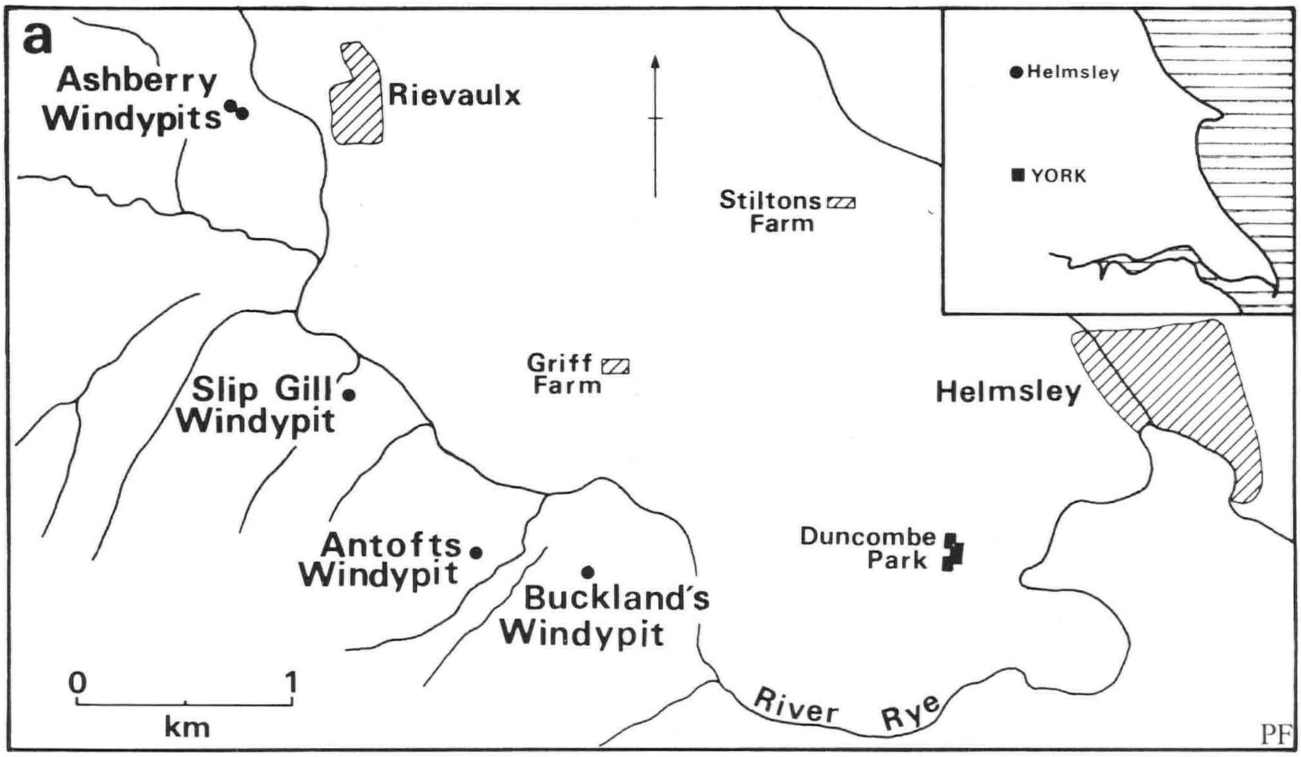
In 1976 the present authors compiled a review of information on the twenty-six North Yorkshire windypits then known, including descriptions and new surveys of many of them (Cooper, Ryder and Solman, 1976). Unfortunately, we were obliged to omit surveys of three of the largest windypits, of which outline descriptions only were given. The present paper is designed to remedy this deficiency, as we have now surveyed these windypits.

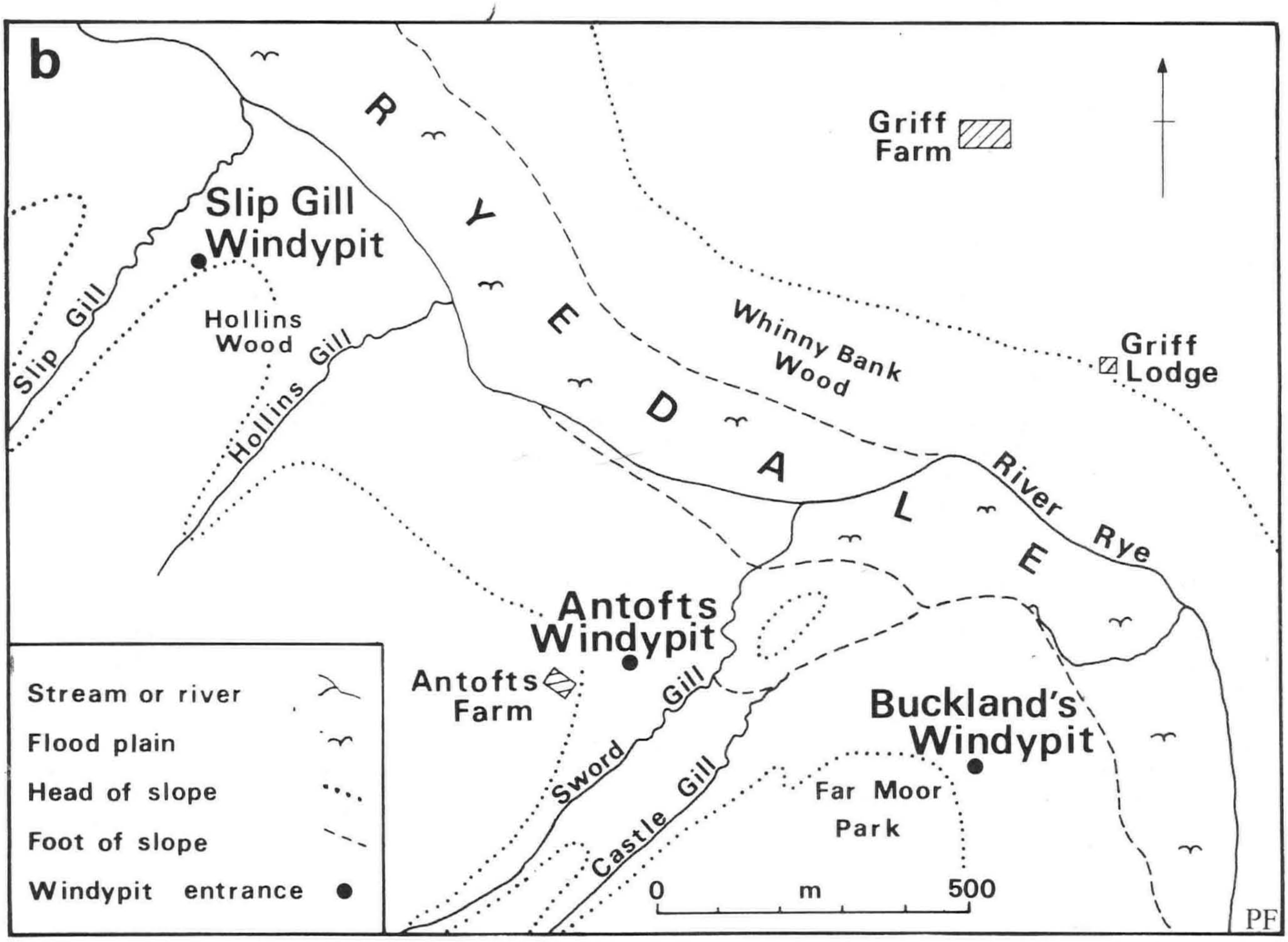
'Windypits' are vertical or near-vertical fissures in the calcareous sandstone bedrock (Corallian, Upper Jurassic) of the Hambleton Hills, 35 km to the north of York. They are roofed-over by boulders but enterable often by foxhole-like openings. They have been formed by an interesting type of mass movement which involves the valleyward movement by sliding of large masses of the hillside bedrock (Cooper, 1979, 1980), leaving the windypit fissures in their rear. Therefore they are not caves of solutional origin. Nevertheless, their exploration requires the skills and equipment of the caver.

During the 1950s and early 1960s, several windypits were the subject of archaeological investigation. Four of them, Buckland's, Antofts, Snip Gill and Ashberry Windypit 1, contained beaker artefacts (Bronze Age), and have become recognized as regionally important archaeological sites (Longworth, 1965; Marsden, 1971). Ashberry Windypits 1 and 2 have suffered sporadic archaeological investigation during the 1970s (R. H. Hayes, personal communication, 1980), and have been accurately surveyed (Ryder, 1973), but Buckland's, Antofts and Snip Gill Windypits, all of which lie within the Duncombe Park Estate, have been closed to all visitors since the early 1960s. Several presumably clandestine visits have been made to them since then (Brittain, 1965; Coghlan, 1972; and Coghlan in Brook et al, 1974, 1977), and our earlier outline descriptions (Cooper et al, 1976) were based on the accounts provided by these authors.

The opportunity to enter and survey the three windypits in Duncombe Park arose in connection with the Nature Conservancy Council's Geological Conservation Review, and was not due to a change in the policy of the land-owners with regard to access. The permission obtained to visit was entirely exceptional and the policy of the landowners is still to forbid access. The Geological Conservation Review is concerned with the identification of all those localities in Britain whose conservation is regarded as essential for the continued prosecution of geological and geomorphological research and education. It includes 'the unique labyrinthodont amphibian-bearing lower Carboniferous locality in Fife, Buckman's classic Inferior Oolite series near Sherborne in Dorset and a "new and top-secret Pre-Cambrian jellyfish site" somewhere in South Wales' ('Saving fossils from a fate worse than death', The Guardian, 3rd September 1980). In 1977, at the request of the Nature Conservancy Council, a small working group was established jointly by the British Cave Research Association and the National Caving Association, to carry out that part of the Review concerned with caves (Black, 1978; Judson, 1978). However, the group's remit did not include the windypits. The present study was carried out in connection with that part of the Review concerned with mass movement sites. It was necessary to obtain surveys of the windypits in order to establish which if any of them should be designated as 'key sites' worthy of conservation.

Fig . 1 .


a
Ashberry
Windypits
Rievaulx
Helmsley
YORK
Stiltons
Farm
Griff
Farm
Slip Gill
Windypit
Helmsley
Antofts
Windypit
Buckland's
Windypit
Duncombe
Park
River Rye
0
1
km
PF


b
RYEDALE
Griff
Farm
Slip Gill
Windypit
Slip Gill
Hollins
Wood
Hollins Gill
Whinny Bank
Wood
Griff
Lodge
River Rye
Antofts
Windypit
Antofts
Farm
Sword Gill
Castle Gill
Buckland's
Windypit
Far Moor
Park
0
m
500
Stream or river
Flood plain
Head of slope
Foot of slope
Windypit entrance
PF

The present paper may also be viewed as a response to repeated calls in the archaeological literature for more information on the windypits, and more especially for accurate plans of them. This is of particular relevance in view of the damage currently being done to their archaeological deposits (Ryder and Cooper, 1981). McDonnell (1963) noted that the windypits 'urgently need fuller attention', and an interim policy statement produced by the (now defunct) Yorkshire-Humberside Area Archaeological Committee of the Department of the Environment, identified them as a priority for rescue archaeology. This policy statement ('Towards a policy for rescue archaeology in Yorkshire-Humberside: first draft' (unpublished, no date)) gave a view of the 'main problem' facing cave archaeology in the area, which is seen as communication between archaeologists and the cave explorers who discover archaeological deposits. In particular, accurate surveys are seldom made before clearance takes place. It is hoped that the surveys of Ryder (1973) and those presented here will be of service to archaeologists. Certainly it should not prove too difficult to locate many of the finds noted on sketch plans and sections by Hayes (1962, 1963a, 1963b) at their correct positions on our surveys.

Lists of references to descriptions and accounts of Buckland's, Antofts and Snip Gill Windypits were given in Cooper et al (1976), and the discovery and exploration of these windypits was described by Cooper (1978). Therefore, this material will not be repeated here. The locations of the three windypits, on the western slope of Ryedale between Rievaulx and Helmsley, are shown in Fig. 1. Despite our earlier statement to the contrary (Cooper et al, 1976) we now accept 'Slip Gill' rather than 'Snip Gill' as the name of this windypit. This follows correspondence with R. H. Hayes, who has pointed out (personal communication, 1976) that the valley was always called 'Slape' or 'Slip' Gill by the local residents in the early years of this Century.

THE CAVES

Buckland's Windypit (Fig. 2 and Plate 1.)

The entrance lies within a wire fence, surrounded by a recent plantation of conifers, a few metres uphill from a new forestry track crossing Far Moor Park. It is marked by a large fallen tree trunk. Buckland (1823) described the entrance as 'a great irregular crack or chasm ... about twenty feet long and three or four feet broad'. The tree trunk has at some time since 1822 fallen across this crack, covering it in the middle section and leaving two entrances, one at either end. The windypit is large and complex. It must be something of a record for a North of England cave as large as this to have been known about for so long without a complete exploration and survey having taken place. In the survey (Fig. 2) and this description, the names of fissures and features are largely those of Fitton and Mitchell (1950) and Hayes (1962).

The larger entrance, A, is distinguished by a holly bush growing above it. A 7.6 m ladder is required for this 'hollybush pitch'. However, the other entrance, B, may be negotiated without tackle. Using entrance 'B' the entire windypit can be explored without the use of ropes or ladders. A drop of 2 m lands on a boulder wedged in the top of the fissure. A fixed chain on the right-hand wall can be used to traverse along a ledge leading past a boulder bridge before dropping into the large, light chamber at the foot of hollybush pitch. To the south from this chamber, a short climb and squeeze emerges at the top of Fissure 'S'. Any descent here would involve a ladder pitch (estimated at 22 m) among very loose and dangerous boulders wedged in the fissure. This route has been negotiated (Hayes, 1962) but is not recommended.

At the other end of the entrance chamber a descent through boulders and dead sheep leads after 7 m to a vertical drop/overhang of 2 m. A climb down to the right-hand side of this gains an obvious ledge skirting under the overhang and following the left wall of the fissure to the head of a steep scree slope. At this point a small branch fissure runs north-west to Chamber 'R', a small chamber at the intersection of several fissures.

To the left in Chamber 'R' there is a low crawl, referred to by N. Coghlan (in Brook et al, 1974) as The Letterbox, and originally recorded by Hayes (1962).

as a very tight squeeze. It was not noticed by Fitton and Mitchell (1950). The crawl leads into Fissure 'S', which is a lower level of the same rift as that which forms the entrance chamber. Fissure 'S' is about 20 m long, 13.7 m high and 1.2 - 2.1 m wide, ending in a boulder ruckle. It was the main source of archaeological material in the windypit (Hayes, 1962, 1963b). There are two cross-rifts part of the way along Fissure 'S'. Fissure 'T', on the left, becomes impenetrable after 12.8 m, with a narrow branch fissure on the right which is 6.6 m long. Fissure 'U', running to the right from Fissure 'S', chokes after 10.2 m. A drop of 3.5 m near its end leads to a tight passage 6.9 m long. At the foot of the 3.5 m drop, on the calcited north wall, a former water level was noted, 27.7 m below the entrance level. From Chamber 'R' a climb up into the roof among very loose boulders reveals a passage running northwest. This was not entered due to the presence of unsafe overhanging boulders. At floor level a further fissure runs north-north-east from Chamber 'R'. This is very tight and was not explored, but it is about 10 m high and 0.4 m wide.

At the point where the small branch fissure runs from the main entrance route to Chamber 'R' (Point 'E'), a steep scree slope, the Stony Corridor, descends for 9 m to the head of a 4.6 m drop, which is easily free climbed. At its foot, Fissure 'J' runs off to the right. This is a descending rift leading to a choke. Six metres before the choke a traverse leads above it into the further reaches of the fissure, ending too tight, but with a voice connection to the end of Fissure 'T'.

Returning to the main fissure, a climb behind an overhanging boulder leads into Oxtail Chamber, an impressive chamber formed by the junction of five high fissures. These are:
- The main fissure, by which Oxtail Chamber has been entered.
- Fissure 'F1', or Dead Man's Gulch. This is reached by a scramble through boulders. A traverse over a hole in the floor, followed by a series of climbable descents from chock-stones and false floors, reaches the floor proper. To the south the fissure is choked beneath Oxtail Chamber, while to the north a scramble down leads to the deepest point in the windypit, 40 m below the entrance.
- Fissure 'F2'. This is very narrow, but may be descended to a depth of about 9 m with the aid of a ladder, before becoming too tight (Fitton and Mitchell, 1950).
- Fissure 'F3'. This involves a scramble up among boulders and ends after 10 m in a loose boulder choke.
- Fissure 'F4'. This is a twisting fissure, about 13 m long. It is the main way on.

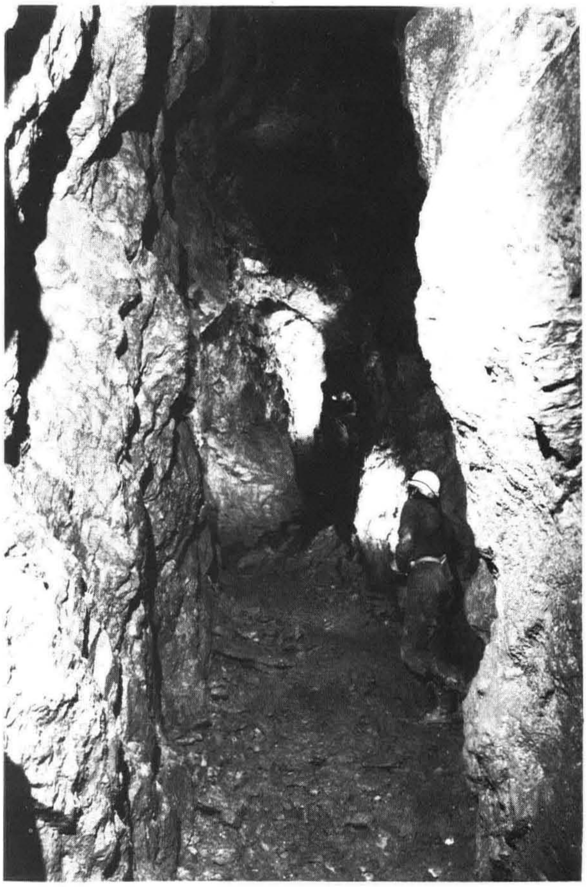
Fissure 'F4' connects with Fissure 'F3' in the roof of Oxtail Chamber. A roof traverse from Fissure 'F3' to Fissure 'F4' may be followed which clearly illustrates the 'stepped' nature of the rift. The offset between the top of Fissure 'F4' and its floor is about 3 m. Several other dangerous high-level routes in Oxtail Chamber have been described by R. H. Hayes (personal communication, 1976), but these were not explored. Many of them are roof-level continuations of the surveyed fissures.

