Cave Science

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Dushan karst geomorphology Guizhou

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Cave Science

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TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

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Contents

Cover: Typical fengcong-valley karst topography in China, with a large fossil cave overlooking an alluviated valley floor. This is near Nantan, Guangxi, close to the Guizhou border. By Tim Atkinson.

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Karst Geomorphology and Subterranean Drainage in South Dushan, Guizhou Province, China

SONG Linhua

Abstract: South Dushan is located on the regional topographic slope between the Guizhou Plateau and the Guangxi basin in South China. Carbonate rocks 3000 m thick cover 80% of the study area. The development of karst geomorphology and underground drainage systems is closely controlled by the lithology, geological structure, neotectonic movements and hydrology. The karst has developed geomorphically through four main stages : doline-depression, Fengcong-depression, Fenglin-basin and a rejuvenated Fengcong-canyon stage caused by neotectonic uplift especially during the Quaternary. Each stage can be recognised in different geomorphologic zones of the study area. In the Fenglin-basin zone, old, mature plateau karst features have not been destroyed by rejuvenation and groundwater flow occurs in dendritic cave systems and fissure-networks with shallow groundwater tables. Deep karst ponds contain hundreds and thousands of cubic metres of water. Fenglin-basin topography is mixed with Fengcong-depression topography in a partially rejuvenated zone, in which conduit flow is the predominant mode of groundwater flow, with the groundwater table 60-90m below the surface. In the fully rejuvenated Fengcong areas, near the major river canyons, conduit flows predominate, with high gradients of 5 % or more.

Seven subterranean drainage systems are briefly described. The development of karst water resources is very diverse in the different morphologic zones. Wells are generally successful in karst basins, and dams have been constructed in some caves. In the Fengcong-canyon area, steep conduit flow with high velocity and large water heads is ideal for developing hydroelectric power.

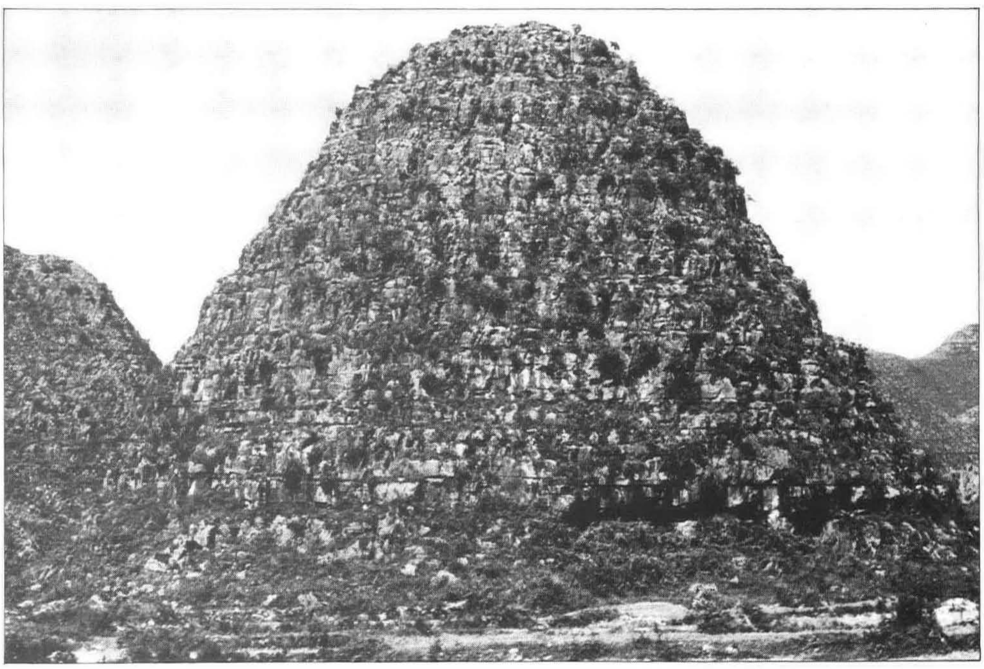
INTRODUCTION

South Dushan is located between the Guizhou Plateau and the Guangxi basin, between 107°47' East, and 25°13' North (Fig.1). In geomorphic terms, it occupies a transitional position between the elevated karst topography of the plateau and the well known tower karst of the Guangxi basin. Topographically, the area is highest in the north, the highest peak being Gandinshan with an altitude of 1665 m above the sea level (a.s.l.). The land falls towards the west and southeast with the lowest points in the southeast being only 385 m a.s.l. The study area constitutes part of the interfluve between the Longjiang and Hongshuihe rivers (the characters jiang and he both mean river). Both of these southwards-flowing streams are part of the Zhujiang (Pearl River) drainage system.