In Fissure 'F4', a 3 m descent leads to the floor of the fissure which at this level ends after 7.5 m. However, by continuing over the 3 m drop and following an ascending traverse and sections of false floor along the fissure, Hayes Hall is reached. This was first entered by R. H. Hayes, accompanied by a group of local youths, during the late 1950s, but remained unpublished until now. Hayes Hall is a large collapse at the junction of several fissures. In this respect it resembles Oxtail Chamber, although it is not as large. To the south all ways are choked, except a small tight fissure which was followed for 9 m to a choke, where a wider, lower level could be seen but not safely entered. The main fissure runs north-east into the New Series, and is 1.2 m wide and 12 m high - an impressive section of passage. This continues for 17.5 m to a junction. Ahead is a 3.7 m descent into a roomy fissure which after 10 m terminates in a choke. At the junction, a crawl under, or climb over, a large boulder on the right leads into a parallel fissure, 2 m wide and 12 m high. To the north-east this fissure ends in a very large boulder choke after 23 m - the Great Stone Slide. Here the floor is of shattered angular debris noticeably smaller than the usual boulders which floor the rifts. This may indicate that the head of the Great Stone Slide is quite near the surface. To the south-east the passage

1. Entrance 'A'.

PLATE 1 BUCKLAND'S WINDYPIT

(photos by Ian Davinson)



2. Looking up the slope in Fissure 'S' from the junction with Fissure 'T' towards The Letterbox.

3. Far end of the New Series, just short of the Great Stone Slide.

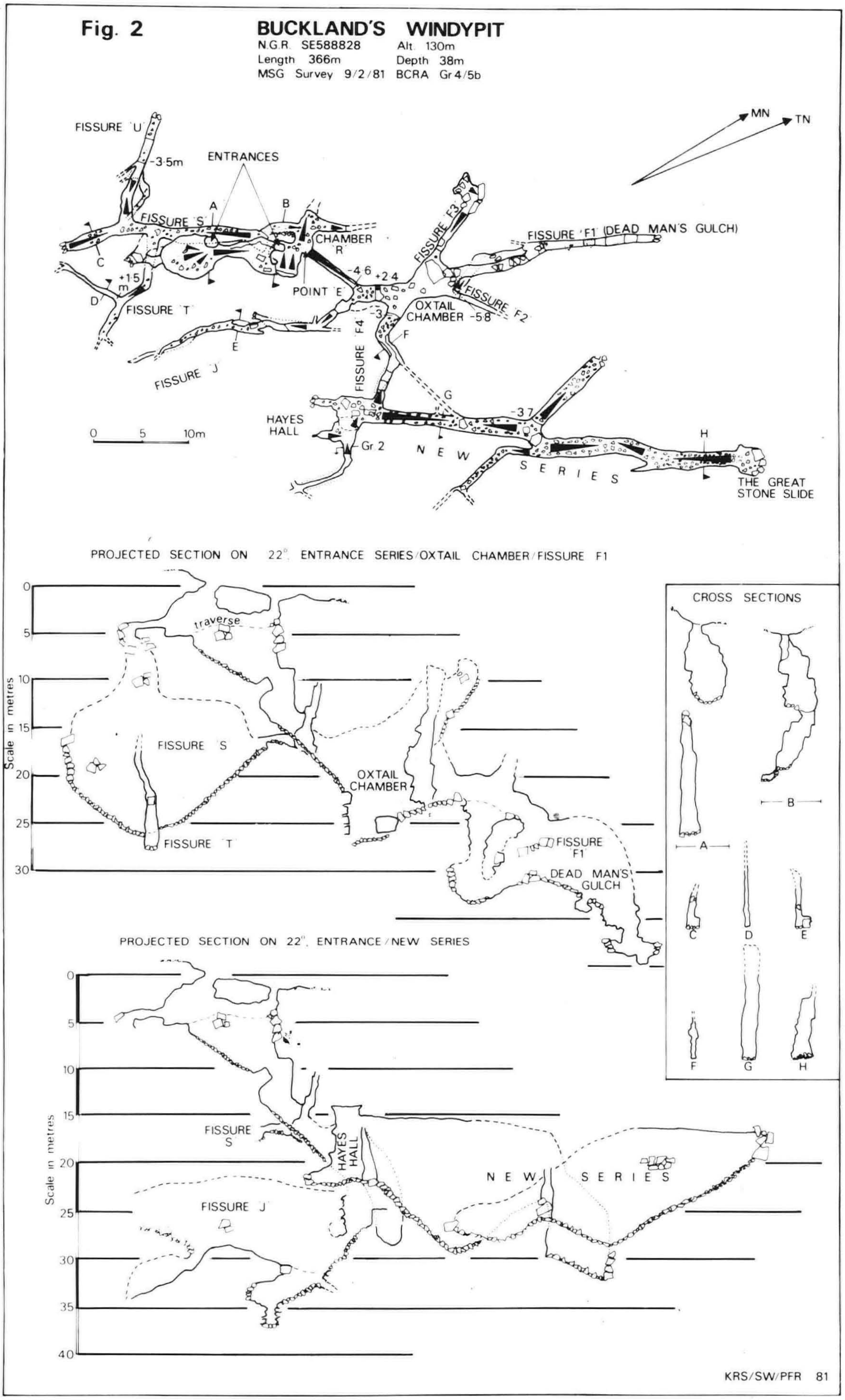
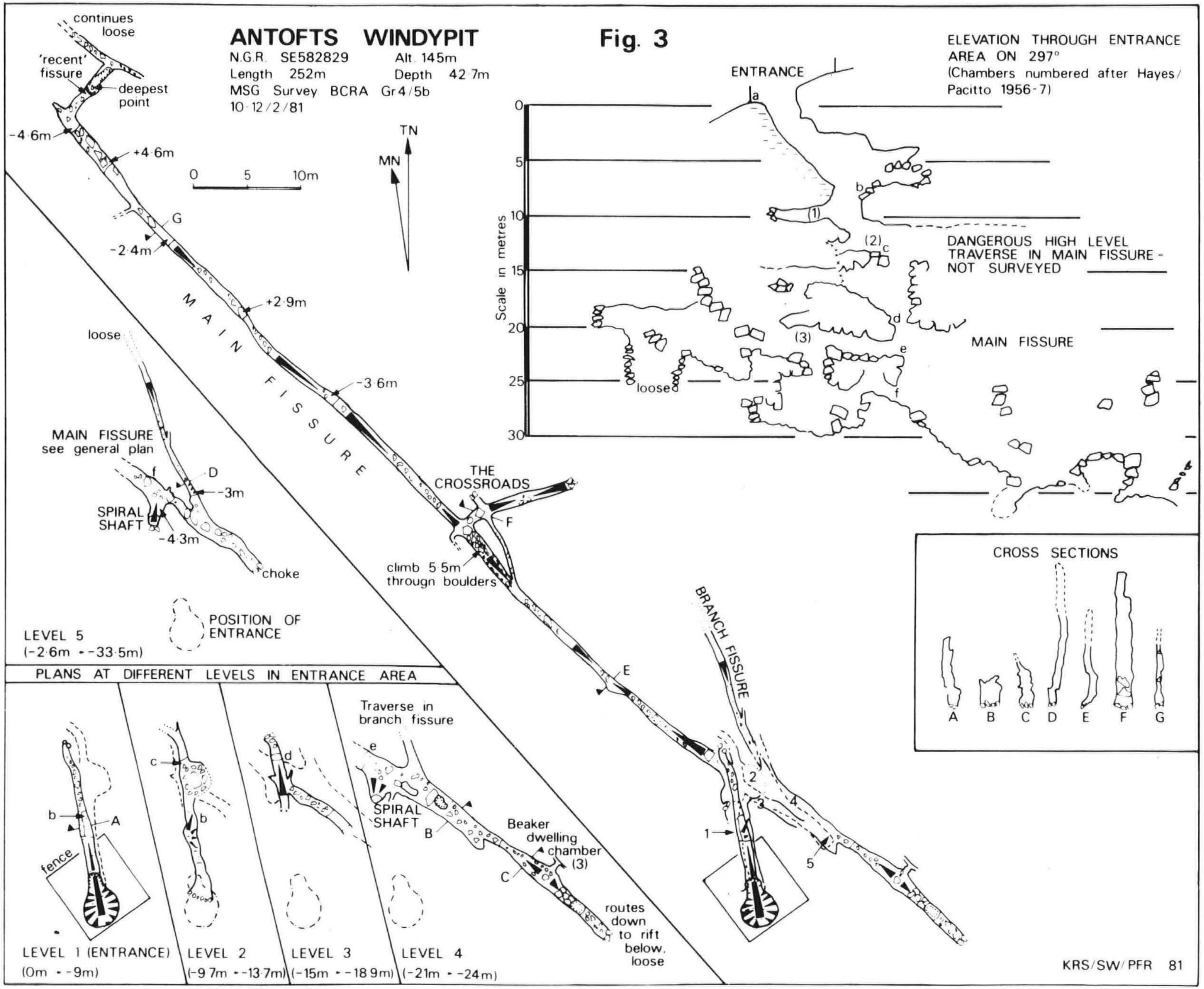


Fig. 2
BUCKLAND'S WINDYPIT
N.G.R. SE588828 Alt. 130m
Length 366m Depth 38m
MSG Survey 9/2/81 BCRA Gr 4/5b
MN
TN
FISSURE 'U'
-3·5m
ENTRANCES
A
B
FISSURE 'S'
CHAMBER 'R'
C
+1·5 m
D
FISSURE 'T'
POINT 'E'
-4·6
+2·4
FISSURE 'F3'
FISSURE 'F1' (DEAD MAN'S GULCH)
FISSURE 'F2'
OXTAIL CHAMBER -5·8
-3
F
FISSURE 'F4'
E
FISSURE 'J'
G
-3·7
HAYES HALL
Gr 2
NEW SERIES
H
THE GREAT STONE SLIDE
0 5 10m
PROJECTED SECTION ON 22°, ENTRANCE SERIES/OXTAIL CHAMBER/FISSURE F1
Scale in metres
traverse
FISSURE 'S'
OXTAIL CHAMBER
FISSURE 'T'
FISSURE 'F1'
DEAD MAN'S GULCH
CROSS SECTIONS
A
B
C
D
E
F
G
H
PROJECTED SECTION ON 22°, ENTRANCE/NEW SERIES
FISSURE 'S'
HAYES HALL
NEW SERIES
FISSURE 'J'
KRS/SW/PFR 81


ANTOFTS WINDYPIT
N.G.R. SE582829
Alt. 145m
Length 252m
Depth 42·7m
MSG Survey BCRA Gr4/5b
10-12/2/81
0 5 10m
TN
MN
Fig. 3
ELEVATION THROUGH ENTRANCE AREA ON 297°
(Chambers numbered after Hayes/Pacitto 1956-7)
ENTRANCE
Scale in metres
0
5
10
15
20
25
30
a
b
c
d
e
f
(1)
(2)
(3)
loose
DANGEROUS HIGH LEVEL TRAVERSE IN MAIN FISSURE - NOT SURVEYED
MAIN FISSURE
continues loose
'recent' fissure
deepest point
-4·6m
+4·6m
G
-2·4m
+2·9m
-3·6m
MAIN FISSURE
THE CROSSROADS
F
climb 5·5m through boulders
E
BRANCH FISSURE
1
2
3
4
5
loose
MAIN FISSURE see general plan
f
D
-3m
SPIRAL SHAFT
-4·3m
choke
POSITION OF ENTRANCE
LEVEL 5
(-2·6m - -33·5m)
CROSS SECTIONS
A B C D E F G
PLANS AT DIFFERENT LEVELS IN ENTRANCE AREA
fence
b
A
c
b
d
Traverse in branch fissure
e
SPIRAL SHAFT
B
Beaker dwelling chamber
(3)
C
routes down to rift below, loose
LEVEL 1 (ENTRANCE)
(0m - -9m)
LEVEL 2
(-9·7m - -13·7m)
LEVEL 3
(-15m - -18·9m)
LEVEL 4
(-21m - -24m)
KRS/SW/PFR 81

continues narrower for 11 m, ending too tight.

The survey of Buckland's Windypit produced by Fitton and Mitchell (1950) includes the entrance fissure, Chamber 'R', the Stony Corridor, Oxtail Chamber, Fissure 'F1' (Dead Man's Gulch) and the beginnings of Fissures 'J', 'F2', 'F3' and 'F4'. Hayes (1962) includes a sketch section (credited to E. P. Fitton and R. H. Hayes) which shows the entrances, Chamber 'R', Oxtail Chamber, the proximal end of Fissure 'F4', and Fissures 'S', 'T' and 'U'. A plan view of Fissure 'S' and the proximal ends of Fissures 'T' and 'U', is included in Hayes (1963b), together with a longitudinal cross-section of Fissure 'S'.

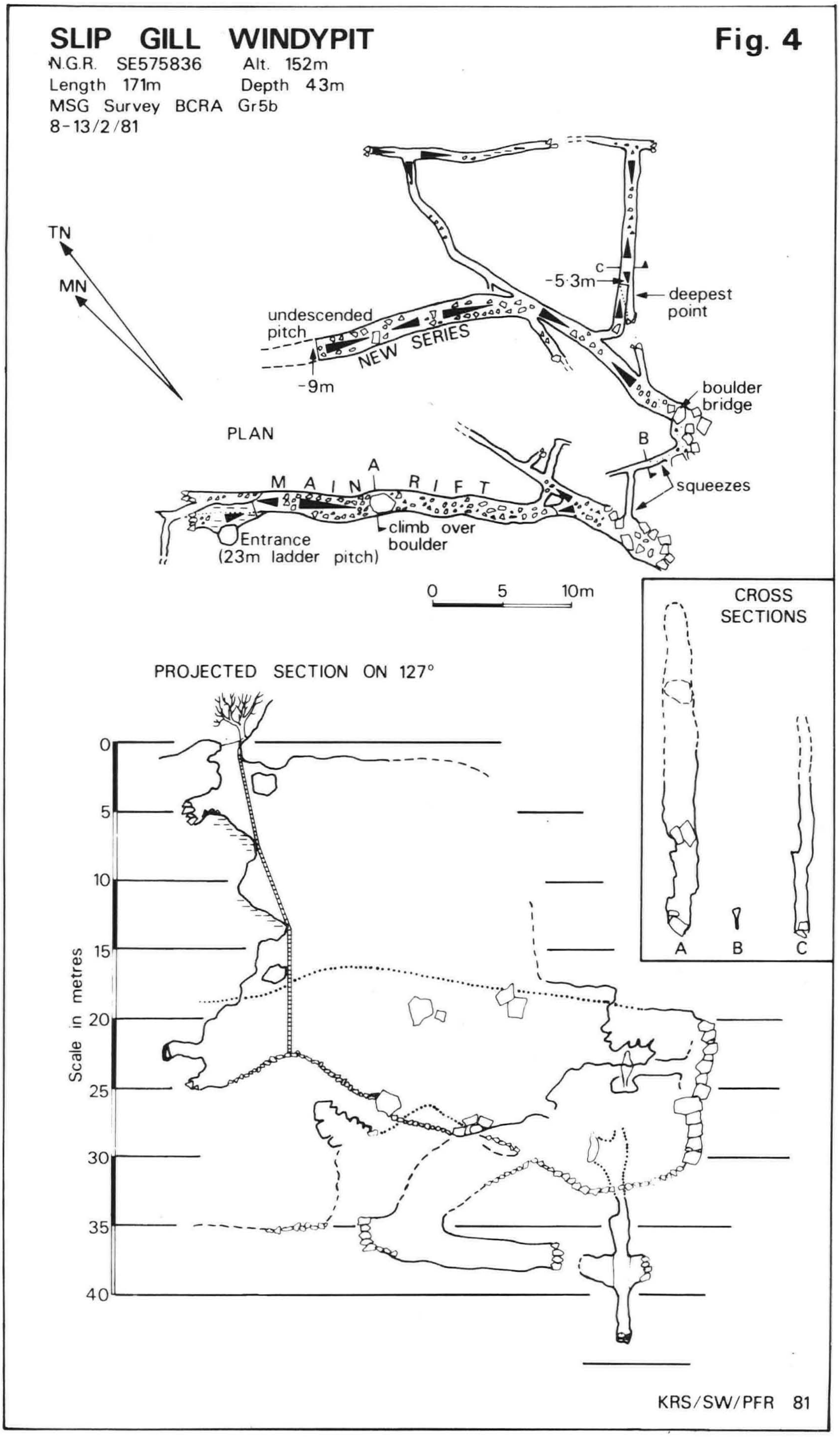
Antofts Windypit (Fig. 3)

The entrance is surrounded by a high wooden fence, 18 m east of Antofts farmhouse. A steep debris slope in a fissure leads to a 2 m drop under the east wall of the fissure, while ahead the passage is choked after 8 m. A muddy slope continues at the foot of the drop and leads to the head of the main fissure. A 13 m ladder may be rigged from this point, dropping through a 'trapdoor'-like opening into the lower reaches of the main fissure. Traversing over the head of the pitch, a corner is reached. Ahead there is a high-level traverse in the main fissure, and below there is a climbable route down to the 'trapdoor'. Using this route the floor of the main fissure may be reached without using tackle, but a lifeline at least is recommended. The high-level traverse is made dangerous by numerous loose boulders, and as the main fissure can easily be followed at floor level there seems little point in following it at roof level.

About 9 m down the pitch the main fissure may be followed south-eastward on a chock-stone floor for 28 m. This is referred to as 'Chamber 3' by Hayes (1963a, 1963b), and is where most of the archaeological finds were made ('level 4' in Fig. 3). About 3.7 m from the terminal boulder choke at this level, a hole in the floor descends very steeply through loose boulders for 10 m. The descent was not made and is not recommended. A 'spiral shaft' (Hayes, 1963a) descends from Chamber 3 to emerge at the floor of the main fissure. This forms an alternative, easier route to the last few metres of ladder.

The main fissure is up to 22 m high, and with a length of 115 m it is the longest known continuous fissure in all the windypits. To the south-east from the foot of the ladder, or the foot of the spiral shaft, the main fissure chokes after about 11 m. However, after 4 m a branch fissure runs north-eastwards for 15 m. There is a 3 m vertical step down in its floor, for which a ladder is an advantage. Thirty metres along the main fissure to the north-west from the foot of the ladder or the foot of the spiral shaft, a massive boulder fall is encountered. To the right an 8 m long squeeze leads to 'The Crossroads', where a large cross-rift joins the narrow rift. The ways ahead and right are choked after a few metres. The way to the left also appears to be choked, but a scramble involving a vertical ascent of 5.3 m leads back to the main fissure, beyond the massive boulder fall. The long squeeze to The Crossroads may be avoided by climbing 5.5 m up the boulder fall in the main fissure and squeezing under some dangerous loose boulders. A third alternative route was found by climbing 10 m vertically up the main fissure and traversing over the fall at high level. Beyond the fall the fissure continues for 52 m before closing down to a narrow slit because the passage is blocked by thick deposits of flowstone on each wall. A few small side fissures enter the main fissure along this stretch but they were not explored due to the presence of unstable hanging boulders in them.

At the point where the main fissure closes down, a cross-rift leads off in a north-easterly direction. This is 7.6 m long, 12 m high and 0.6 m wide. There are several indications that it may have opened up more recently than the other fissures. At the far end of this 'recent' fissure, a rift is encountered running parallel to the main fissure. This is choked to the right and continues unsurveyed to the left. It was not fully investigated because of its very loose walls, and the loose boulders wedged in it. Several boulders moved when touched and these will have to be cleared before attempts are made to explore the fissure further. The deepest point of the surveyed windypit lies at the bottom of the 'recent' fissure, 43 m below the level of the entrance.


SLIP GILL WINDYPIT
Fig. 4
N.G.R. SE575836 Alt. 152m
Length 171m Depth 43m
MSG Survey BCRA Gr5b
8-13/2/81
TN
MN
undescended pitch
NEW SERIES
-9m
c
-5·3m
deepest point
boulder bridge
PLAN
B
squeezes
A
MAIN RIFT
Entrance (23m ladder pitch)
climb over boulder
0 5 10m
CROSS SECTIONS
A B C
PROJECTED SECTION ON 127°
Scale in metres
0
5
10
15
20
25
30
35
40
KRS/SW/PFR 81

The survey of Antofts Windypit produced by Fitton and Mitchell (1950) includes the entrance fissure only, extending almost as far down as the head of the 13 m pitch. This is because at that time the way on was blocked by rubbish (Cooper, 1978). Hayes (1963a) gave a sketch section through those parts of the windypit vertically below the entrance, after the way on had been forced. This reaches the floor of the main fissure, and includes the 13 m pitch, and the archaeologically important Chamber 3. This diagram, which was used by Longworth (1965) and is credited to R. H. Hayes and A. Pacitto, provides the chamber numbering system used in Fig. 3. A plan of the floor of Chamber 3 was given by Hayes (1963b).

Slip Gill Windypit (Fig. 4)

The keyhole-shaped entrance lies beneath a tree, a few metres downslope from a forestry track on the summit convexity of the eastern slope of the Slip Gill valley (Snip Gill on Ordnance Survey maps). A 4.6 m climb down leads to a landing on a slope of leaves, pebbles and mud at the head of the main rift. Three and a half metres down this slope is a vertical pitch 15.3 m deep. Loose material should be cleared from the slope before the first person descends the pitch. This is best laddered as a single pitch of 25 m from the tree above the entrance. The vertical pitch is broken by a small ledge 6.7 m down, where a prehistoric beaker was found in 1952 (Hayes, 1955). A landing is eventually made on a heap of debris fallen in from above. Seven metres to the north-west the rift ends in a boulder choke, 25.3 m below the surface. A short climb up leads after 2.4 m to a narrow rift running south-west wbich becomes too tight after 3 m.

South-east from the foot of the pitch, the main rift is 1.5 - 2.8 m wide and up to 24 m high. The floor slopes down for about 7.5 m to a large over-hanging boulder, necessitating a 2.4 m climb down. After a further 12 m a pair of narrow fissures penetrate northward for about 6 m. In the main rift, a scramble up leads after 7.6 m to a large boulder ruckle. A route was found through two squeezes amidst this dangerous and loose choke, leading into a 'New Series'. This is a series of rifts not mentioned in any of the published sources. An old battery left by a previous visitor was found in the widest of the New Series rifts, but the rifts beyond had probably not been entered previously. Emerging from the squeezes, a 4.6 m climb down from a boulder bridge leads to the floor of a large rift, 1 - 2 m wide and 6 - 12 m high. After 7.5 m a narrower rift, 1 m wide, runs in a northeast direction for about 14 m, dropping to the deepest point in the windypit (42 m below the entrance level) then rising to a junction with a cross-rift which is choked to the right and too tight to the left after only 3.5m.

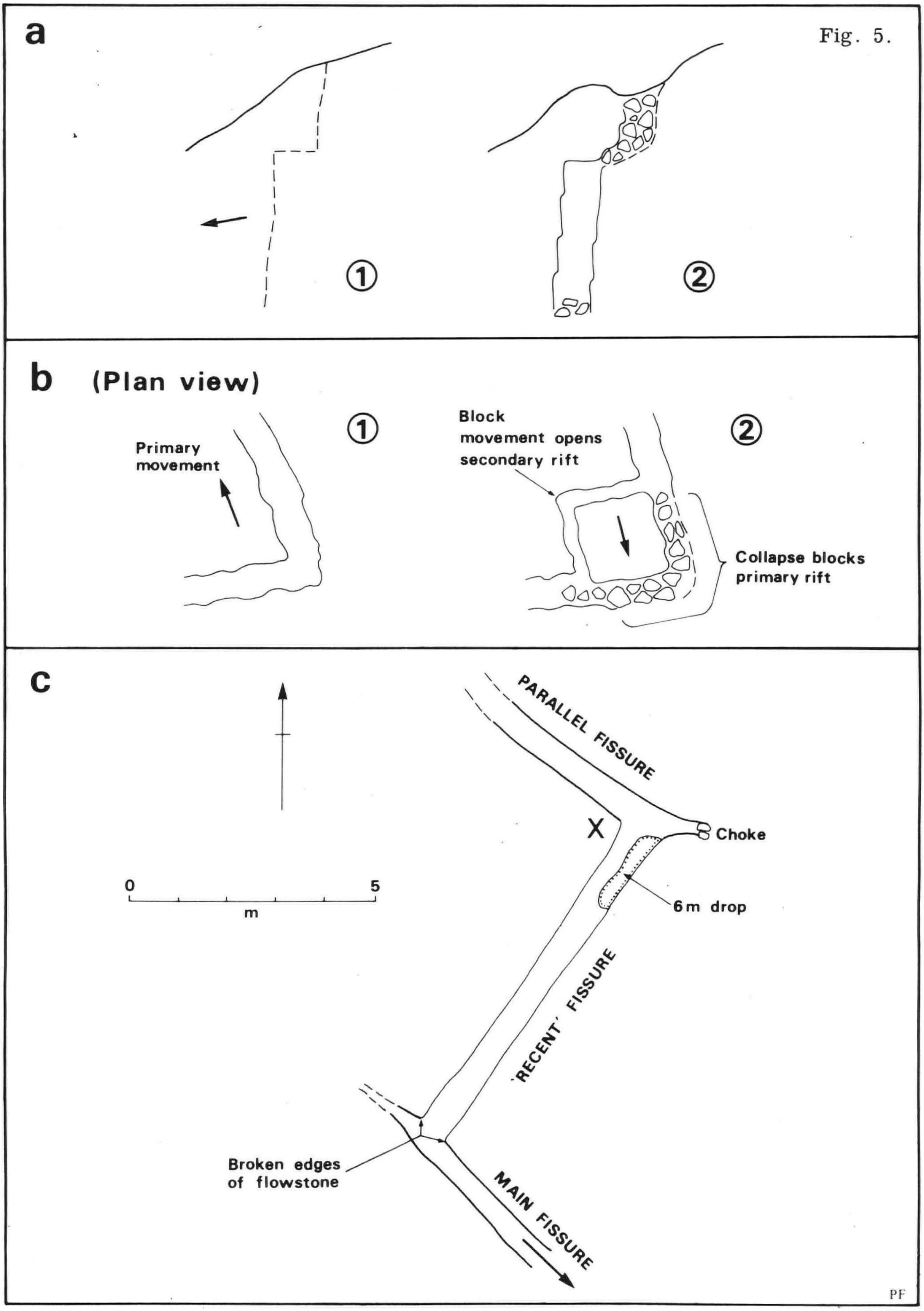
Seven metres further along the widest rift of the New Series, another narrow rift (0.6 m wide) leads roughly northwards for 13 m to a cross-rift which appears to be a continuation of the cross-rift in the first narrow fissure. The widest rift of the New Series continues for a further 14.3 m to the head of a 9 m pitch. The rift continues beyond this point but the pitch was not descended due to the absence of a safe belay-point.

The earlier survey of Slip Gill Windypit by Fitton and Mitchell (1950) extended along the main rift as far as the boulder ruckle at its south-eastern end and up to that point shows a good agreement with the present survey.

SOME GEOLOGICAL OBSERVATIONS

The roofs of windypit fissures

Although in places the roofs of windypit fissures consist of wedged boulders the stability and safety of which are uncertain, for much of their length most fissures appear to be roofed by large blocks of which the orientation has not been greatly disturbed. A logical explanation would be that the joint which has opened to form a fissure is 'stepped' in cross-section, as with Fissures 'F3' and 'F4' in Buckland's Windypit, or the transverse fissures in Noddle End Windypit (Fitton and Mitchell, 1950). A 'step' would not only provide a total or partial roof to a passage, but also prevent its infilling by debris from above (Fig. 5a). It follows that windypits (unfilled open fissures) are only likely to be found where this near-surface stepping has taken place.


a
Fig. 5.
①
②
b
(Plan view)
Primary movement
①
Block movement opens secondary rift
②
Collapse blocks primary rift
c
0
5
m
PARALLEL FISSURE
Choke
6 m drop
'RECENT' FISSURE
Broken edges of flowstone
MAIN FISSURE
PF

Collapses at the intersection of fissures

Progress in several windypits is halted by ruckles of large boulders, the result of large-scale collapse of the rift walls. This often seems to take place where the rift changes direction through an angle of 90° or more. This collapse action may involve the movement of large blocks, which in turn may open up narrower rifts parallel to the main one choked by the collapse (Fig. 5b). The phenomenon is well seen in Slip Gill Windypit, where the massive ruckle which terminates the main rift can in fact be bypassed into the New Series beyond, by way of small and constricted rifts that probably result from collapse and block movement around the major junction. This view of the way in which windypit formation 'works' is essentially an extension of ideas expressed by Davies and Ryder (1973). Whether the major and minor fissures represent two separate periods of movement is not certain. Evidence indicating a second phase of slipping in Antofts Windypit (see below) would suggest that this is possible.

The 'recent' fissure in Antofts Windypit

This fissure lies between 31 m and 43 m below the entrance level of the windypit. Thick deposits of flowstone cloak both walls of the main and parallel fissures but there is no sign of flowstone anywhere along either wall of the fissure which connects them. All three fissures have fairly active 'drips' and at several positions water was noted flowing down the walls in small amounts. There appears to be more seepage into these windypit passages than into any others so far surveyed, with the possible exception of the 'long' fissure in Noddle End Windypit (Solman, 1976a). Where the 'recent' fissure intersects the main fissure the 2 cm thick flowstone deposits on the walls of the main fissure abruptly terminate. The broken 'ends' of the flowstone show the structure clearly and have not become smoothed-over as might be expected if the fracture had occurred a long time ago. The walls of the 'recent' fissure are loose and 'peeling' in many places. On the map (Fig. 5c), 'X' marks the position of a column of loose rock which shows extensive splitting and peeling. If it were pushed it would topple over and break into many pieces. Fresh angular boulders forming the floor and wedged in the rift add to the impression that the fissure opened later than the main and parallel fissures, and that this was probably a comparatively recent event.

DISCUSSION

In their account of the windypits, Fitton and Mitchell (1950) made much of the variety of bats found 'in and around the Duncombe Park Windypits'. Our own observations, made in February 1981, tend to suggest that either the bat population has decreased markedly in the last 30 years, or that the observations which were reported by Fitton and Mitchell were rather more 'around' than 'in' the windypits. We saw three bats, all of them Daubenton's Bat (*Leuconoe daubentonii* Leisler), which is common in the British Isles. Two were in Slip Gill Windypit, one on the south-western wall of the main rift, about 3 m above the lowest point of the floor, and the other in a rock crevice just inside the entrance to the windypit. The third bat was on a wall at the far end of the Chamber 3 level in the main rift of Antofts Windypit. Apart from the bats, the fauna of the windypits owed much to the presence of decaying sheep and vegetation, and differed little from that described from other caves in the North York Moors area (Solman, 1976b, 1976c).

Bones were found lying on the floors of rifts in all three windypits. Particular concentrations were found on the floor of the main rift in Slip Gill Windypit, and in Fissures 'S' and 'U' in Buckland's Windypit. Most of them were modern, but two of the bones found in Slip Gill Windypit have since been identified as human (report forthcoming). Antofts Windypit, the site of a not-so-old rubbish dump which formerly consisted largely of the offal of slaughtered deer, and live cartridges (Fitton and Mitchell, 1950), contained broken pieces of willow pattern pottery and several rusty kettles.

On a more general note, further 'discoveries' of windypits continue to be made. During the week in which the surveys reported here were being made, two fissures on the south side of Caydale were visited, and have since been surveyed together with two previously undescribed fissures in Ducken Dale, near Ampleforth (Cooper, 1981).

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THE MICROFLORA OF LIMESTONE PERCOLATION WATER AND THE IMPLICATIONS FOR LIMESTONE SPRINGS

by H. Friederich, P. L. Smart and R. P. Hobbs

Abstract

This paper reports on the results of bacteriological research, undertaken in G.B. Cave, Charterhouse on Mendip, Somerset. During several visits to the cave system in 1979, the discharge of some 20 percolation water inlets, ranging from slow drips to small streams, was measured. Samples were collected in sterilized bottles to determine the microbial flora. Total Viable Counts were performed after 24 hours incubation at 37°C, three days at 22°C and one set of samples was incubated for seven days at 8°C. There were significant differences between estimates at the first two temperatures, but not at the two lower ones. Samples were also analysed for *Azotobacter* spp., nitrifying bacteria and *Clostridium* spp. Separate samples were analysed for dissolved organic matter. Particulate organic matter was not present in the percolation water.

The bacterial population of percolation water is low, and is not controlled by discharge fluctuations. No relation exists with dissolved organic matter, type of percolation inlet or depth below the surface, and it is therefore postulated that the microbial population represents a random input from the soil. Using data for selected Mendip sources provided by Bristol Waterworks Ltd., it was possible to separate three water types using Total Viable Counts (TVC) after 24 hours at 37°C: (1) swallet recharge flowing in conduits (high TVC); (2) percolation water in fissures and conduits (moderate TVC), and (3) saturated diffuse flow water (low TVC). In contrast to saturated diffuse flow, the unsaturated zone of limestone aquifers does not appear to filter bacterial polulations significantly during recharge. It is suggested that study of bacterial populations in karst waters would enable reasonable estimates of the proportions of the three water types in spring discharge to be made.

There are two major types of bacteria, both of which are found in caves: chemoorganotrophic bacteria derive energy from the oxidation of organic compounds, while chemolithotrophic bacteria utilise the oxidation of inorganic compounds (Hawker and Linton 1979). Those photolithotrophs dependent on photosynthesis are of course absent in the dark zones of caves, but chemolithotrophic bacteria have been recorded in Hungarian caves by Dudich (1930, 1933) and more recently by Varga and Takats (1960). Their presence has been confirmed in caves in France (Caumartin 1957, 1961, 1963; Gounot 1967b, 1969), Kentucky, USA (Fliermans and Schmidt 1977) and Wales (Mason-Williams and Benson-Evans 1958).

Chemoorganotrophic bacteria have been the subject of an extensive study in French caves (Gounot 1967a, 1967b, 1969) and have also been discussed by Ginet (1960), Hodorogea (1972) and Mason-Williams (1969). All the above papers were concerned with cave sediments and research on water-borne bacteria is more limited. Population density figures have been quoted for cave waters in Hungary (Molnar 1961), Poland (Fischer 1958), Kentucky, USA, (Barr and Kuehne 1971) and Wales (Mason-Williams 1969) without a clear definition of the source of water. Because of the importance of bacteria for water quality, data are also available for groundwaters, for instance Allen and Geldreich (1975) and Robeck (1969). Table 1 summarizes microbial population densities in sediments and water in limestone caves, derived from the above sources.

Table 1 Published bacterial counts for cave sediments and waters. Figures are Total Viable Counts after 3 days at 22°C.

Author	Heterotrophic Bacteria	Autotrophic Bacteria
Cave sediments	($x10^6 g^{-1}$ sediment)	(g^{-1} sediment)
Barr and Kuehne 1971	0.004 - 36.5	-
Fliermans and Schmidt 1977	-	*Nitrobacter* $6x10^5$
Ginet 1960	10 -150	-
Gounot 1967a	0.5 - 3.5*	-
Gounot 1967b	11 - 45	*Azotobacter* 50-250 *Clostridium* 950-2500 Nitrifying bacteria 50-26000
Gounot 1969	1.9 - 22	10 - 1500+
Hodorogea 1972	0.09 - 25	-
Varga and Takats 1960	10	100 - 10000+
Cave Waters	(ml^{-1})	(ml^{-1})
Barr and Kuehne 1971	38 - 109000	-
Fischer 1958	300	2500+
Mason-Williams 1969b	1010 - 1570	-
Molnar 1961	0 - 800	-

* *Arthrobacter* only

+ Type not specified

METHODS

To determine the microbial population of percolation water Total Viable Counts (TVC), in colony-forming units, were performed on water samples from several percolation water inlets in G.B. Cave, ranging in size from less than one litre per hour to several hundreds of litres per hour, and at different depths throughout the cave system (Fig. 1). G.B. Cave is one of the swallet caves of the Cheddar Resurgence catchment in the Mendip Hills, Somerset (Smith, 1975). The entrance (ST47595623) is situated on the south flank of Blackdown, some 2.5 kilometres northeast of Cheddar. The cave system has been surveyed to C.R.G. grade 5 (Crickmay and Bendall 1949-1950; Savage 1969) and principal points have been checked by radio-location. Recently intensive research has been carried out on the percolation water system by one of the authors (Friederich in prep.) and full description and discussion of the results will be published in due course. The sampling points are shown in Fig. 1 and a brief description of each site is given in Table 2.

The water samples were collected in sterilized bottles and returned to the laboratory for analysis within five hours. Prolonged contact with the atmosphere was avoided to minimize the risk of contamination, but for slow drips and showers the sampling time exceeded several minutes.

TVC were performed by standard pour plate, and the Spiral Plater technique (Spiral Systems Inc., Cincinnati, USA). The medium used was Difco Blood Agar base number 2, which has the following composition - Proteose peptone Difco 15g., Liver Digest 2.5g., Bacto Yeast extract 5g., Sodium chloride 5g., Bacto-agar 12g., Distilled Water 1 litre pH 7.4. According to Meynell and Meynell (1965) estimates of bacterial numbers by colony counts in plates are more precise than that of dilution counts in liquid media. They quote the standard sampling error as the square root of the mean count, which means that the accuracy increases with the number of counted colonies. Because some micro-organisms may not develop colonies on the particular culture medium (Jones 1979), TVC can be an underestimate of the total bacterial population, an error that Gounot (1967b) claims to be up to 10%. Thus while TVC does not measure the total bacteria population, it does provide precise comparative data.

The plates were incubated at both 37°C for 24 hours and at 22°C for three days. Incubation at 37°C is a standard technique, because the majority of pathogens grow best at this temperature. The counts at 37°C were very low for percolation

Table 2. Total Viable Counts (ml^{-1}) after 3 days at 22°C for G.B. cave. The sites refer to Fig. 1.

Site	Description	Site Type	Depth under surface (m)	11/4/79	25/4/79	16/5/79	21/5/79	6/7/79	24/8/79	25/2/80
E N B	drip from boulder choke	seep	10	70	<40	-	-	-	-	-
E N P	drip from small rift	seep	15	240	<40	1200	5700	1400	<40	930
U G S L	slow drip stalactite	seep	27	1000	-	300	-	-	-	-
E N T	slow drip stalactite	seep	27	34000	<40	520	590	410	1306	-
D A V	shower from aven	shaft	40	1000	<40	850	-	110	-	-
G O T O	drips from aven	flow	46	-	-	590	6700	300	6800	-
M U D	large shower inlet	shaft	53	10000	<40	1400	1000	40	10000	2100
W P P C	small stream inlet	flow	50	70	<40	140	<40	3200	<40	74
W P O V	intermittent inlet	flow	53	200	-	-	-	-	-	780
W P A V	shower from large aven	shaft	55	-	-	520	-	-	190	74
W P N W	drip stalactite	seep	60	-	<40	1900	220	<40	190	-
W P 3	slow drip from roof	seep	60	<40	<40	1000	1600	110	-	-
R A	drip stalactite	seep	63	-	74	740	1400	-	520	260
R I	drip inlet	seep	63	300	<40	440	110	110	-	-
H A V	shower from aven	shaft	78	8000	<40	6900	410	<40	220	-
H S L	slow drip stalactite	seep	82	3000	-	>3000	190	1300	<40	1500
G O H A	slow drip stalactite	seep	82	3000	<40	1200	480	<40	300	-
G O P I	drip from roof	seep	82	5000	<40	7100	560	110	670	-
G O T W	slow drip stalactite	seep	115	7500	110	-	-	-	850	-
G C F	fast drip stalactite	flow	131	-	-	-	-	-	-	370
G C S L	slow drip stalactite	seep	135	-	-	-	-	-	-	440
B A V	shower from aven	shaft	140	-	-	-	-	-	-	220
Stream	see text	-	-	-	520	>1000	1000	520	5500	-
Soil	see text	-	-	-	-	-	-	520000	-	-

water, often less than forty, the minimum limit of detection when using a Spiral Plater. No direct statistical relation existed between the 37°C and 22°C data sets (linear correlation 0.58 not significant at 95% level) due to the different microorganisms cultured at these two temperatures. Because the average temperature for percolation water in G.B. Cave is 8.5°C to 10°C, one set of samples was also incubated at 8°C for seven days. The TVC for the 8°C culture were slightly higher than those for the 22°C culture, but not enought to make a significant difference in the discussion of the results. This agrees with Gounot's observation that decreasing the incubation temperature merely slows down the development of the culture, but that it does not materially alter the viability of the different species (Gounot 1967a, p.34; 1969, p.105). Therefore 22°C was adopted as the standard incubation temperature. Table 2 presents TVC after 3 days at 22°C using the Spiral Plate Method for all sites sampled on

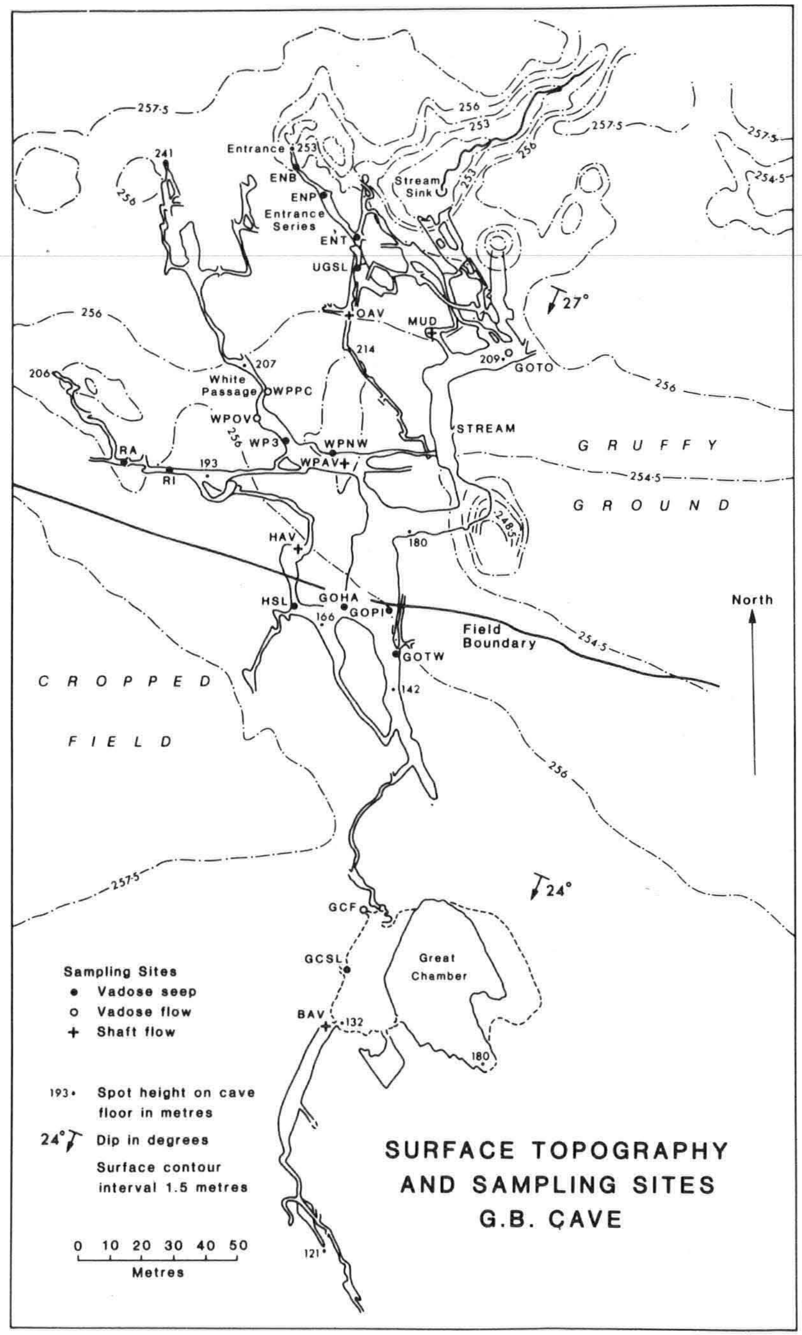

Fig. 1

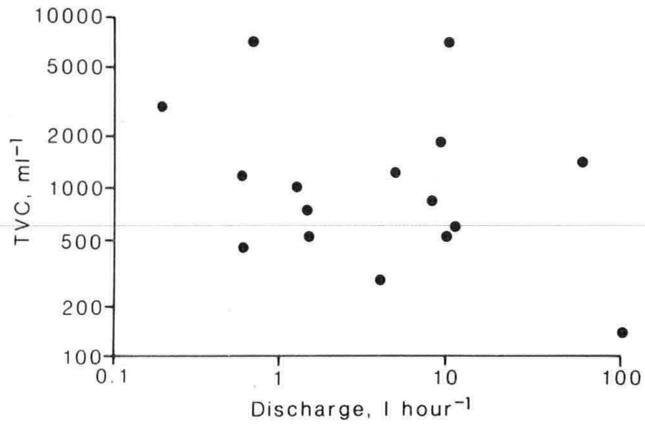

Fig.2 Total viable counts after 3 days at 22°C in relation to discharge for samples collected 16 May 1979

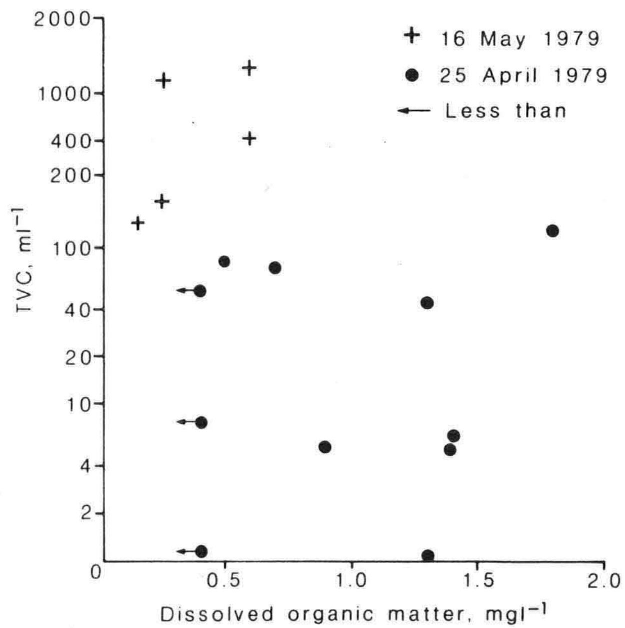

Fig.3 Total viable counts after 3 days at 22°C in relation to dissolved organic matter for samples collected 16 May and 25 April 1979.

seven separate occasions. "Stream" is a sample from Tynings Swallet stream where it emerges underground in the Gorge, and "soil" is a sample from a soil water suction sampler (Soiltest Inc. Evanston, USA) situated at -100 cm in the soil above the Gorge.