The area has a subtropical climate with annual average temperature 15°C, about 280 frost-free days per year and annual average precipitation 1313 mm (1965-76; maximum 1670 mm, minimum 1090 mm). The rainy season from April to October accounts for 84% of the annual total, but most of the rain occurs as heavy storms and quite serious drought periods can occur. During the dry season there are serious water shortages in parts of the karst area.

South Dushan is underlain by 3000 m of Palaeozoic carbonate rocks. A long history of karstification has resulted in a variety of karst

All photos by Tim Atkinson



Fenglin hill in horizontally bedded limestone, near Yaopang, South Dushan, Guizhou.

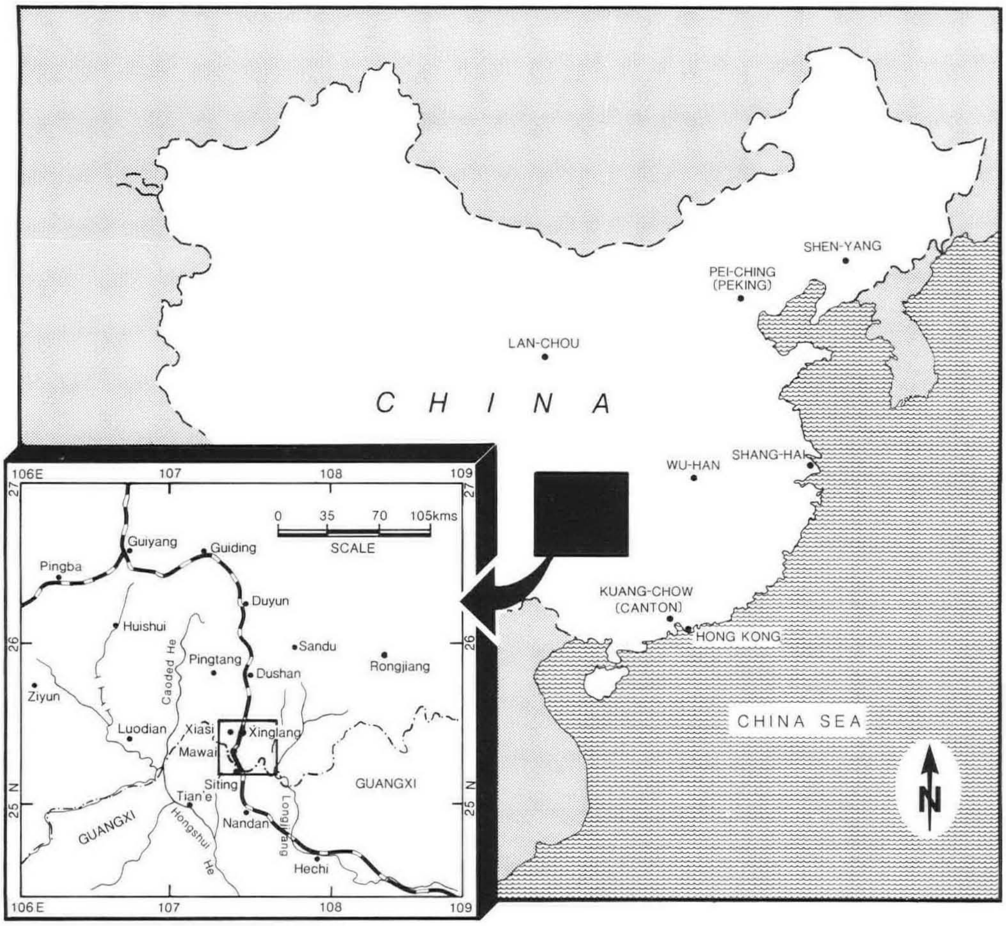


Fig.1 Map of China showing location of the study area.

landscapes, known in the Chinese literature as Fenglin-basin, Fengcong-depression and Fengcong-canyon types (these terms will be explained in more detail below). Beneath the surface, an active karstic groundwater flow has created many underground drainage systems. Overall, South Dushan is typical of the geomorphology and hydrology of sub-tropical karst plateau areas in China.