Because Fischer (1958) recorded chemotrophs in water, we also attempted to isolate colonies of *Azotobacter* spp., *Nitrobacter* spp., *Nitrosomonas* spp. and the anaerobe *Clostridium* spp. *Azotobacter* spp. and *Clostridium* spp. were grown on media described in the Oxoid manual (1961); the nitrifying bacteria were determined with the method of U.S. Department of the Interior (1977), pp.73-78.

RESULTS

In order to investigate the consistency of bacterial counts through times at each site, the data from Table 2 were ranked according to their TVC. The figures for 25 April 1979, when all counts but two were less than forty, were not included, neither were TVC for Stream or Soil (Table 2). To test if the figures for each site are from one or more populations the Kruskall Wallis one way analysis of variance was applied (Siegel 1956). The results indicate that data from all sites are drawn from the same population (Probability 0.5). Even when the sites were grouped into shafts, flows and seeps using the size of void from which they issue (m, cm and mm respectively), or when they were grouped in four groups with different depths (0-30, 31-60, 61-90, >91 m below the surface), the data still form a homogenous population (Probability 0.5 and Probability 0.9 respectively). This indicates that there is no tendency for any systematic variation between sites, neither the depth nor the type of inflow controlling the bacterial numbers in percolation water. The conclusions are not changed if missing data is eliminated by using sites which were sampled on every date.

Table 3 Average ranks for Total Viable Counts, grouped according to: (a) sampling date and (b) sampling site. A high similarity in TVC is indicated by similar values for the average ranks. Data from Table 2.

a) Date:

Date	Rank
11/4/79	48
16/5/79	51
21/5/79	42
6/7/79	26
24/8/79	35
25/2/80	37

b) Site:

Sites except White Passage.

Site	Rank
ENB	40X
ENP	40
UGSL	42
ENT	51
OAV	39
GOTO	54
MUD	57
RA	43
HAV	43
HSL	46
GOHA	39
GOPI	50
GOTW, GOI, GCSL, BAV	44X
Average Rank	42

White Passage Sites.

Site	Rank
WPPC	20
WPOC	35
WPAV	25
WPNW	29
WP3	34
RI	25
RA	43
Average Rank	28

X = only 1 measurement

However, the average ranks (Table 3) show that sites in White Passage appear to have consistently low counts. When the inlets in White Passage are grouped and tested against all others, a significant difference exists (Probability 0.01). These low counts may be attributed to the stony nature of the soil above this area, which has been mined extensively in the past. The lower biological activity in this area is supported by lower carbon dioxide concentrations in soil air, although this may also be explained by increased soil permeability. The soil above the entrance series is a relatively undisturbed clay loam, while the deepest drips are situated under a cultivated field.

WPPC in particular has a consistently low count, although a sample from this inlet did contain more bacteria than any of the other samples on 6 July 1979. MUD on the other hand was almost free of bacteria that day, while it had a high average rank. The possibility of confusion between samples from these sites cannot be rejected. Examination of other data for this day, however, shows that the values tend to be lower than for other sampling times, as indicated by the low rank (Table 3). This may be related to the much drier soil on this date, when a soil moisture deficit of 76 mm existed; the soil was saturated on all other sampling days. How this change in soil moisture affects the underground microbial population is not certain because the variations in TVC cannot be explained by differences in flow between the various sites, as is shown in Figure 2 for 16 May 1979. Nor do the chronological variations in TVC for one site relate to variations in discharge as is illustrated by Table 4. The explanation may therefore be related to decreased micro-organism activity caused by drying of the soil rather than hydrological factors. To test if seasonal variations are important the Kruskall Wallis test was also applied to the data grouped according to sampling data. At a significance level of 0.05 no difference exists between the various groups, but at a significance level of 0.1 the different dates form separate populations. When the figures for 25 April are included the populations are different at a significance level of 0.001. This implies either a temperature or soil moisture effect may be important and therefore suggests a shallow soil source for the bateria, rather than a deepseated, isothermal, fissure source. A similar conclusion was reached by Sinton (1980), who explained the relation between antecedent rainfall and the numbers of *Bacillus stearothemophilus* in groundwater in the Canterbury Plain as due to the translocation of bacteria from the soil to ground water during infiltration.

Table 4 Discharge and Total Viable Counts after 3 days at 22°C for 3 sites in G.B. Cave. For sites see Fig. 1.

Site	ENT		ENP		MUD	
Date	T V C ml^{-1}	Discharge $l\ sec^{-1}$	T V C ml^{-1}	Discharge $l\ sec^{-1}$	T V C ml^{-1}	Discharge $l\ sec^{-1}$
11/4/70	34000	2.8	240	2.9	10000	108
25/04/70	<40	1.5	<40	0.3	<40	80
18/05/79	520	1.2	1200	1.5	1400	60
21/05/79	590	1.5	5700	0.5	1000	20
06/07/79	410	0.45	1400	0.01	<40	70
24/08/79	1300	0.5	<40	5.0	10000	60
25/02/79	not sampled		930	1.4	2100	600

If the population of bacteria in the limestone fissures is resident, a source of nutrients must be available to support them, presumably either particulate or dissolved organic matter washed in from the soil above. If dissolved organic matter (DOM) is the main nutrient source (as is suggested by Atkinson 1977b) one would expect that a high DOM content would relate to high TVC, but figure 3 shows that this is not the case in G.B. Cave. Because most values for 25 April 1979 are less than forty when determined by the Spiral method, figures are used in Fig. 3 that were determined by the standard pour plate technique, which has a lower minimum detectability. This is acceptable, because the counts yielded by the Spiral method are at least as precise as those obtained by standard methods (Hedges, Shannon and Hobbs, 1978). Determination of particulate organic matter by oxidising the filtrate from large samples of percolation water was unsuccessful, and indicated that the organic content was very low even for shaft flows. Yet, Laverty (1977) found that particulate matter in cave streams contained organic material in almost all cases; he did not investigate percolation water. Material in suspension will be filtered out in tight fractures, and therefore particulate matter will be restricted to the near surface horizons and to the more open fissures. If particulate organic matter is the source of nutrients for the microbes in percolation water we would therefore expect the large avens and the highest drips to have the highest TVC. Yet, when these inlets (ENB, ENP, DAV, GOTO, WPAV, HAV, WPOV) are grouped and tested against all other drips, no significant difference exists between the two populations (Probability 0.5). Therefore, we must conclude that the bacterial counts merely reflect random fluctuations in the numbers of bacteria washed out from the soil. This indicates that there is a ready movement of bacteria from the surface to depth in the unsaturated zone, which is unrelated to the probable size of the fissures feeding the various drips. We therefore accept that, in contrast to the diffuse flow component of the saturated zone of the aquifer discussed below, the unsaturated zone of a limestone aquifer is not able to filter water adequately, a fact also recognised by Allen and Morrison (1973) and Sinton (1980).

Percolation water was also investigated for chemotrophic bacteria. The combined test for *Nitrosomonas* spp. and *Nitrobacter* spp. showed that no nitrifying bacteria were present in the samples. Harrigan and McCance (1966, p.101) described colonies of *Azotobacter* spp. as "raised, convex, smooth, white, semi-opaque, moist and viscous, 4-8 mm diameter" and such colonies were not present on the mannitol agar cultures. However, strains of *A. insignis* and *A. macrocytogenes*, grown on the same medium, developed small translucent colonies, which may have been present on the test cultures but were not recorded. The test for *Clostridium* spp. was negative for all samples apart from WPAV which contained 1 colony per ml.

We must conclude that percolation water in G.B. Cave does not contain chemotrophic bacteria, an observation that is supported by the results of Barr and Kuehne (1971). They failed to isolate nitrifying bacteria from mud in a drip pool and from soil beneath a large stalactite in the Mammoth cave system, Kentucky, USA, whilst the microbe is found in abundance in stream sediments throughout this cave (Fliermans and Schmidt, 1977). Whitelaw and Rees (1980) found that the vadose zone of the chalk aquifer in England contained large numbers of chemotrophic bacteria. They suggested that the microbes were resident on the fissure walls, a possibility that we did not investigate in G.B. Cave.

Although we found that percolation water has a microflora that is not directly controlled by discharge fluctuations, Barr and Kuehne (1971), p.90) claimed that water samples from underground rivers: "revealed maximum 14000 to 35000 per ml, counts during flood stage...." They also maintained that the productivity of bottom silts in a percolation-water-fed pool is about one tenth of that of the floor of the underground river, perhaps related to the availability of a suitable organic substrate. This suggests that swallet water will generally have higher bacterial counts than percolation water, an assumption that we investigated in the Mendip Hills. Table 6 shows TVC after 24 hours at 37°C for four major swallets on Mendip analysed by Bristol Waterworks on 11 November 1980. Comparative data are also given in Table 5 for percolation and swallet water in G.B. Cave on six different dates. The TVC for the swallet is generally higher than that for percolation water. Thus a high swallet component in the recharge to a spring should result in higher bacterial numbers than when percolation water is dominant. All swallet water from the Mendip Hills, and much of the saturated zone, is drained by conduit flow. The success of particulate tracers such as *Lycopodium* spores has indicated that conduits have turbulent flow and a very low

Table 5 Average and range (in brackets) of Total Viable Counts (ml^{-1}) after 24 hours at 37°C for percolation and swallet water in G.B. Cave

Date	Percolation Water	Swallet Water
11/4/79	130+ (<40 - 780)	-
25/4/79	<40 (-)	<40
16/5/79	990+ (<40 - 7800)	1200
22/5/79	52+ (<40 - 150)	150
6/7/79	88+ (<40 - 440)	<40
24/8/79	290+ (<40 - 1300)	1400
Average	270+	560+

Note: + indicates values <40 included in average as 40

Table 6 Total Viable Counts (ml^{-1}) after 24 hours at 37°C for swallet streams sampled November 1980. Data from Bristol Waterworks Ltd.

Blackmoor Swallet	360
Longwood Swallet	500
Tynings Swallet	660
Manor Farm Swallet+	2000

+ sampled above farm

filtering capacity (Atkinson 1977a). Therefore high inputs of bacteria into a conduit will result in high TVC at the springs. Following these arguments TVC might be an additional indicator of the ratio of swallet water to percolation water. We checked this for springs in the Mendip Hills that are sampled and analyzed on a fortnightly basis by Bristol Waterworks. Average counts for selected springs are given in Table 7. Because the swallet component of most of the springs will be much lower in summer than in winter two additional figures are given, one for the June/July (dry) and one for November/December (wet). These figures are averages, calculated from TVC given for the years stated in column 4 of Table 7.

Table 7 Average Total Viable Counts (ml^{-1}) after 24 hours at 37°C for Mendip Sources. Data from Bristol Waterworks Ltd. Figures in brackets are for years 1974, 1975 and 1976 only.

Source	Annual Mean	June/July Mean	November/December Mean	Years of Record
Springs				
St. Dunstans Well	500	1256(1940)	545(370)	69,71,74,75,76
Rickford	250	250	250	79
Cheddar	151	109(107)	180(122)	68 to 78
Rodney Stoke	20	20	20	74,75,76
Gurney Slade	30	8	24	74,75,76
Banwell	21	18(27)	45(23)	74,75,76,78,79
Cross	30	43(47)	16(19)	74,75,76,78
Sherbourne	24	4(4)	18(8)	74,75,76,78
Boreholes				
Egford	19	12(18)	26(10)	74,75,76,79
Oldford	9	3(3)	1(1)	74,75,76,79
Chelvey Batch	3	2	2	74,75,76
Wells Athletic Ground	5	1	2	
Callow Rocks Quarry	-	-		80

St. Dunstans Well (ST659479) is known to be fed by a large proportion of swallet water mainly through the large Stoke Lane Slocker stream (ST669474); Smith(1975) quoted a swallet water proportion of 26%. Both Cheddar spring (ST466539) and Rickford (ST485594) have several known sizeable swallets but are thought to be primarily fed by percolation water. Rodney Stoke (ST487503), Gurney Slade (ST631495) and Banwell (ST399592) have only minor swallet inputs, while Sherbourne (ST586550) and Cross Springs (ST416547) have no known swallets at all. Oldford (ST786506), Egford (ST756481), Chelvey Batch (ST474679), Wells Athletic Ground (ST786506) and Callow Rocks Quarry (ST450551) are boreholes into the Carboniferous Limestone for which the swallet component is unknown but probably very small (ST450551). In general the bacterial counts follow the expected pattern with greater TVC values with increasing amounts of swallet recharge. The winter counts are also higher than the summer values, again indicating increased swallet components. The converse of this pattern for St. Dunstans Well may be due to groundwater pumped into the swallet from Moons Hill Quarry in the winter months, while the high summer count for Cross Springs can be attributed to one exceptionally high count in June 1975.

The low counts for the boreholes are of particlar interest, because they draw water from the deep saturated aquifer and are presumably fed to a large extent, if not totally, by diffuse flow, although several are sited at historic spring locations. The reason for the low counts might be that the deep aquifer is a hostile environment for microbes, but this is in contradiction to Altovskii's (1961) and McNabb and Dunlop's (1975) observations. Therefore we suggest that the diffuse saturated groundwater flow in limestones has significant filtration capacity due to a combination of laminar flow and tight fractures. Unfortunately no other absolute indicators are established to differentiate between the diffuse and conduit component of limestone springs, and it is thus not possible to further test this suggestion. Recently, research has indicated that concentrations of Radon in spring water may give an answer to this problem, but the results are not yet conclusive.

We therefore propose that in the Carboniferous Limestone aquifer of the Mendip Hills three water types may be distinguished using the TVC figures. Firstly, swallet recharge which flows in the aquifer in conduits has a high TVC (>500 ml^{-1}). Secondly, percolation recharge which is integrated into solutionally enlarged fissures and conduits has an intermediate TVC (50 to 300 ml^{-1}). Finally, diffuse flow waters in the saturated aquifer in tight fractures have a low TVC (<50 ml^{-1}). This diffuse flow water can be derived from two sources, either vertical percolation from the unsaturated zone, or lateral recharge of conduit waters caused by head differences between the conduit and fractures adjacent to it (Atkinson et al, 1973). There is a considerable overlap in the TVC values between the three categories.

Unfortunately it is difficult to distinguish between the three classes in the data so far discussed, e.g. Table 7. However, during the lowest summer flows, swallet contributions are often negligible compared to the spring discharge. The spring TVC may therefore indicate the ratio between percolation/conduit and diffuse flow waters. Fig. 4 presents TVC and discharge data for Cheddar Resurgence for 1977/78. Long recessions during July and August, and October gave low TVC of about 50 ml^{-1}. In contrast significant summer recharge in late August increased TVC to a maximum of 760 ml^{-1}, and was undoubtedly associated with both increased swallet recharge and percolation into conduits.

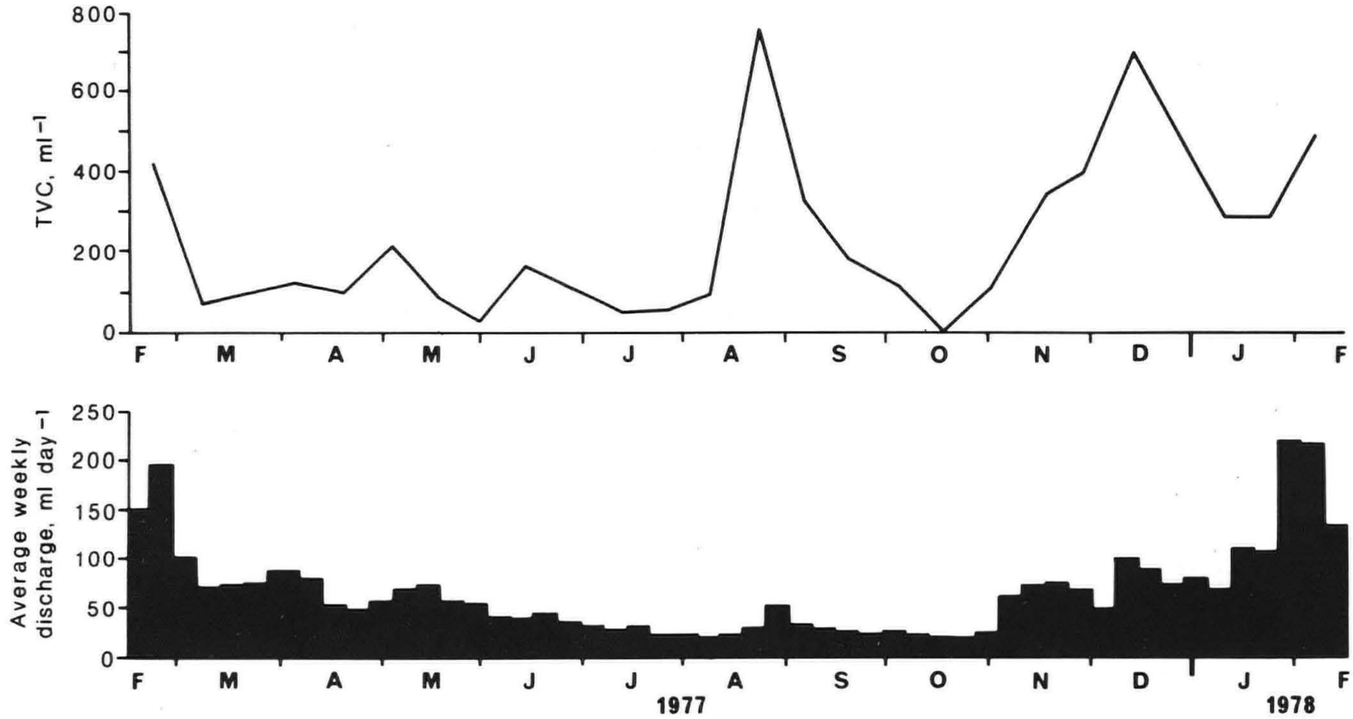

Fig.4 Total viable counts after 24hours at 37°C and discharge for Cheddar Resurgence 1977/78 (data from Bristol Waterworks)

If the TVC of diffuse flow is 2 ml^{-1} (from borehole data) and the percolation/ conduit TVC average is 88 ml^{-1} (GB data 6 July 1979 under dry conditions) then the spring TVC of 50 ml^{-1} indicates a diffuse flow proportion of about 55%. The probable error in this figure is large, and a more detailed sampling and analysis scheme would be required before much confidence could be attached to the results. However, the calculation does suggest that further work on bacterial populations in karst groundwaters would significantly contribute to our understanding of the flow dynamics and storage of karst aquifers.