In 1638 the great geographer and karstologist Xu Xiake investigated the karst geomorphology, hydrology and caves in South Dushan. Much more recently, Chen Supeng (1954) studied the geomorphic and hydrologic features and described how several hundred kilometres of rivers in South Dushan alternate between surface and subterranean courses. He reported that surface rivers are rare on the limestone plateau, but there are great numbers of sinkholes and deep karst ponds in flat-floored karst basins. In some, subterranean water can be heard. Chen Supeng set the karst geomorphology in the South Dushan area into the wider context of river canyon and subterranean drainage of the Guizhou region.

The Karst Group of the Institute of Geography, Academia Sinica, Beijing, of which the author is a member, have systematically studied the karst geomorphology and underground drainage systems in South Dushan (Karst Group, 1977). The present paper summarises some of their findings, stressing the basic characteristics of the underground drainage systems and their relationships with lithology, geological structure, geomorphology and neotectonic uplift.

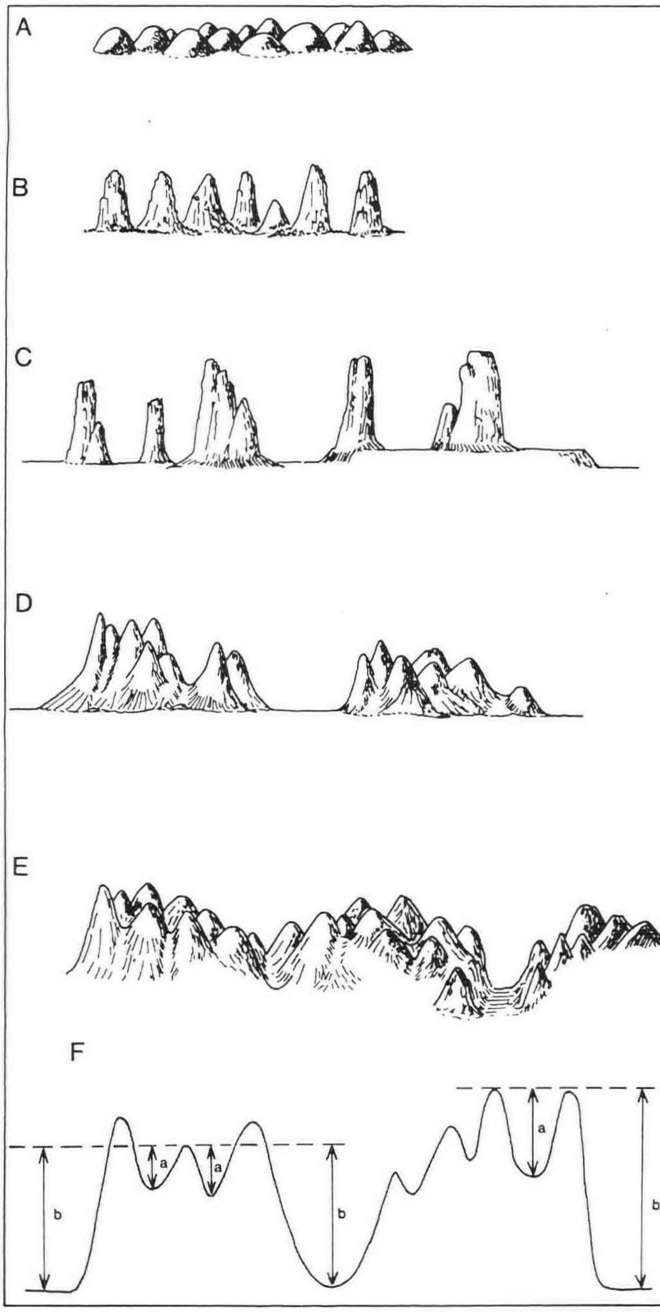
KARST GEOMORPHIC TERMS USED IN CHINA
(notes by T.C. Atkinson)

The study of karst in China goes back several centuries and Chinese geographers and geologists have evolved their own terms to describe karst landforms. Not surprisingly, these do not correspond exactly to the terms used by Western geomorphologists and some explanation is necessary.

The vast areas of tower and cone karst in south China have caused Chinese workers to concentrate on the karst hills (or positive elements in the landscape) as much as on the various types and sizes of closed hollows (or negative elements). Karst hills are classified into two main groups, called Fenglin and Fengcong (pronounced fung-tzong). These may be roughly translated as peak forest and peak cluster. Neither term corresponds exactly to any category used in Western geomorphology.

Fenglin consists of separate hills, each culminating in a single summit. They may vary in shape and size, and may occur either in isolation or in closely spaced ranks. The diagnostic feature of Fenglin is that each hill is separated from its neighbours by a more or less level surface from which all the hills in the group appear to rise. The term is applied to hills ranging in style from karst cones separated by a network of narrow valleys, all with their floors at much the same level, to spectacular, vertical-sided karst towers rising from alluvial plains. Fig.2 A, B and C are sketches showing three different styles of Fenglin which in English might be described as cone karst, tower karst and alluvial karst respectively.

Fengcong are compound hills comprised of groups or clusters of peaks. The peaks themselves may vary in shape and size from cones to towers, as with Fenglin. The diagnostic feature of Fengcong is that each of the hills in a cluster rises from a common plinth, not from a relatively level surface as in Fenglin. Within the cluster, the peaks may surround closed hollows which would be described as dolines, uvalas or cockpits in English geomorphological usage. The hollows can vary in depth and size, even within one cluster. Lower ground separates the plinth of each Fengcong cluster from neighbouring clusters. The lower ground may be composed of large depressions, flat-floored basins network valleys or alluvial plains. Fig.2 D and E show two different styles of Fengcong which might be described in English as tower karst and cone or cockpit karst



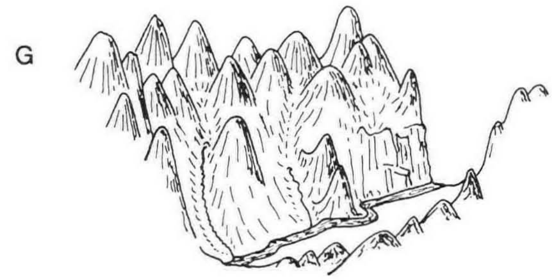


Fig.2 Sketches to illustrate the meaning of Chinese geomorphological terms (see Section 2 of the text). A, B and C all show different varieties of Fenglin - hills whose bases are all at a similar level. D, E, F and G show Fengcong - clusters of hills separated from each other by depressions, valleys or low ground.

A. Fenglin: Karst cones, as found in Gunung Sewu, Java, and some areas of the Guizhou Plateau. The cone- or sinusoidally shaped hills are separated by a network of valleys and closed depressions.

B. Fenglin: Closely-spaced karst towers separated by networks of narrow, level-floored corridors. Common in Fenglin-basin areas of Guizhou Plateau.

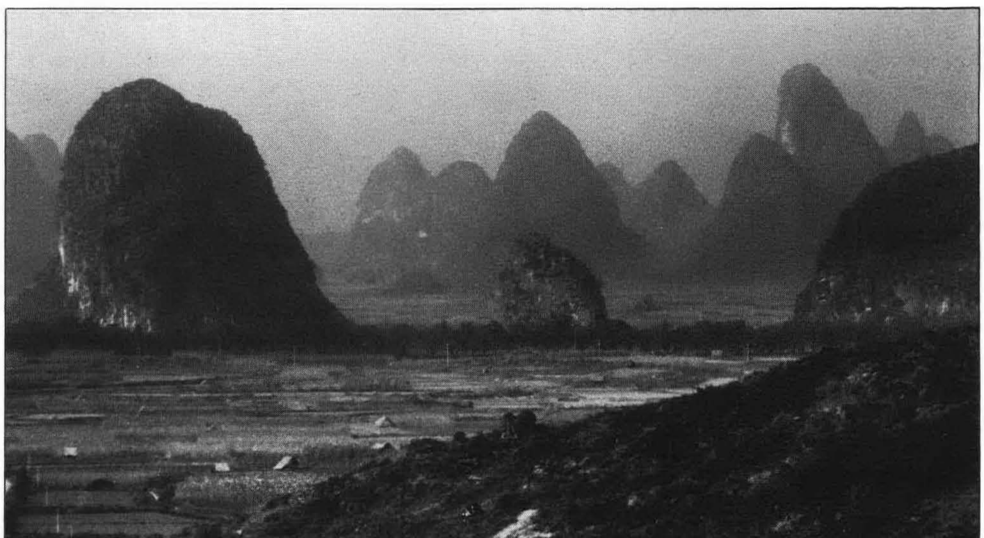
C. Fenglin: Isolated karst towers rising from level plains. This style of tower karst is usually associated with river drainage of the karst plains. Two levels are shown, the upper one representing a river terrace. This style is common in the Fenglin parts of the Li River tower karst, Guilin region, Guangxi.