CONCLUSION

The unsaturated zone of the limestone aquifer allows unhindered movement of bacteria from the soil to depth whether the flow is of conduit (shafts) or diffuse (seeps) type. Concentrated saturated drainage (conduit flow) does not have the ability to filter this microbial input. Diffuse saturated flow, however, has a significant filtration capacity, and yields water with low TVC. Further work on bacterial populations in karst areas may therefore permit separation of conduit and diffuse flow components to spring flow. Although TVC per se are not a criterion for water quality (Allen and Geldreich, 1975; the preference for low counts in domestic water supplies is recognized internationally (Allen and Geldreich 1975; Bonde 1978; Robeck 1969). In view of these recommendations the results for the Mendip Hills are important and stress once more the vulnerability of conduit-fed karst springs to microbial pollution.

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THE INFLUENCE OF SOME MATERIAL PROPERTIES ON THE DEVELOPMENT OF TROPICAL KARST TERRAIN

by Michael J. Day

Abstract

The role of material properties in the development of tropical karst terrain deserves greater attention. Previously developed morphometric indices make it possible to compare areas of terrain and hence to begin to examine lithological controls upon morphology. Three properties, purity, petrographic character, and hardness, were analysed in each of 13 areas of tropical karst terrain in the Caribbean and Central America. Most of the limestones are very pure. Petrographically, biomicrites and micrites dominate. The limestones present a wide range of hardnesses. A negative correlation exists between purity and hardness. Limestone purity is reflected in different terrain types and there is a correlation between terrain type and hardness of the limestone. These initial investigations deserve further continuation.

Tropical karst terrain is characterised by great variety but there have been very few attempts to examine this with respect to differences in material properties of the limestones upon which the landforms are developed.

In large part, investigation of the influence of bedrock nature upon karst terrain morphology has been hindered by the absence of a coherent classification of landform and terrain types. Development of morphometric indices both of individual landforms and assemblages (Day, 1977, 1978, 1979, 1981) has made it possible to compare different areas of terrain realistically; this in turn makes it possible to begin to examine lithological controls upon morphology.

Tropical karst terrain is of basically three types:

- Type I Terrain characterised by enclosed depressions of all types and subdued hills.
- Type II Terrain in which enclosed depressions and residual hills attain approximately equal prominence.
- Type III Terrain characterised by isolated residual hills separated by extensive near-planar surfaces.

There is a gradual transition between the three types and, in any one given area, more than one type may coexist. Type I terrain constitutes "doline karst". Types II and III are generally referred to as "kegelkarst", type II equating with "cone/cock pit karst" and type III with "tower karst". On the basis of the ratio of their vertical component (C_v) compared with their horizontal component (C_h) twelve types of landform unit can be recognised within these three categories. If it is a combination of these individual units, terrain can be classified in terms of the classes of the positive and negative components (Figs. 1 & 2). The 36 possible unit associations mesh with the tripartite terrain classification (Fig. 3). Where the category of positive and negative components diverges by two or more units the one having the higher value is dominant both in terms of visual appearance and contribution to the overall terrain nature, where values differ by less than two units both components are of similar importance. Although elementary and possessing limitations (Day, 1978) this scheme provides an index of terrain type upon which comparisons may be based.

A variety of lithological properties, especially purity, porosity and permeability, have been suggested to be influential in promoting the development of different tropical karst types. Sweeting (1958) and Urquhart (1958) noted that in Jamaica "cockpit karst" is developed on pure, hard and fissile limestones while "doline karst" is present on those which are marly or impure. Monroe (1964, 1968) pointed to the restriction of specific karst types in northern Puerto Rico to distinct limestone units and suggested that purity is an important factor. Jennings and Bik (1962) indicated, however, that there was no clear association between limestone purity and terrain type in New Guinea.

This paper is dedicated to the memory of George Sweeting.

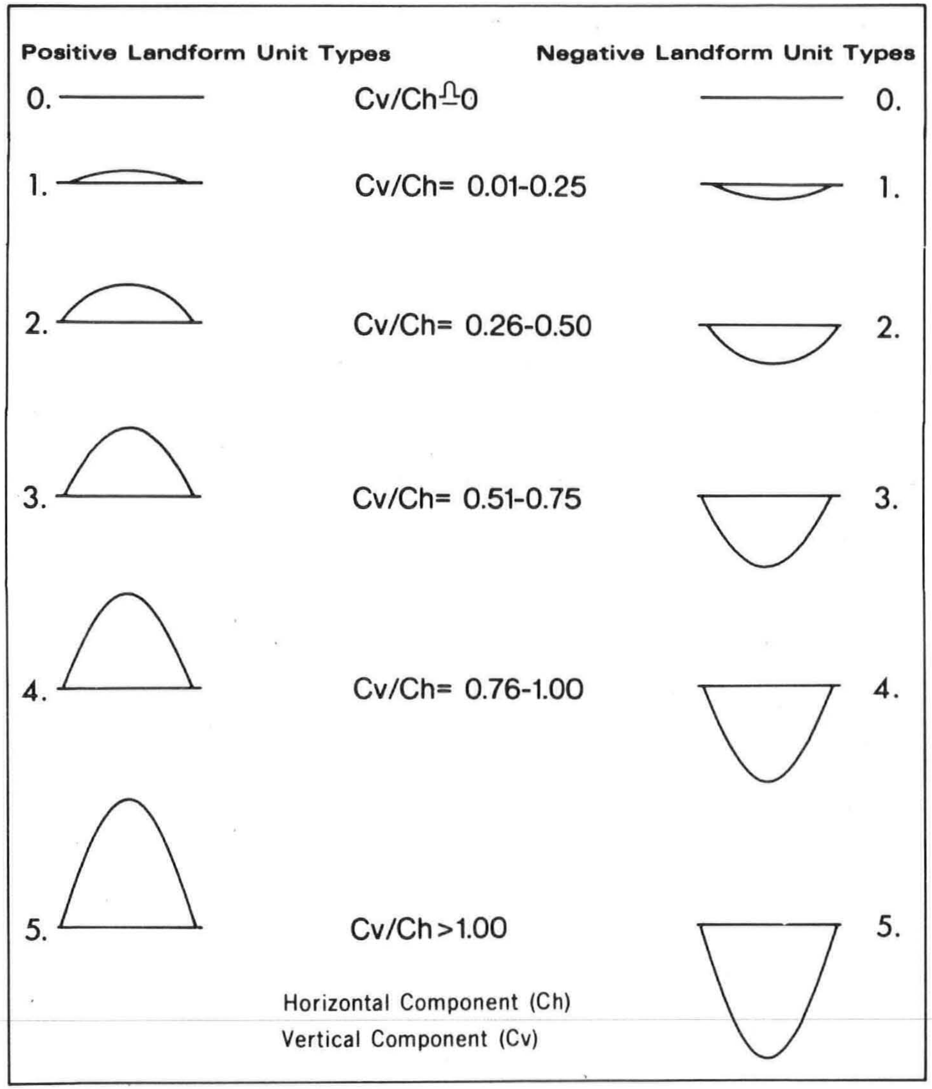

Figure 1. Morphological delimitation of individual positive and negative landform units.

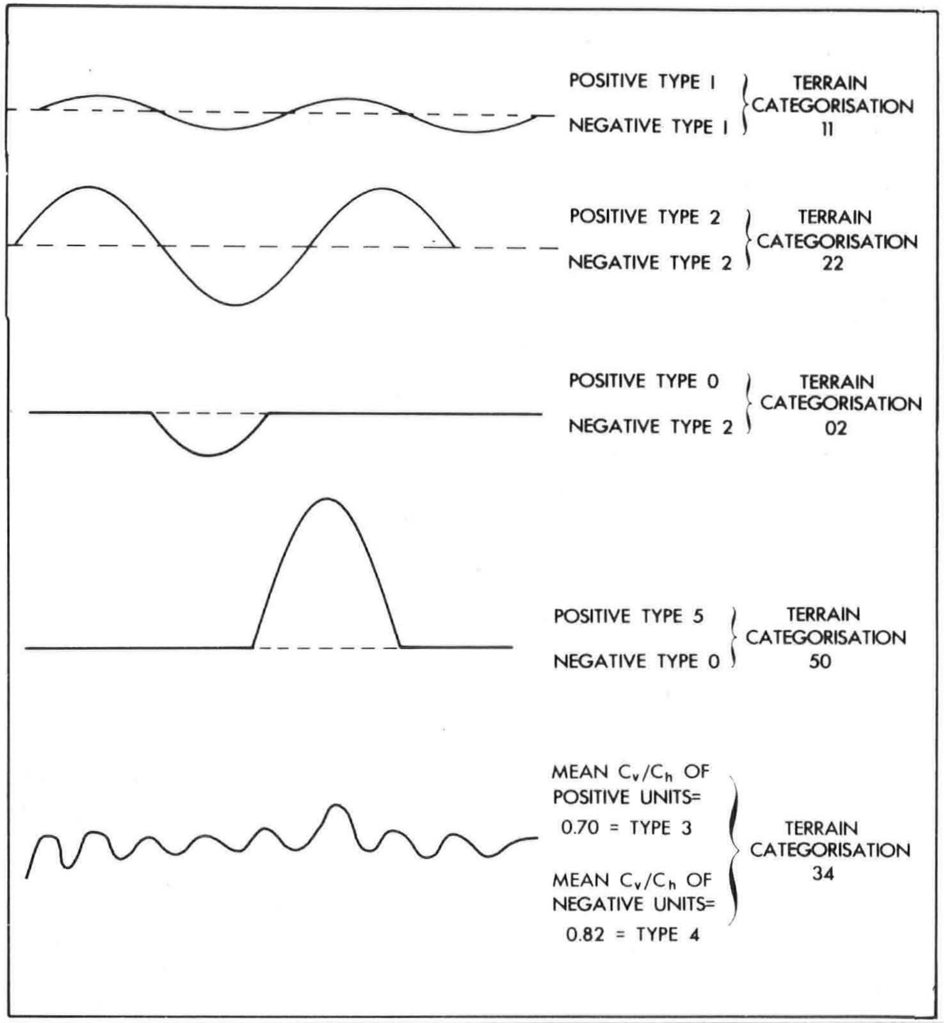

Figure 2. Application of landform unit classification in some theoretical tropical karst terrains.

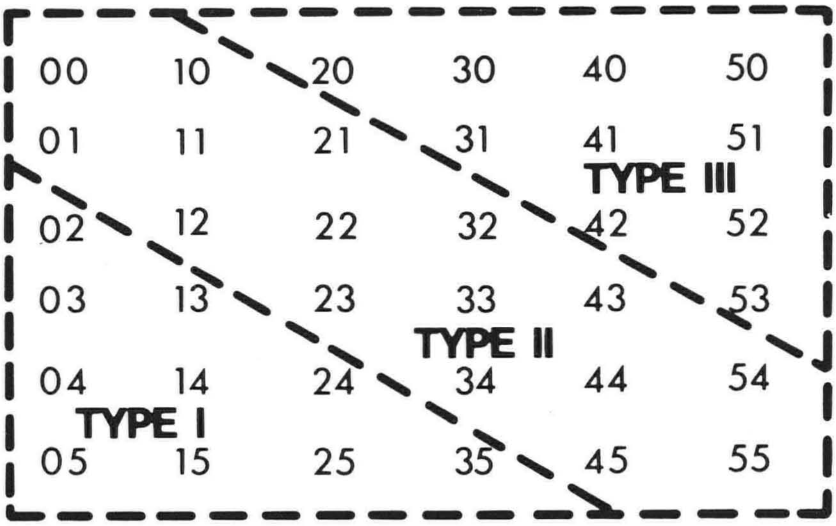

Figure 3. Terrain types on the basis of landform unit association.

Verstappen (1964) concluded tentatively from observations in New Guinea that water absorption capacity and porosity are important factors and that kegelkarst is developed especially on limestones with a high porosity. Low porosity was suggested also by Wilford and Wall (1965) to account for the lack of kegelkarst in Sarawak.

The petrographic nature of limestones is one variable which can be expected to influence landform development, particularly since it is closely associated with other variables such as purity, porosity, water absorption capacity and mechanical strength. Textural differences are influential in the development of landforms on a single limestone formation (Sweeting and Sweeting, 1969); Sweeting (1973, p.326) suggested that "Both grain size and porosity may be more important on the macro-scale."

In Folk's (1959, 1962) system of classification emphasis is placed upon determination of texture, sparry calcite content and porosity, aspects of the composition which are likely to influence and be reflected in the morphology of landforms. Texture is one principal factor indicating susceptibility to corrosion because it is a reflection of the internal construction of the rock, particularly with regard to spacing of the constituents and available interstices between these. Water absorption, retention and transportation capacity of a rock depend largely upon porosity,in terms both of pore size and connectivity. Limestones of differing texture exhibit distinctly varied porosities. Micrites have a low porosity, generally 5% or less, owing to the dense, compact nature of the microcrystalline paste or cement. Sparites possess porosities generally between 5 and 10%; large juxtaposed sparry calcite plates and/or mosaics restrict the available pore space. Biomicrites and biosparites have porosities up to 25% where the granular and fragmental nature of the groundmass and allochems permits maximum interstitial development.

Ignoring the affects of lithologic factors such as fissuring, jointing and stylolite development, increasing porosity results in increasing susceptibility to corrosion because the carbonate is in contact with more water (Schoeller, 1950; Sweeting, 1972).

Dolomitisation involves recrystallisation, which reduces porosity by the infilling of interstices. According to Powers (1962), dolomitisation of up to 80% of the limestone results in decreasing porosity; this increases in the 80% to 90% dolomite range and again decreases as dolomite exceeds 90%. Within dolomites the importance of voids, either primary or secondary, was demonstrated by Jennings and Sweeting (1963) and by Newell et al (1953).

The presence of quartz as an associated (parent) mineral has been correlated with resistance to corrosion (Schwarzacher, 1958). Conversely, the presence of accessory minerals, particularly pyrite, has been indicated to lead to increased corrosion of the limestones; the sulphide is converted to the more soluble sulphate (gypsum) by oxidation and the sulphuric acid which is produced in this reaction itself promotes corrosion of the limestone (Schwarzacher, 1958; White, 1960).

Apart from the chemical implications of limestone texture and content, these also affect the mechanical properties of the rock. For example, the mechanical strength of rocks is closely related to their porosity and consolidation (Jennings, 1971; Day, 1978).

The mechanical properties of limestones are as important in controlling landform development as are the chemical contents, despite the fact that the denudation of limestone terrains is accomplished essentially by chemical corrosion. Although process variables may be affected by the chemical and petrologic nature of the rock they are no less influenced by mechanical factors and ultimately these are probably more important in determining whether for example, steep slopes are developed and maintained in a limestone terrain. In the Yucatan for example, the alternation of coherent lithified beds and weaker, unlithified beds may account for cenote formation (Sweeting, 1973). One important aspect of rock mechanics is the strength of the material in terms of resistance to stresses imposed by erosive agents. Surface strengths, both compressive and shear, are obviously of critical importance in this context.

PROCEDURE

During the course of an extensive investigation of karst terrain morphology in the Caribbean and Central America (Day, 1978) the relationships between landform morphology and three properties, purity, petrographic character, and mechanical strength, were investigated. In areas where terrain morphology was quantified rock samples were collected for laboratory analysis and experimentation. Thin sections were prepared for petrographic analysis and chemical purity of the limestones was established by determination of their acid insoluble residue content (for details see Day, 1978). In the field in situ measurements of compressive strength were made using a Schmidt Test Hammer (Day and Goudie, 1977; Day, 1980).

RESULTS

Table I summarises the results of the insoluble residue determinations undertaken. In view of the small number of samples analysed, caution is necessary in any interpretation of these results but certain general conclusions can be drawn.

<u>Table 1</u> Summary of insoluble residue contents of Caribbean and Central American limestones

Location	Lithology	Insoluble residue content (% by weight) $\bar{x}$	s	N
Mexico (Yucatan)	Carrillo Puerto	1.98	0.037	7
" "	Pisté	3.10	0.100	5
" "	Petèn	2.61	0.285	2
Guatemala (Peten)	Petèn	4.11	0.109	6
" "	Petèn(dolomitic)	3.87	0.099	3
Belize	Dolomitic facies	4.54	0.393	5
"	Biomicrites	2.11	0.094	3
"	Micrites	1.78	0.097	4
Jamaica	Claremont *	0.13	0.010	5
"	Swanswick	0.09	0.012	10
"	Somerset *	0.08	0.012	5
"	Browns Town *	0.12	0.035	25
"	Walderston	0.16	0.014	5
"	Montpelier *	0.23	0.020	10
Puerto Rico	Lares	1.27	0.056	6
" "	Aguada	12.75	4.372	4
" "	Aymamón	1.25	0.084	5
" "	Cibao	8.59	0.301	3
" "	Ponce	1.17	0.008	4
Antigua	Antigua Formation	18.07	10.654	10
Guadeloupe	Biomicrites	2.11	0.244	5
Barbados	Pliocene facies	1.84	0.265	8
	Pleistocene facies	0.99	0.054	3

All determinations except those marked * carried out using 5N Hydrochloric acid; those marked * carried out using 1N Acetic acid (see Day, 1978).

With the exception of the Puerto Rican Aguada limestone and the Antigua Formation limestone, the facies sampled are very pure, containing less than 10% acid insoluble residue. Outstanding are the various members of the Jamaican White Limestone Formation, the least pure of which, the Montpelier limestone, contains only 0.23% insoluble residue and the purest of which, the Somerset limestone, contains only 0.08% insoluble residue. All other facies, with the exception of recent Pleistocene reef limestone in Barbados, contain insoluble residues amounting to more than 1%. Within the context of carbonate rock analyses (Sweeting, 1972, Table 1 (a), p.11) these results are not remarkable. The highest insoluble residues determined, 12.75% in the Puerto Rican Aguada limestone and 18.07% in the Antigua Formation limestone, appear exceptional. Although the residues were not analysed with respect to their chemical or lithologic content, it is apparent from inspection that in the Aguada limestone the residue is mainly quartz and in the Antigua Formation limestone the residue is mainly clay.

Table 2 summarises the results of the petrographic analyses with respect to location and geological formation. The full analyses of individual sections are presented elsewhere (Day, 1978). Only seven of the limestone sections examined are sparry; by contrast 44 are either biomicrites or micrites. This is not surprising in that "...since limestones are particularly susceptible to alteration, older limestones tend to be more crystalline and sparry." (Sweeting, 1972, p.19). The limestones examined are all Cretaceous or younger, most are Tertiary. The youth of these rocks may also be the most important factor in explaining the relative absence of recrystallisation.

Texturally the rocks are variable although there is a dominance of fine to medium-grained examples. This textural tendency is also reflected in the estimated porosities.

In terms of mineral contents 47 (83%) of the sections are of limestones composed entirely of calcite and ten (18%) are of dolomitic limestones. Quartz is present, both in prismatic and granular forms, in 36 (63%) of the sections. The only accessory mineral detected is pyrite and the only other mineral recorded is limonite, which occurs in the form of cloudy brown patches in 13 sections.

Table 3 presents a summary of the results obtained from in situ Schmidt Hammer testing of unweathered limestones. Limestones are highly variable in terms of their compressive strength (Carson and Kirkby, 1972, p.88; Sweeting, 1972, p.11) and the Caribbean and Central American examples are not unusual, presenting a representative limestone sample ranging from very soft to very strong materials. The softest (non-weathered) limestones recorded are the poorly lithified Pleistocene limestones in Barbados (<10) and Yucatan (<10) and the poorly lithified beds in the other Yucatan limestones (15.0 and 19.1). Among the lithified older limestones the softest is the Aymamón limestone of Puerto Rico (12.5). The hardest limestone recorded in the study is the dolomitic Petén limestone of the Yucatan and Guatemala (39.9).

CORRELATIONS BETWEEN THESE FACTORS AND THEIR REFLECTION IN TERRAIN TYPES

Mechanical strength might be expected to vary with differences in chemical composition and petrographic nature of the limestones as these relate to density, coherence and porosity. Table 4 presents data on insoluble residue contents and hardnesses; Table 5 presents a comparison of hardnesses and results of the petrographic analyses.

There is, at the 0.05 significance level, a negative correlation $r_s = -0.50$, between limestone purity, as expressed by the insoluble residue content, and the hardness. In other words, the hardest limestones are those with the highest percentage of non-carbonate material. This result is rather unexpected in that the inclusion of non-carbonate material might be expected to indicate a less homogeneous rock in which differential compaction is present. The primary mineral, apart from calcite and dolomite, present in the limestone is quartz, which is much harder than calcite. Similarly, from the petrographic evidence it appears that those rocks containing significant amounts of quartz are no less compact and coherent than the purer examples. This result suggests that the hardness of the limestones is more dependent on internal structure than upon the mineralogical content. This finding indirectly substantiates the value of the petrographic classification utilised here in that it is the texture of the rock which is a critical factor in determining its strength.

A comparison of the petrographic determinations with the results of the in situ Schmidt Hammer testing (Tables 5 and 6) indicates several important points. The most striking of these is the fact that the three lithologies

Table 2 Summary of limestone petrographic analyses

Area	Lithology	Dominant specification	Texture	Associated (parent) minerals	Recrystallization	% sparry calcite	Estimated porosity in %	Mean R value	Number of sections examined
Yucatan (Mexico)	Carrillo Puerto	Siliceous* biomicrite	Fine-medium	Calcite/ quartz/ limonite	----	30-40	10-15	35.9	5
"	Pisté	Biomicrite	Fine	Calcite/ quartz/ limonite	----	30-40	10-15	35.7	2
"	Petèn	Biomicrite	Medium	Calcite/ quartz/ limonite	----	20-30	10-15	37.7	2
Guatemala	Petèn	Biomicrite	Medium	Calcite/ quartz	----	20-30	10-15	37.9	2
"	Dolomitic facies	Dolomitic biomicrite	Medium	Dolomite/ calcite	----	<10	<10	39.9	3
Belize	A	Dolomitic limestone	Medium-coarse	Dolomite/ calcite	++++	<10	<10	39.8	3
"	B	Biomicrite	Medium	Calcite/ quartz	----	30-40	10-15	38.2	3
"	C	Micrite	Fine	Calcite	----	<10	<5	38.2	2
Jamaica	Montpelier	Fossiliferous Micrite	Fine	Calcite (with accessory pyrite)	----	<10 10	<5 5	32.6 32.6	2 2
"	Troy	Dolomitic limestone*	Medium	Dolomite/ calcite	++++	10 20	<10	42.3(s)	2
"	Browns Town	Biomicrite	Fine-medium	Calcite/ quartz	----	30-40	10-15	32.1	3
"	Walderston	Biomicrite (?)	Fine-medium	Calcite/ quartz	----	20-30	10-15	29.7	2
"	Swanswick	Biosparite *	Fine-medium	Calcite/ quartz	----	30-40	10-15	36.3	2
"	Somerset	Biosparite	Medium	Calcite/ quartz	----	40-50	<10	33.1	2
"	Bonnygate	Foraminiferal Micrite	Fine	Calcite/ quartz	----	<10	<10	30.4	2
Puerto Rico	Lares	Biomicrite	Medium-coarse	Calcite/ quartz	---	30-40	10-15	35.2	3
" "	Aguada	Biomicrite	Medium	Calcite/ quartz	---	30-40	10-15	34.5	2
" "	Surface crust	Sparite*	Fine	Calcite/ quartz	+++	70-80	<10	47.5	2
" "	Aymamón	Biomicrite	Medium	Calcite/ quartz	---	30-40	10-15	12.5	2
" "	Ponce	Sparite	Fine	Calcite/ quartz	---	50-60	<10	35.2	2
Antigua	Antigua Formation	Biomicrite	Fine-Medium	Calcite/ quartz	---	30-40	10-15	33.3	3
Guadeloupe	Miocene limestone	Biomicrite	Fine-medium	Calcite/ quartz	----	30-40	10-15	33.4	2
Barbados	Pliocene limestone	Biomicrite	Medium	Calcite	----	20-30	15-20	29.8	2
	Pleistocene limestone	Biomicrite	Coarse	Calcite	----	<10	50	<10.0	2

*Indicates significant variations from this specification.

Table 3 Summary of Schmidt Hammer hardness values for unweathered limestones, Central America and the Caribbean

Location	Lithology	R value $\bar{x}$	R value s	Number of impacts
Mexico (Yucatan)	Carrillo Puerto	35.9	2.97	40
"	Poorly lithified beds in above	19.1	0.77	20
"	Pisté	35.7	3.05	20
"	Poorly lithified beds in above	15.0	1.00	10
"	Pleistocene limestone	26.5	0.81	10
"	Poorly lithified beds in above	<10.0	0.00	10
"	Dolomitic Petèn limestone	40.1	2.11	50
Guatemala (Peten)	Petèn limestone	37.9	1.90	30
	Dolomitic Petèn limestone	39.7	1.25	35
Belize	Dolomitic limestone	39.8	2.87	30
	Biomicrites	38.2	2.51	40
	Micrites	38.2	2.51	40
Jamaica	Montpelier	32.6	2.21	40
"	Browns Town	32.1	2.32	80
"	Walderston	29.7	2.50	30
"	Swanswick	36.3	1.25	200
"	Bonnygate	30.4	2.01	30
"	Somerset	33.1	3.22	20
Puerto Rico	Lares	35.2	1.02	40
" "	Aguada	34.5	0.91	140
" "	Aymamón	12.5	3.78	110
" "	Lower Ponce	35.2	2.11	20
Antigua	Antigua Formation	33.3	4.27	55
Guadeloupe (Grande Terre)	Miocene limestone	33.4	2.13	40
Barbados	Pliocene limestone	29.8	2.12	35
"	Poorly lithified Pleistocene limestone	<10.0	0.00	15

which exhibit the highest Schmidt Hammer hardness values, the Petèn dolomitic facies, the Belize dolomite facies and the Troy limestone of Jamaica, are all dolomitic. Only in the case of Troy limestone was extensive recrystallisation detected in the thin section yet recrystallisation has probably occurred in all three cases, destroying the original limestone texture and leading to increased cementation strength. All three rocks exhibit fairly low porosities suggesting, within the context of Powers' (1962) results, that the extent of dolomitisation is considerably less than 75%.

Hardnesses for the other textural groups are similar although the predominance of biomicrites over other groups makes it difficult to assess the constancy of any distinction. Biomicrites and biosparites have similar hardnesses yet micrites, whose low porosity might be expected to result in higher values, are rather lower than the other groups. The two biosparites have R values very similar to those of the biomicrites, 34.7 as opposed to 34.2. Sparites are

Table 4 Insoluble residue contents and compressive strengths of Caribbean and Central American limestones.

Location	Lithology	Mean insoluble residue (% by weight)	Purity rank	Mean R value	Hardness rank
Mexico (Yucatan)	Carrillo Puerto	1.98	12	35.9	8
	Pisté	3.10	16	35.7	9
	Petèn	2.61	15	40.1	1
Guatemala (Petèn)	Petèn	4.11	18	37.9	6
	Dolomitic Petèn limestone	3.87	17	39.7	3
Belize	Dolomitic limestone	4.54	19	39.8	2
	Biomicrites	2.11	13.5	38.2	4.5
	Micrites	1.78	10	38.2	4.5
Jamaica	Montpelier	0.23	5	32.6	16
	Browns Town	0.12	3	32.1	17
	Walderston	0.16	4	29.7	19
	Swanswick	0.09	2	36.3	7
	Somerset	0.08	1	33.1	15
Puerto Rico	Lares	1.27	9	35.2	10.5
	Aguada	12.75	20	34.5	12
	Aymamón	1.25	8	12.5	20
	Lower Ponce	1.17	7	35.2	10.5
Antigua	Antigua Formation	18.07	21	33.3	14
Guadeloupe	Biomicrites	2.11	13.5	33.4	13
Barbados	Pliocene limestone	1.84	11	29.8	18
	Pleistocene "	0.99	6	<10.0	21

Table 5 Mean Schmidt Hammer hardness values for different textural classes.

Textural class	Mean R value	Number of lithologies in class
Dolomitic limestones	40.7	3
Sparites	35.2	1
Biosparites	34.7	2
Biomicrites	34.2	11 (excluding Puerto Rican Aymamón limestone)
Micrites	33.7	3

slightly higher, 35.2, and micrites slightly lower, 33.7 than these (Table 5).

Table 6 indicates the insoluble residue, petrographic nature and mean R value for each of 13 areas of terrain classified according to the system outlined previously. No immediately obvious systematic relationship exists between the terrain type and the three variables which were selected for examination. However, whilst there is no distinct connection between terrain type and petrographic character, all terrain types occurring predominantly on biomicrites, the other two variables demonstrate rather more distinct associations. Type II terrain is, except in the case of Aguada limestone of Puerto Rico, developed on relatively pure limestones (mean insoluble residue 3.23%) whereas Type I and Type III terrain occur on limestones of lesser purity (mean insoluble residues 5.51% and 6.93%, respectively). Apart from this very generalised association, there is very little definite relationship. Type I terrain in Jamaica,

Table 6 Insoluble residue, petrographic determination and mean R value of limestones forming different terrain types.

Terrain type	Location	Lithology	Mean insoluble residue (%)	Petrographic specification	Mean R value
I	Jamaica	Browns Town-Walderston	0.14	Biomicrite	30.9
	Barbados	Pliocene limestone	1.84	Biomicrite	29.8
	Antigua	Antigua Formation	18.07	Biomicrite	33.3
	Yucatan	Carrillo Puerto	1.98	Siliceous biomicrite	35.9
II	Guatemala	Petèn limestone	4.11	Biomicrite	37.9
	Belize	Cretaceous limestone	2.11	Biomicrite	38.2
	Jamaica	Browns Town-Walderston	0.14	Biomicrite	30.9
		Swanswick	0.09	Biosparite	36.3
	Puerto Rico	Lares	1.27	Biomicrite	35.2
		Aguada	12.75	Biomicrite	34.5
	Guadeloupe	Miocene limestone	2.11	Biomicrite	33.4
III	Belize	Cretaceous limestone	4.54	Dolomitic limestone	39.8
	Guatemala	Dolomitic Petèn limestone	3.87	Dolomitic limestone	39.7
	Puerto Rico	Aymamón	1.25	Biomicrite	12.5
	Antigua	Antigua Formation	18.07	Biomicrite	33.3

Barbados and the Yucatan, for example, is developed on relatively pure limestones, as is Type III terrain developed on the Aymamón limestone in Puerto Rico. There is no significant variation between the insoluble residue contents of limestones from the three terrain types, as determined by the Kruskal-Wallis H test (Kruskal and Wallis, 1952).

The most striking correlation is between terrain type and the hardness of the rock types as demonstrated by the Schmidt Hammer. Type I terrain is developed on limestones having a mean R value of 32.5, Type II on limestones with a mean R value of 35.2 and Type III on limestones with a mean R value (ignoring the Aymamón of Puerto Rico) of 37.6. Application on the Kruskal-Wallis H test demonstrates that there is, at the 0.05 level, a significant difference between the R values obtained in the three terrain types; limestones on which type III terrain is developed demonstrate the greatest hardness and those on which Type I terrain is developed exhibit the lowest R values. This result ignores the Puerto Rican Aymamón limestone where type III terrain is developed on a limestone which demonstrates extremely well developed surface hardening and hence higher effective surface R values (Day, 1978; Ireland, 1979).

Although these three variables, purity, texture and hardness, have all been alluded to as important controls on the development of tropical karst terrain, in this study only hardness demonstrates any correlation with terrain type, the most upstanding and spectacular forms of Type III terrain being developed on hard limestones and Type I terrain being most evident on limestones having lower R values. This result must be treated judiciously, however, as the sample size is small. Also the predominance of biomicrites makes it difficult to investigate fully the role of petrographic character. The observed correlation between insoluble residue and R values also suggests that terrain type may show a correlation with the former, as well as the latter, if a larger sample could be utilized. In summary, these initial investigations, although inconclusive in themselves, suggest that the role of lithological variation, particularly hardness, as a measure of mechanical strength, is deserving of greater attention from karst geomorphologists working in the tropics.

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TEMPERATURE CHARACTERISTICS OF SEEPAGES IN FOUR WEST MALAYSIAN CAVES

by J. Crowther

Abstract

The temperatures of groundwaters were determined regularly over a one-year period at a total of 121 seepage points in four Malaysian caves. The average temperatures of seepage waters are 2° to 3°C below mean annual surface temperatures, and the temporal variability of temperatures at individual sites varies inversely with residence time within the aquifer and directly with the amount of contact with circulatory cave air. It is shown that in a humid tropical environment, water temperature data provide a sound basis for distinguishing different types of underground seepage and for characterising the hydrological properties of the aquifer overlying a given cave.

Seepages in caves are particularly important from a geomorphological viewpoint in that they often provide the first points of access to groundwater after it has entered the aquifer. Since much of the chemical aggressiveness of soil waters is expended in the uppermost few metres of rock (Pitty, 1968; Williams, 1968), the hardness content of such seepage waters may be used as a basis for estimating limestone erosion rates. Frequently, however, groundwaters become saturated with calcium carbonate before they issue into a cave, and under these circumstances uncertainties arise as to how much secondary deposition may have occurred within the aquifer prior to emergence. This problem is most acute in humid tropical regions where high groundwater temperatures favour rapid deposition. The amount of deposition is likely to be affected by the volume and velocity of flow, by the residence time and, in particular, by the degree of contact with air within the aquifer. Whilst considerable insight into the hydrological properties of a limestone may be gained from water chemistry and discharge measurements (Cooke, 1971; Jennings, 1979; Pitty, 1966; Williams and Dowling, 1979), the amount of contact with air is less easily determined. Water temperature data may be important in this respect. Recent studies have demonstrated that water temperature variability provides an effective means of characterizing karst risings (Jacobson and Langmuir, 1974: Shuster and White, 1971). Hitherto, however, few temperature records are available for diffuse-flow seepages in caves, and the possibility of using these as a basis for distinguishing different types of underground seepage has been largely overlooked.

The temperature of a given cave seepage depends essentially upon three factors. Firstly, the initial temperature of water entering the limestone is important, especially in the upper part of the aquifer. Changes in the temperature of recharge waters have been detected in many groundwaters (Domenico and Paliauskas, 1973; Hackbarth, 1978). Secondly, groundwater temperatures are modified by contact with rock within the aquifer. Heat transfer is primarily by conduction, with the rock acting as a source or sink of heat depending on the direction of the temperature gradient. Finally, heat transfers occur where waters encounter circulatory air within the aquifer. Underground air temperatures are affected by a wide range of variables. These include air movement, external conditions, the configuration of underground passages, distance from the surface and the liberation and absorption of latent heat by condensation and evaporation (Wigley and Brown, 1976). Because of the diverse natural controls which influence the temperature of seepage waters, the effects of individual variables are difficult to isolate at a single site. However, when a large number of sites are investigated within a given cave or series of caves, broad trends in the data may suggest some overriding controls. The present study reports on measurements made at regular intervals over a one-year period at a total of 121 autogenic seepages in four caves in West Malaysia. Attention focuses specifically upon the mean temperatures and temperature variabilities of these sites.

FIELD AREA

The four caves investigated lie to the west of the Main Range of the Malay Peninsula at between 3 and 7°N (Fig. 1). The climate is of an equatorial

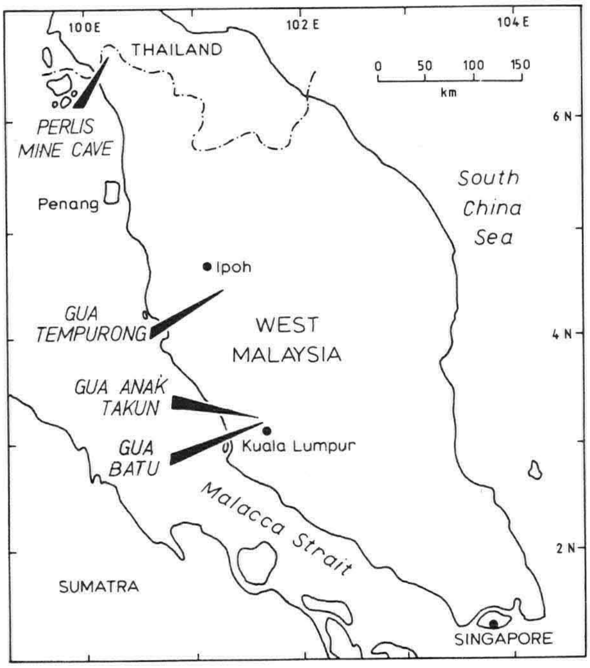

Figure 1. Location of caves investigated.

monsoon type, with rainfall in excess of 2000 mm. Temperatures are uniformly high throughout the year and exhibit little seasonality. The mean annual temperature varies from 26.3 to 26.9°C and the annual temperature range varies from 1.0 to 1.6°C (Table 1). Gua Batu, Gua Anak Takun and Gua Tempurong have developed in very pure, massive, Palaeozoic limestones which have been recrystallized by regional metamorphism (Table 2). In contrast, the Perlis Mine Cave/Subway Tunnel system occurs in relatively impure Palaeozoic limestones which havebeen less strongly affected by metamorphism and retain much of their original bedding. A general account of the geology and geomorphology of the region was presented in an earlier volume of the Transactions (Crowther, 1978a).

Table 1 Climatic data for meteorological stations in the vicinity of the four caves (*data after Dale, 1963).

	GUA BATU & GUA ANAK TAKUN	GUA TEMPURONG	PERLIS MINE CAVE/SUBWAY TUNNEL
Mean annual rainfall (mm)	2441	3260	2089
Mean annual temperature (°C)	26.3	26.5	26.9
Annual temperature range* (°C)	1.0	1.3	1.6
Annual mean diurnal temperature range* (°C)	9.9	10.4	8.8

Table 2 Geohydrological characteristics of the four caves. (*Data based on all seepages investigated by the author. The low flow rate of many of the seepages prevented reliable temperature determination, and the sites discussed in the present paper mostly have discharges in excess of 10 ml/min.)

	GUA BATU	GUA ANAK TAKUN	GUA TEMPURONG	PERLIS MINE CAVE/SUBWAY TUNNEL
Bedrock characteristics	Very pure, massive marble	Very pure, massive marble	Very pure, massive marble	Some impure beds, moderately metamorphosed
Principal flow paths	Tight joints & air-filled conduits	Tight joints	Tight joints	Joints, bedding planes and air-filled conduits

Table 2 (contd)

Approximate depth of limestone above cave (m)	60-140	30-40	200-400	20-120
Median discharge of seepages* (ml/min)	11.2	1.0	2.6	301.1

1. Gua Batu

This is a large cave system with passages totalling almost 1.5 km in length. It is located in Bt. Batu, an isolated tower karst hill. A detailed survey (Heynes-Wood and Dover, 1929) and descriptions of the cave (Crowther, 1978a; Soepadmo and Ho, 1971) have been published. Although there are no permanent streams, certain sections become flooded to depths of 30 cm or more during heavy rainfall as considerable volumes of water spill into the main caverns from air-filled conduits in the roof. The latter appear to be very old, high-level passages which are closely connected with the surface of the hill. Between storms they yield only small trickles of water. Other seepages in the cave are mostly from stalactites fed by tight bedrock joints. In many cases these waters have percolated through more than 100m of limestone before emergence.

2. Gua Anak Takun

A survey and description of this cave appeared recently (Crowther, 1981). The seepages, which are entirely from stalactites in the cave roof, are distinguished by their low discharge (Table 2). The thickness of the overlying limestone is also considerably less than in the other caves.

3. Gua Tempurong

This passes through the G. Gajah-Tempurong tower karst hill in the Kinta Valley (Crowther, 1978a and 1978b). The roof is unbreached. Most of the seepage water issues from stalactitic deposits after percolating through as much as 400 m of limestone.

4. Perlis Mine Cave/Subway Tunnel

The cave, which is unnamed on topographic maps, is actively mined for tin by Perlis Mines Ltd. It has a permanent vadose stream (mean discharge, 0.28 cumecs) and is located at the south-eastern corner of Wang Tangga, a large enclosed depression in the Setul Boundary Range. In plan the cave comprises a long and generally straight passage which is guided by major bedding planes with a dominant north-south strike. The passage is more than 1.5 km in length, but rarely exceeds 10 m in height or width. Subway Tunnel is the natural underground passage of the Sg. Pelarit, the main river draining Wang Tangga. It lies approximately 100 m downstream from the entrance of Perlis Mine Cave. In addition to seepages from stalactites, groundwater enters both passages from air-filled conduits in the roof. The latter are less flashy in their response to storms than the equivalent features in Gua Batu. On the whole, seepage points are more widely spaced in this cave system than elsewhere, and this probably explains the generally higher flow rates of the sites investigated (Table 2). The presence of bedding planes is probably a key factor in that it allows the development of integrated flow networks within the aquifer, thereby concentrating groundwater movement along certain more favoured lines of weakness. Under these circumstances, it may be anticipated that groundwaters will be transmitted rapidly and that the residence time will be correspondingly short.

METHODS AND EXPERIMENTAL DESIGN

Water temperatures were measured over a period of one year at 3-week intervals in Gua Batu, Gua Anak Takun and Gua Tempurong, and at 6-week intervals in the Perlis Mine Cave/Subway Tunnel system. Total immersion thermometers (0 to 40°C range, graduated to 0.1°C) were used, these being calibrated against each other to ensure consistent measurement. Water from the seepages was channelled by means of a polythene funnel into a narrow-bore, polypropylene cylinder to provide the required depth of water. So as to reduce the possibility of the water temperature changing during collection, the study was confined to the more active seepages, typically with discharges over 10 ml/min.

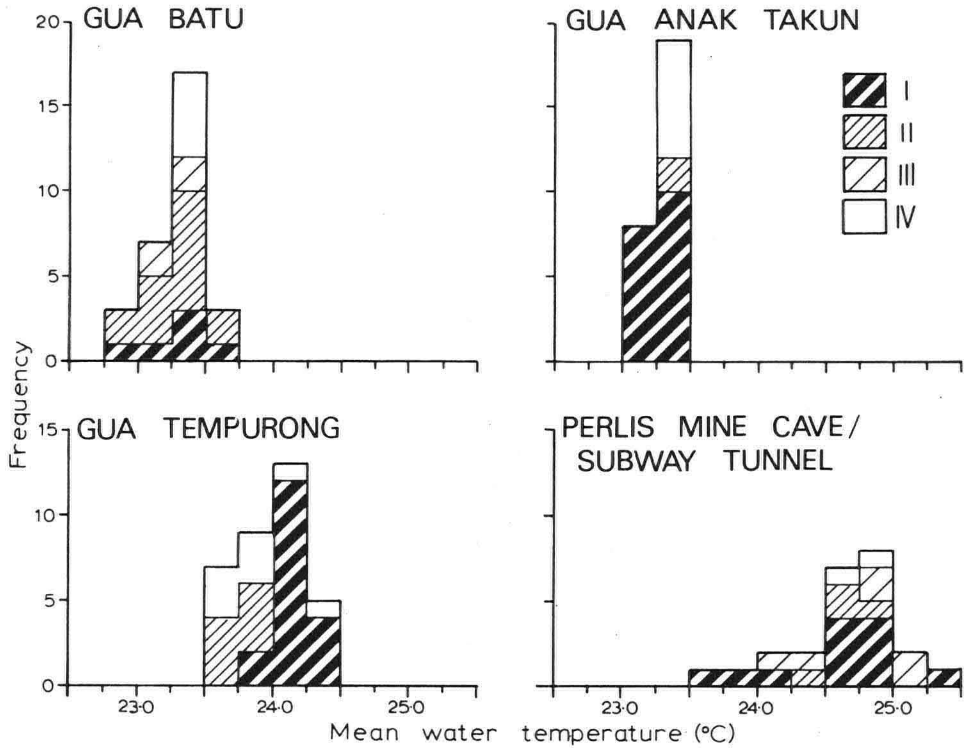

Figure 2. Mean temperature of seepage waters. Key: I. Seepages from stalactites less than 1.5 m in length, II. Seepages from larger stalactiticdeposits, III. Seepages issuing from open conduits, IV. Unclassified seepages, including those direct from bedrock joints and those contaminated by bat guano (see Figure 4).

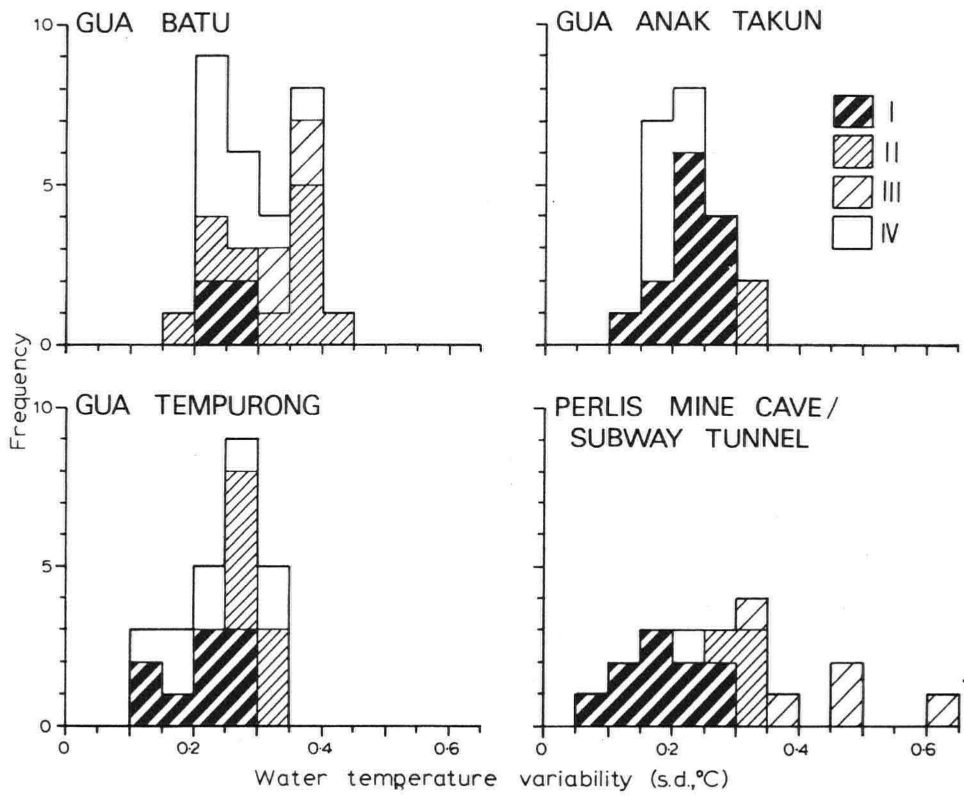

Figure 3. Temperature variability (s.d.) of seepage waters. Key as in Figure 2.

Within this constraint, the sites sampled are broadly representative of the range of se pages present in the four caves. Fewer data were obtained from sites with intermittent flow. The standard deviation (s.d.) of water temperature, which is used as an index of water temperature variability, has only been calculated for those sites at which six or more measurements were made. Most of the sites investigated are of the following three types: (1) seepages dripping from small stalactites less than 1.5 m in length, (2) seepages flowing over or emerging from large stalactitic deposits greater than 1.5 m in length, or (3) seepages issuing from open, air-filled conduits. The precise nature of some sites could not be established with certainty. These, together with several seepages which emerge directly from bedrock joints or are contaminated with bat guano (Crowther, 1981) are unclassified in Figures 2 and 3. Throughout the study period air temperatures were measured in each cave and soil temperatures were determined at 30 cm depth on the slope above Gua Anak Takun.

RESULTS

1. Mean water temperatures

The overall average temperature of the 121 sites is 23.74°C. This is more than 2° below mean annual surface temperatures (Table 1). Two factors may be important in explaining this result. First, soil temperatures, at least on slopes with a fairly continuous vegetation canopy, are approximately 2°C lower than the mean air temperature. For example, the average soil temperature recorded above Gua Anak Takun is 24.3°C. Percolating soil waters thus initially have a relatively low temperature, and the effect of this may be transmitted underground by advection as heat is carried along by water flow. A second factor is that cave air temperatures are consistently low, the measured range being from 22.84 to 24.52°C (Table 3). The fact that the caves receive no direct insolation may be the main reason for this. It is interesting to note that the average air temperature recorded at the ten underground stations (23.90°C) differs by less than 0.2°C from the mean temperature of the seepage waters. Thus, in outcrops with vadose and abandoned cave passages groundwater and, presumably, rock temperatures seem to be in equilibrium with ambient soil and cave air temperatures.

Table 3. Cave air temperatures (°C)

	MEAN	MINIMUM	MAXIMUM	STANDARD DEVIATION
Gua Batu				
Station 1	23.38	22.40	24.66	0.94
" 2	22.84	22.45	23.08	0.34
" 3	23.97	23.45	24.38	0.33
" 4	24.00	23.20	24.46	0.45
Gua Anak Takun				
Station 1	24.13	22.90	24.44	0.71
" 2	23.78	23.00	24.22	0.42
Gua Tempurong				
Station 1	23.93	23.10	24.42	0.37
" 2	24.02	23.70	24.39	0.29
Perlis Mine Cave/Subway Tunnel				
Station 1	24.45	24.12	24.86	0.28
" 2	24.60	23.90	25.60	0.68

Marked differences in water temperature occur between the four caves (Fig. 2). In Gua Batu and Gua Anak Takun, which are located less than 10 km apart, the overall mean values are 23.27 and 23.26°C, respectively. Notably higher temperatures were recorded in Gua Tempurong and Perlis Mine Cave/Subway Tunnel, the corresponding figures being 24.01 and 24.63°C. The progressive increase in water temperature northwards reflects the pattern of surface temperatures within the peninsula (Table 1). A further striking feature of these data is difference in the variability of mean temperatures within each cave. Thus, for example, the seepages in Gua Batu display a much wider range of temperatures than those in nearby Gua Anak Takun. This is probably attributable to the greater diversity of natural controls in the former, larger and more complex cave system, and suggests that this characteristic of water temperature data might be utilized as an index of groundwater behaviour in individual caves. Figures for the standard deviation of mean water temperatures are presented in Table 3.

In Gua Tempurong, seepages from stalactites less than 1.5 m in length are significantly warmer than those from larger stalactites (randomization test, Siegel, 1956; $\underline{P} < 0.001$), the average values being 24.15 and 23.71°C, respectively. Since air temperatures as low as 23.1°C were recorded in Gua Tempurong (Table 2), the lower temperatures of seepages from the larger stalactites are attributed to their greater contact with cave air. In addition to direct cooling, reductions in temperature may also be caused by evaporation from the thin films of water which often occur on the surface of the larger stalactitic deposits, and by endothermic calcite formation as carbon dioxide is lost from the water. However, the effects of the latter mechanism are thought to be small (Gascoyne, 1974). In the remaining caves, no significant differences in mean water temperature were observed between the three systematic groupings of seepages (Fig. 2). As the thickness of limestone overlying the latter caves is considerably less than in Gua Tempurong, spatial variations in groundwater temperature resulting from localized differences in the temperature of surface recharge waters are more likely to persist in the cave seepages. Consequently, the effects of variations in the amount of contact with cave air are likely to be less readily detected.

2. Water temperature variability

Water temperature fluctuations at the 96 seepages for which six or more measurements were made have an average standard deviation of 0.26°C, with a 0.08 to 0.62°C range. This compares with average s.d. values of 0.05° and 1.40°C, respectively, for deep, bore-hole groundwater and surface streams in this karst area (Crowther and Pitty, in press).

Notable differences in water temperature variability occur between the four caves (Fig. 3). Seepages in Gua Anak Takun and Gua Tempurong exhibit small fluctuations, with average standard deviation values of 0.22 and 0.24°C, respectively. In contrast, the corresponding figures for Gua Batu and Perlis Mine Cave/SubwayTunnel are 0.27 and 0.29°C. This pattern appears to be largely determined by relative proportions of the three principal types of seepage (Fig. 3). Thus, seepages from stalactites less than 1.5 m long exhibit least variability, the average s.d. value for the four caves being 0.21°C, with a maximum figure of 0.28°C. Appreciably wider temperature fluctuations occur at those seepages associated with larger stalactitic forms. The average s.d. for 26 such sites is 0.30°C. However, the widest temperature variability (mean s.d., 0.40°C) was observed at those points where water spills from air-filled conduits in the cave roof. With only one exception, the difference in the average s.d. values of these broad groupings of seepages within each cave is statistically significant (Table 5).

These results suggest that water temperature variability increases directly with the duration of contact with cave air. Confirmation of this is provided by a small group of five seepages which emerge directly from bedrock joints and have an average s.d. value of 0.17°C (range, 0.12 to 1.19°c). The mean s.d. figure for cave air temperatures is 0.48°C, with a 0.28 to 0.94°C range (Table 3). The progressive widening of temperature fluctuations from the smaller stalactites, through the larger stalactites to the air-filled conduits clearly reflects differences in the extent to which the waters have adjusted to the more variable temperatures of circulatory cave air. An additional factor might be important in the case of the open conduits. Flow rates at many of these sites respond quickly to storms, indicating rapid transmission of water from the ground surface. Under these circumstances the waters are likely to be influenced by surface temperatures, which are inherently more variable than those underground. Diurnal temperature fluctuations, for example, are in the order of 10.0°C (Table 1).

As in the case of mean water temperatures, the amount of variation in the s.d. values also differs from cave to cave, with Perlis Mine Cave/Subway Tunnel displaying the widest range (Fig. 3). The standard deviations of the s.d. values are presented in Table 4.

Table 4. Indices of temperature characteristics of seepages in the four caves.

	GUA BATU	GUA ANAK TAKUN	GUA TEMPURONG	PERLIS MINE CAVE/SUBWAY TUNNEL
Standard deviation of mean water temperatures (°C)	0.251	0.112	0.247	0.392
Standard deviation of s.d. values for individual sites (°C)	0.072	0.048	0.056	0.130

Table 5. Statistical significance of the difference in the average s.d. of water temperatures of the principal types of seepages in the four caves (randomization test). Figures refer to probability levels (N.S. = not significant) *Key: I. Seepages from stalactites less than 1.5 m in length; II. Seepages from larger stalactitic deposits; III. Seepages from open conduits.

TYPES OF SEEPAGE*	GUA BATU	GUA ANAK TAKUN	GUA TEMPURONG	PERLIS MINE CAVE/SUBWAY TUNNEL
I & II	0.05	0.001	0.05	0.001
I & III	0.05	-	-	0.001
II & III	N.S.	-	-	0.05

DISCUSSION

1. Characterization of cave seepages

The present study clearly demonstrates that water temperature variability is a useful tool for distinguishing different types of seepage water in tropical caves. Most notably, such data provide a means of assessing the extent to which a given groundwater has come in contact with circulatory air within the aquifer, thus enabling researchers to identify more precisely those seepage waters which have encountered little or no air prior to emergence. Such waters are of particular significance in that they are likely to have lost only small amounts of calcium carbonate through secondary deposition and consequently provide a sound basis for estimating gross solution rates.

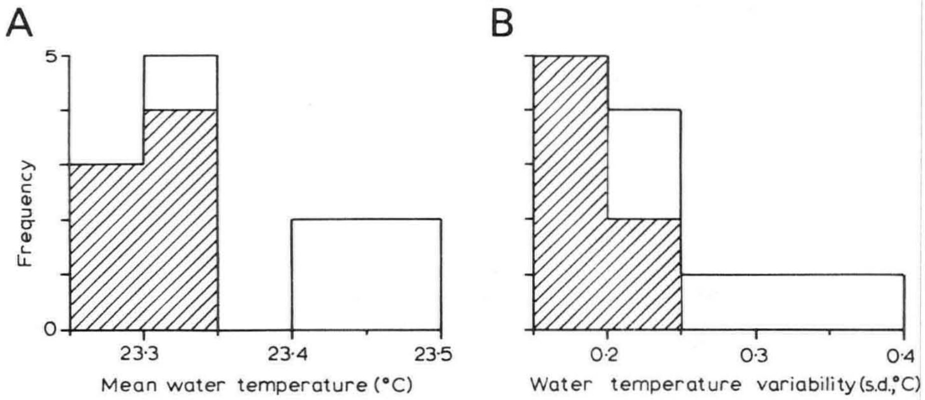

Figure 4. Temperature characteristics of guano-affected seepages in Gua Batu (blank) and Gua Anak Takun (shaded):

A: Mean water temperatures.

B: Water temperature variability (s.d.).

Data from the guano-affected seepages in Gua Batu and Gua Anak Takun further illustrate the usefulness of temperature measurements in this respect (Fig. 4). In the first cave the majority of such waters issue from high-level, air-filled conduits in the roof. By contrast, in Gua Anak Takun they are confined to that part of the main cave located beneath an upper passage which is frequented by bats. The two passages are separated by approximately 12m of bedrock and water emerges into the main cave from tight water-filled fractures. The seepages in Gua Batu exhibit notably wider temperature fluctation than those in Gua Anak Takau, the average s.d. valies being 0.29 and 0.20°C respectively. They are also slightly warmer than those in Gua Anak Takau, the corresponding mean figures being 23.4 and 22.9°C. Whilst the characteristics of these particular seepages were initially established independently of temperature measurements, the potential utility of such data in caves where the precise nature of individual groundwaters is less certain, is readily apparent.

2. Characterization of aquifers

Where the sites investigated are broadly representative of the seepages in a particular cave, then temperature data may also be used to provide some measure of the hydrological complexity of the aquifer. Two simple indices have been proposed in the present study: (1) the standard deviation of the mean temperatures observed at each seepage over a one-year period, and (2) the standard deviation of the s.d. figures for the various sites. These indices have proved useful in distinguishing the four Malaysian caves (Table 4). Thus, groundwater flow in the aquifers overlying Gua Anak Takun and Gua Tempurong, which have the smallest values of these indices, is almost entirely confined within tight, water-filled fractures. Since the residence time of these waters is likely to be quite long, temperature variations present in the recharge waters will be considerably moderated within the aquifer. The Perlis Mine Cave/Subway Tunnel system represents the other extreme. Here a more rapid transmission of water through the limestone favours the persistence at depth of spatial and temporal variations in temperature induced by surface conditions. Additionally some seepage waters, issuing from conduits, have considerable contact with the cave air which causes further variability. Groundwaters entering this cave system are therefore heterogenous in character, and this is reflected in the high values of the proposed indices. Clearly, this approach may have general applicability as a basis for comparing caves within a given climatic zone. The possibility of using indices of temperature variability in world-wide comparisons remains to be explored.

CONCLUSIONS

Despite the diverse natural variables which influence groundwater temperatures, three factors appear to account for much of the spatial and temporal variability of seepage temperatures in Malaysian caves. Firstly, the average temperatures of cave seepages are 2 to 3°C below mean annual surface temperatures. Secondly, water temperature variability diminishes with increased residence time within the aquifer. Finally, water temperature variability varies directly with the amount of contact with circulatory cave air. The study demonstrates that in a humid tropical environment water temperature data, most notably those related to water temperature variability, provide a sound basis for differentiating cave seepages and for characterizing the hydrological properties of the aquifers overlying individual caves.

ACKNOWLEDGEMENTS

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A TECHNIQUE FOR SAMPLING SOIL AIR : SOME RESULTS AND METHODOLOGICAL IMPLICATIONS

J.Crowther

Abstract

This paper describes a diffusion well method for sampling soil air which has proved satisfactory for repetitive carbon dioxide measurements over a one year period in some karst soils of West Malaysia. Results from a tower karst footslope soil demonstrate that carbon dioxide concentrations increase with depth and exhibit a close positive correlation with the total amount of rainfall in periods of 1-32 or 1-64 days before sampling. Evidence is discussed which suggests that: (1) air with markedly different carbon dioxide concentrations may be obtained from a given soil using different methods of sample extraction, and (2) air extracted by existing sampling techniques is atypical of that present in the near-saturated zone which develops at the base of soil profiles at times of substantial groundwater recharge.

The importance of soil carbon dioxide in the chemical weathering of limestones is well-established. The present paper describes a technique for sampling soil air which has been used successfully in a long-term investigation of carbon dioxide in some tropical karst soils in West Malaysia. Important methodological implications which emerge from the results are considered. In particular, attention focuses on the possibility that different results might be obtained at a given site using different methods of air extraction and on the relationship between measured carbon dioxide concentrations and the actual solutional potential of soil waters.

EXISTING METHODS

Bunting and Campbell (1975), Grable (1966) and Macfadyen (1970) outline some of the difficulties associated with soil air sampling. Samples of several ml, suitable for gas chromatographic analysis, can be obtained directly from soil pores using a metal capillary probe and a small glass syringe (Pritchard and Brown, 1979; Wong, 1974). Volumes of up to 40 ml, needed for analysis using a Lloyd type gas analyser (Lloyd, 1958), are usually obtained by installing either diffusion wells (Boynton and Compton, 1944; Burford, 1973; Cooper, 1975; Vine, et al., 1943; Yamaguchi et al., 1962) or carbon dioxide permeable collection vessels (Harley and Brierley, 1953; Macfadyen, 1970; Martin and Pigott, 1965; Nicholson and Nicholson, 1969) in the soil. In the first method samples are extracted by syringe and the soil remains undisturbed once the well has been installed. The second method is less satisfactory for repetitive measurements at a single site since some disturbance is inevitable during sampling. A mechanical pump is normally required to extract the larger samples of over 100 ml needed in the Draeger (Miotke, 1974) and Orsat methods of analysis (Jakucs, 1977).

PRESENT METHOD

The equipment used in the present study (Fig. 1) was designed to provide samples of 30 to 40 ml for replicate analysis using a Lloyd-Gallenkamp gas analyser. The diffusion well, which is inserted into an auger hole in the soil, comprises thick-walled steel pipe, 34 mm internal diameter and of a length equal to the sampling depth. The pipe is open at the bottom to allow free entry of soil air, and an access tube (6 mm o.d.) passes through a metal plate which is welded at the top. Throughout the sampling system air-flow is controlled by Hoffman clips attached to flexible PVC tubing of 6 mm bore. One such valve is pushed firmly onto the access tube, forming an air-tight seal. Because the area of PVC tubing exposed below the clip is small and a carbon dioxide diffusion through such tubing is likely to be slow, errors arising from this source are considered to be negligible. However, in field trials in West Malaysia the PVC proved to be extremely vulnerable to termite attack. Plasticine moulded around the tubing was a satisfactory deterrent.

A large and robust syringe was required to extract the required volume of air, particularly from wetter and denser soils. The outer casing, constructed of clear perspex, allows immediate detection of defects in the piston.

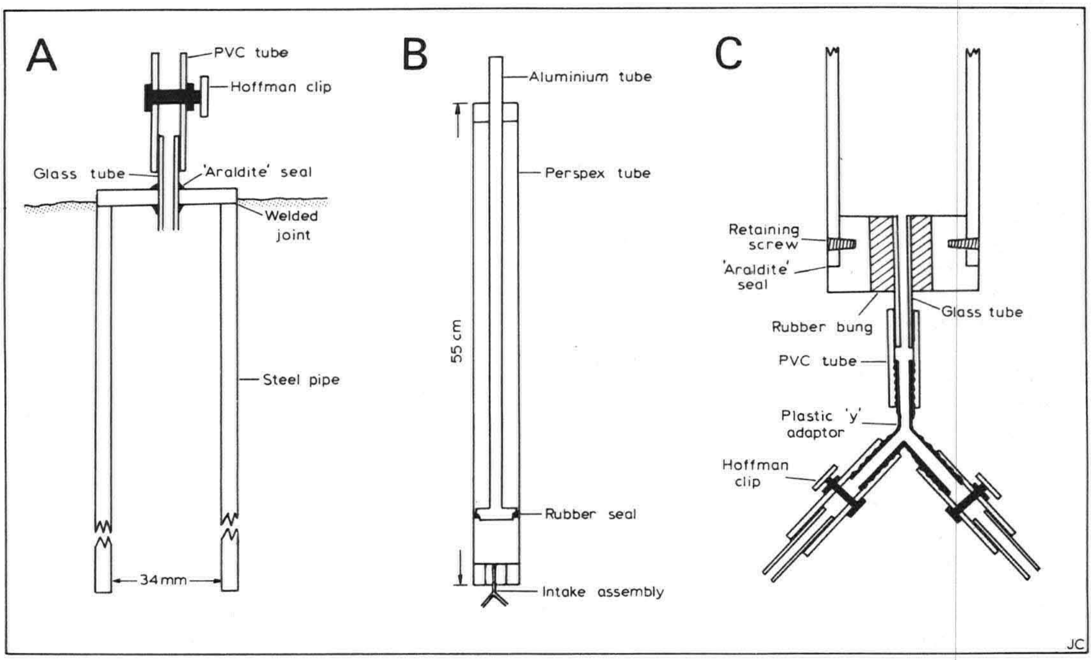

Figure 1. Equipment used for sampling soil air: A:Diffusion well, B:Syringe, C:Enlarged section of sample intake assembly.

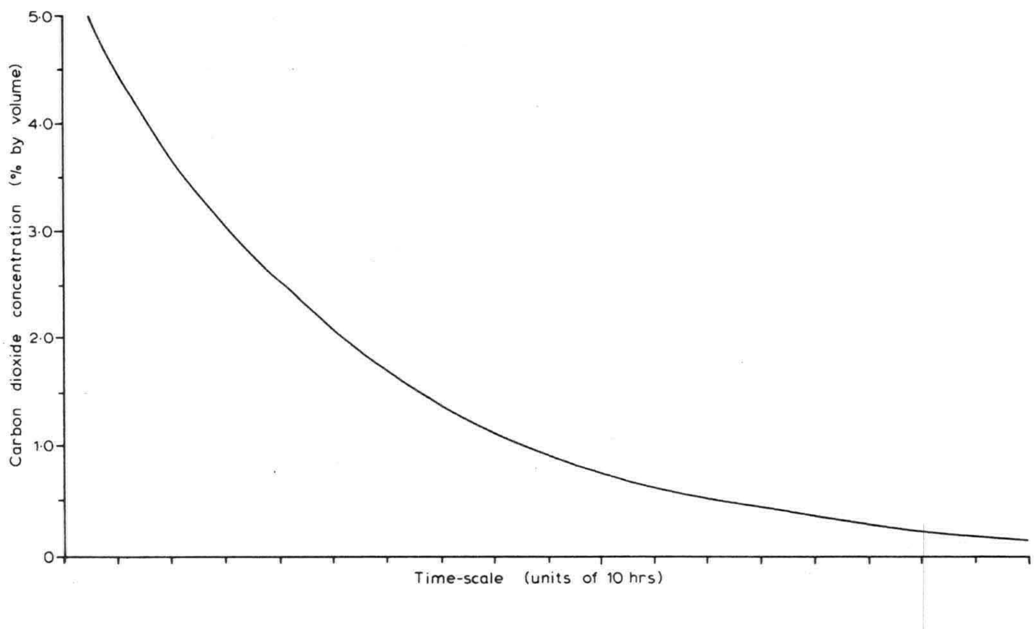

Figure 2. Typical curve showing rate of carbon dioxide loss from a football bladder during sample storage.

The latter is made from aluminium with a rubber seal, and the rod is of light-weight aluminium tube. The sample intake assembly comprises a glass tube connected to the base of a polypropylene y-shaped adaptor (6 mm o.d.) by means of a short length of PVC tubing. One arm of the adaptor leads to the diffusion well and the second to the storage bladder. In order to make the intake assembly more resilient to knocks, it is mounted in a rubber bung. The internal walls of the syringe and the joint between the bung and the perspex case are lightly coated with silicone grease to maintain air-tight seals.

Marked changes in gaseous composition can occur during the storage of soil air samples (Bunting and Campbell, 1975; de Jong and Schappert, 1972; Macfadyen, 1970). In tests on a wide range of storage vessels, rubber football bladders were among the least permeable to carbon dioxide and proved particularly suitable for field use. Throughout the study samples were taken between 13.00 and 14.00 hrs and were transported to the laboratory in a well-ventilated position in the rear of the field vehicle. The rate of carbon dioxide loss under these conditions was determined experimentally. When expressed as:

$$\frac{\text{Amount of } CO_2 \text{ lost in 1 hr}}{\text{Initial concentration of } CO_2} \times 100$$

the values for the 15 sampling bladders used in the study ranged between 1.6 and 2.3. A typical diffusion curve is shown in Fig. 2. Such curves were used to estimate carbon dioxide loss during storage, which never exceeded 4 hrs. There was no significant change in the permeability of the bladders over the one year study period.

SOME RESULTS FROM KARST OUTCROPS IN WEST MALAYSIA

Temporal variations in carbon dioxide in a tower karst footslope soil, Kinta Valley, Perak.

The study site is located on a forested colluvial (or alluvial?) footslope of G. Tempurong (Crowther, 1982). The soil is neutral to slightly acidic in reaction and has a clay to sandy clay texture. It has moderately developed, subangular blocky peds in the surface horizons (bulk density, 1.06 g/cm^3), but is more massive at depth (b.d., 1.65 g/cm^3). Carbon dioxide concentrations at 15, 30 and 60 cm, and soil moisture at 15 cm, were determined at approximately 6-week intervals over a one year period.

The carbon dioxide and soil moisture data are summarised in Table 1.

Table 1 Carbon dioxide and moisture levels (expressed as % by volume) in a footslope soil, G. Tempurong.

	MEAN	MINIMUM	MAXIMUM	STANDARD DEVIATION
Carbon dioxide				
15 cm	0.65	0.38	0.96	0.21
30 cm	0.94	0.71	1.36	0.26
60 cm	1.94	1.03	3.67	0.98
Moisture				
15 cm	25.4	19.4	30.8	4.55

The increase in mean carbon dioxide levels with depth suggests that gaseous diffusion, the principal mechanism of soil aeration (Grable, 1966; Stolzy, 1972), is sufficiently impeded from the deeper soil horizons by the long flow paths to the surface that carbon dioxidebuilds up to concentrations in excess of those in the uppermost horizons, where rates of biogenic carbon dioxide production are usually higher. Marked fluctuations in carbon dioxide were observed at each depth over the study period, the range at 60 cm, for example, being from 1.03 to 3.67 per cent. From the standard deviations it can be shown that the number of samples required to estimate the mean carbon dioxide content to within 10 per cent at the 0.05 probability level ranges from 29 at 30 cm to 98 at 60 cm. Correlation coefficients were calculated for the relationships between soil carbon dioxide (and soil moisture) and rainfall totals during a wide range of pre-set antecedent periods, using the method outlined by Pitty (1966) for the investigation of karst waters. For each sampling depth the closest correlation is with an antecedent period, such as 1-2 or 1-64 days, which begins on the day of sampling, rather than with periods such as 16-31 days where there is a lagged response. The results obtained are summarised in Figs. 3 and 4. In each case the peak correlation coefficient is statistically significant ($\underline{P} < 0.05$). Soil moisture at 15 cm correlates most closely with rainfall in the antecedent period 1-8 days. This suggests that on average rainwater from most storms is retained by the soil for about 8 days in amounts which are sufficient to affect significantly the moisture level at 15 cm. In contrast, fluctuations in carbon dioxide are most strongly related to rainfall amounts during antecedent periods of 1-32 or 1-64 days. It is well-established that where a soil has adequate aeration the number of micro-organisms and, hence, rates of soil respiration vary directly with soil moisture (Campbell and Biederbeck, 1976; Shameemulla et al, 1971). The present results suggest that there are periodic oscillations in the microbial population of the footslope soil in response to long spells of wet or dry weather.

<u>Comparison of measured carbon dioxide concentrations and the calcium hardness of shallow subsurface flow in the Setul Boundary Range, Perlis.</u>

The site is located on a forested, 35° hillslope at the south-eastern corner of Wang Tangga, a large enclosed depression in the Setul Boundary Range. The soil is a slightly acid clay, with a well developed crumb structure (bulk density, 0.72 to 0.91 g/cm^3). At 60 cm, which is typical of the depth of the thicker soils in the area, the carbon dioxide concentration averaged 0.78 per cent, with a 0.53 to 1.21 per cent range over the one year period. Nearby, a combination of natural collapse, caused by gully erosion during storm runoff, and the activities of local tin prospectors have exposed a section of the soil and upper part of the bedrock. The exposure yields considerable volumes of water during wetter periods or after particularly heavy downpours. The precise position of the soil-rock interface cannot be determined with certainty because the surface is thickly mantled by secondary deposits. It seems likely, however, that the majority of seepages correspond with flow lines at the base of the soil in the upper, most weathered layer of bedrock. 92 water samples were analysed from a total of 16 seepage points. The results are summarised in Table 2.

<u>Table 2</u> Hardness properties (expressed as ppm $CaCO_3$) of shallow-depth subsurface waters in Wang Tangga.

	MEAN	MINIMUM*	MAXIMUM*	STANDARD DEVIATION
Total hardness	341.9	263.6	395.9	38.6
Calcium hardness	280.8	211.0	326.0	31.1
Magnesium hardness	61.1	49.6	80.2	10.2
Alkaline hardness	340.7	263.3	395.3	37.7
Non-alkaline hardness	1.2	0.0	5.9	2.24

*Based on means of 3 to 8 samples from each of 16 seepage points.

All the waters are supersaturated with respect to calcite (Crowther, 1980). While pH may change considerably in response to a fall in the partial pressure of carbon dioxide as the waters seep towards the exposed face and emerge at the surface, changes in total hardness are thought to be small. This is confirmed by the fact that no detectable decrease in hardness was found in water which had flowed as a thin surface film for a distance of 1.5 m from a seepage point. It is assumed, therefore, that the observed hardness values provide a reliable estimate of the solutional potential of soil waters at this site.

The relationship between the calcium content of saturated calcite solutions and the partial pressure of carbon dioxide in the pure $CaCO_3$-CO_2-H_2O system is well established (Picknett, 1973). A curve for this relationship at 25°C (cf. mean seepage temperature of 24.4°C) may be constructed from the data presented by Picknett (1973, Table 5, p.72). From this the concentration of carbon dioxide corresponding with a mean calcium hardness of 280.8 ppm is approximately 2.6 per cent, which is more than three times greater than the measured mean value of 0.78 per cent at 60 cm. Whilst the former figure must be regarded with some caution because of the complex nature of natural karst waters (see, for example, review by Picknett et al, 1976), especially in this case the presence of magnesium ions, it is unlikely that errors from this source can account completely for a difference of this magnitude. Furthermore, the ephemeral flow of seepages and their topographic setting suggest the waters have a very shallow subsurface origin. Consequently, the carbon dioxide rich 'ground air'

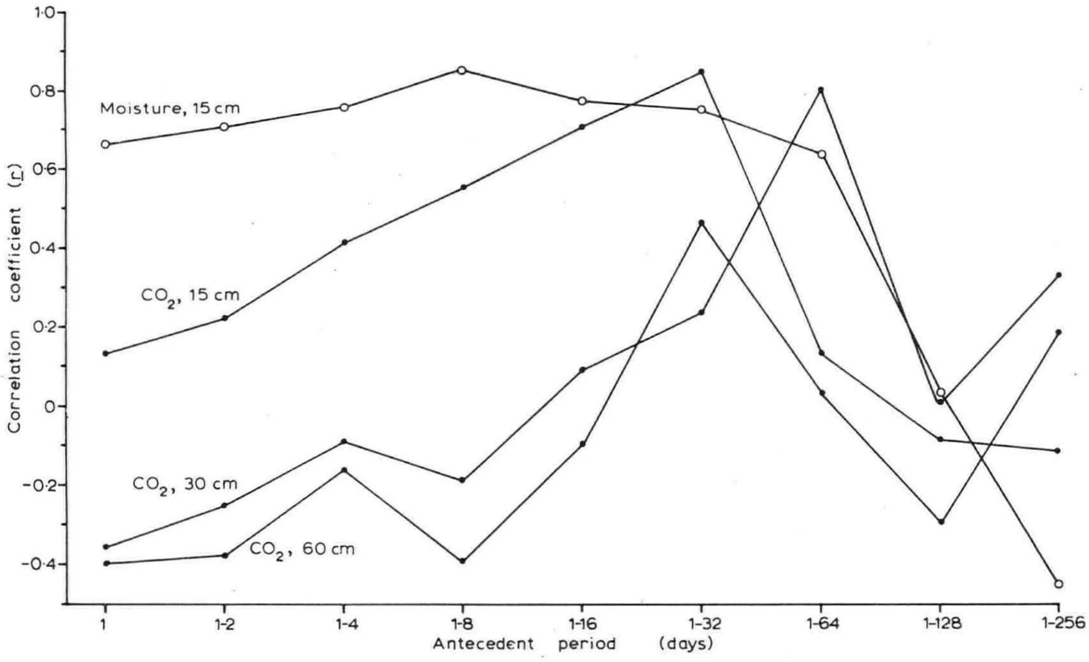

Figure 3. Correlation coefficients (r) for the relationship between soil carbon dioxide (and moisture) and rainfall amounts during selected antecedent periods in a tower karst footslope soil.

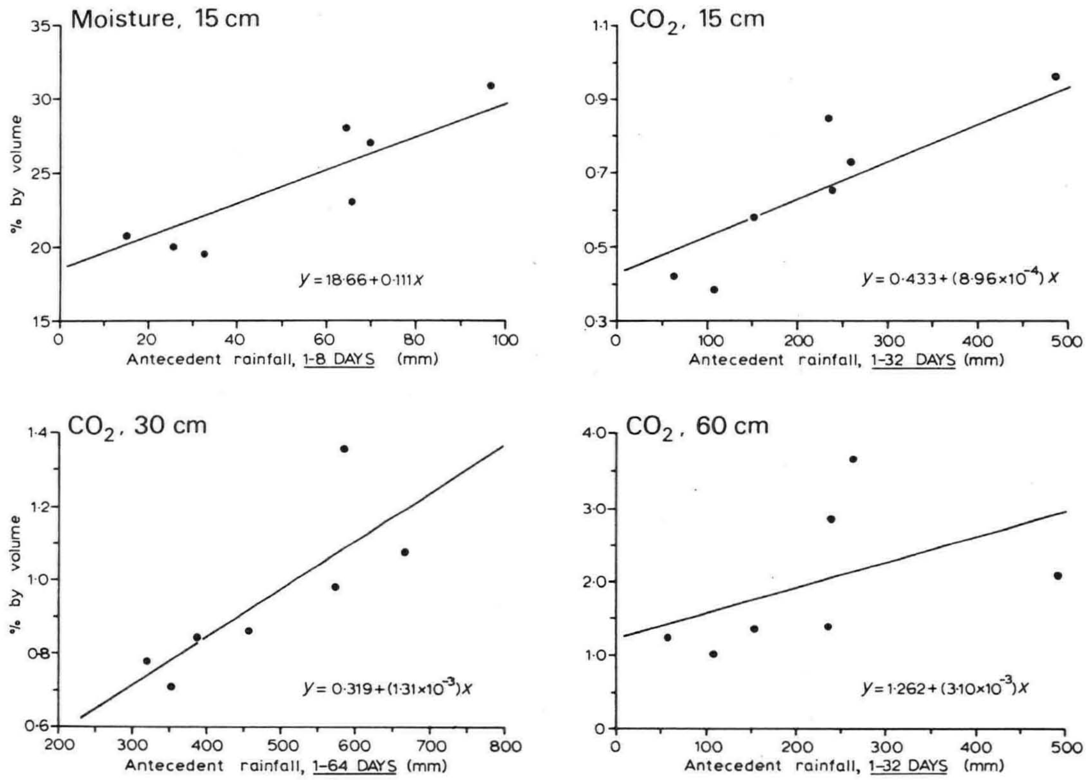

Figure 4. Measured soil carbon dioxide and moisture levels shown in relation to the rainfall amounts in the antecedent periods with which they exhibit the strongest positive correlation.

effect, postulated by Atkinson (1977) to explain the discrepancy between measured soil carbon dioxide concentrations and the hardness of seepage waters in the Mendip Hills, is not thought to be operative. Thus, it is concluded that the soil air sampled by the present method of extraction is unrepresentative of the air with which soil waters come into equilibrium during periods of groundwater recharge.

IMPLICATIONS FOR SOIL AIR SAMPLING IN LIMESTONE SOLUTION STUDIES

Use of different methods of soil air sampling.

Since the presence of water reduces the volume of air-filled pore space in a soil, thereby impeding diffusion, it may be anticipated that carbon dioxide levels will increase after storms. The absence of a significant positive correlation in the tower karst footslope soil between carbon dioxide and rainfall amounts during antecedent periods shorter than 1-8 days may simply be caused by the dominant effect of longer-term fluctuations in microbial activity as outlined above. Additionally, however, it might reflect the soil air sampling technique adopted. The diffusion wells have a cross-sectional area of only 9.1 cm^2, whereas the internal volumes of the 15, 30 and 60 cm wells are approximately 135, 270 and 540 cm^3, respectively. As a consequence, changes in the gaseous composition of a diffusion well will take place very slowly compared with those of the air-filled pore spaces in the soil. Thus, while carbon dioxide levels in the soil pores may fluctuate considerably from day to day or from hour to hour, the present sampling method and, presumably, others which utilize diffusion wells or carbon dioxide permeable collection devices are relatively insensitive to such changes. It is postulated, therefore, that techniques of air extraction which rely on gaseous diffusion have a low degree of resolution with respect to temporal variations in soil carbon dioxide and that short-term fluctuations can only be reliably monitored using those methods which permit direct extraction of air from soil pores. An important corollary of this is that samples with different carbon dioxide concentrations might be obtained from a given site using different extraction methods.

Relationship between measured carbon dioxide levels and the actual solutional potential of aquifer recharge waters.

Where a soil cover is present groundwater recharge can only take place when the water-holding capacity of the soil is exceeded. Because of the high rates of evapotranspiration which obtain in the Malay Peninsula, such conditions will only occur during spells of wet weather or following particularly heavy downpours. On the other hand, in temperate regions, such as Britain, most recharge occurs during the winter months (Pitty, 1974). At such times the soil immediately above the soil-rock interface will be almost saturated and the air in this zone will be largely confined to isolated bubbles in the otherwise water-filled macro-pores. Gaseous diffusion will virtually cease and it is reasonable to suppose that the carbon dioxide content of the gas bubbles will increase as a result of microbial and root respiration in the soil which is in direct contact with the air. Air in such bubbles cannot be sampled directly in the field using metal capillary probes or the Draeger method since water will be drawn into the equipment during sampling. Also, there will be little gaseous exchange between the air in the soil and that in diffusion wells (or carbon dioxide permeable containers) which penetrate the near-saturated horizons. Consequently, even when samples can be obtained at times of groundwater recharge, they will have lower carbon dioxide concentrations than the air in the saturated zone. The results from Wang Tangga certainly indicate that the carbon dioxide content of air sampled by the diffusion well method is considerably less than that predicted from the chemistry of shallow subsurface waters. This finding has important implications for limestone solution studies in that the carbon dioxide concentration of air obtained by any of the existing sampling methods is unlikely to be representative of air present in the near-saturated zone during the critical periods when groundwater recharge occurs.

CONCLUSIONS

Four main conclusions may be drawn from the results and experience gained in investigating soil carbon dioxide in the Malay Peninsula.

(1) The diffusion well and method of sample extraction and storage developed in the present study provide a reliable, yet relatively cheap and extremely robust, means for repetitive field sampling at a range of depths.

(2) Marked temporal and depth variations in soil carbon dioxide may be encountered in a tropical karst terrain. Measured carbon dioxide levels in a tower karst footslope soil vary directly with rainfall totals during antecedent periods of 1-32 or 1-64 days, and increase with depth. Detailed long-term data are required before mean carbon dioxide levels at a given site can be specified with some certainty.
(3) Air in diffusion wells is relatively insensitive to short-term fluctuations in soil carbon dioxide. Results obtained by the present method, and by others which rely on diffusion, might therefore differ significantly from those obtained using direct methods of soil air extraction.
(4) Field evidence and theoretical considerations suggest that soil air extracted by existing sampling techniques is atypical of the air present in the near-saturated zone which develops at the base of soil profiles at times of substantial groundwater recharge.

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