D. Fengcong: Clustered peaks sharing a common base, or plinth, with a flat surface between the clusters. Common in the Guangxi tower karst plains and on the Guizhou Plateau.

E. Fengcong: Clusters of karst cones and towers with deeper depressions or valleys between the clusters. Smaller depressions occur within the clusters. This style is what is meant by Fengcong-depression and Fengcong-valley topography. It occurs widely on the Guizhou Plateau, frequently in zones around the edges of the undissected parts of the plateau.

F. Fengcong: Diagramatic cross-section across a Fengcong-depression area. A rough working definition of Fengcong (as opposed to the Fenglin style shown in A.) is that the depths of the depressions within the clusters should be no more than one third of the depth of the depressions between them, i.e. $a/b < 1/3$.

G. Fengcong-canyon landscape: Produced by uplift of a pre-existing karst plateau, seen on the left skyline of the sketch. The river valley (canyon) has been produced by rapid downcutting, in response to the uplift, developing steep vertical walls. New Fengcong cones have formed on the valleys sides. Karst springs may hang hundreds of metres above the valley floor.



Fenglin towers rising from karst plain, west of Yangti, near Guilin, Guangxi. The large tower on the left is about 100 m high.

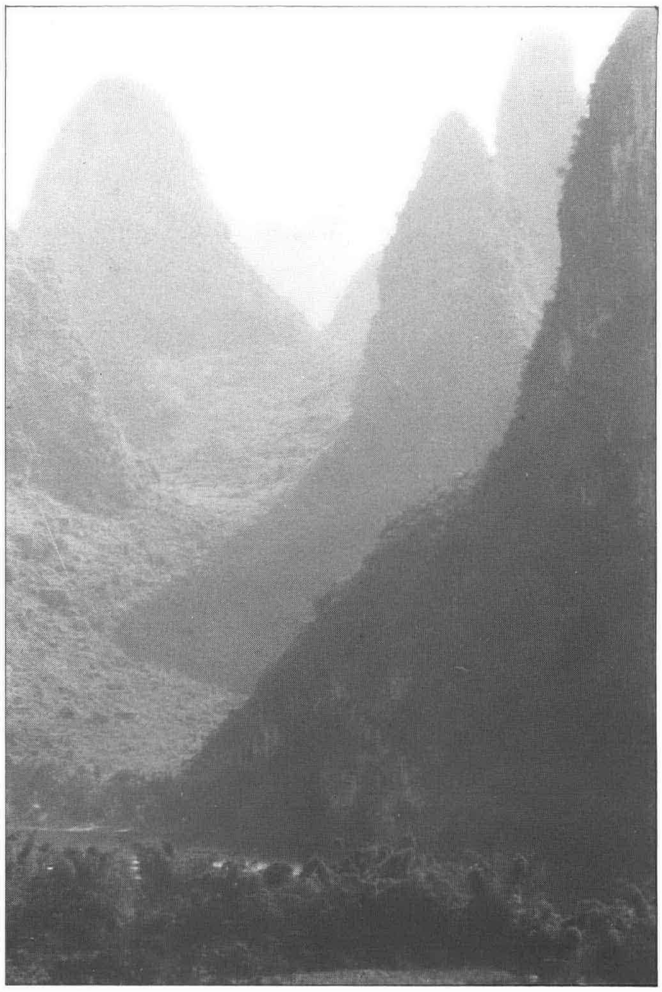
respectively. There is obviously a gradation between some types of Fenglin and Fengcong. A loose working distinction is that in Fengcong the closed depressions within the peak clusters are less than one third of the depth of the depressions or low ground between the clusters as measured from the depression rims (Fig.2 F).

Closed hollows are classified in Chinese usage into four types. Dolines or Funnels are small hollows up to a few tens of metres across. The larger hollows are categorised on the basis of the relationship between the floor of the hollow and groundwater saturation level. Depressions are hollows larger than dolines whose floors are always above saturation level (although some depressions may experience short periods of flooding due to impeded drainage). They may be up to several hundred metres across. Basins are larger hollows, sometimes irregular in plan with flat floors which flood occasionally or seasonally. In some respects basins resemble the European polje but the two terms should not be used synonymously. Karst Valleys are elongated hollows often several kilometres long whose floors may carry seasonal streams (i.e. they are within the zone of water table fluctuation). Karst Plains are extensive flat-floored areas crossed and drained by perennial streams.

It is important to realise that these terms are descriptive not genetic. They describe the shape of a landform and not its supposed origin.

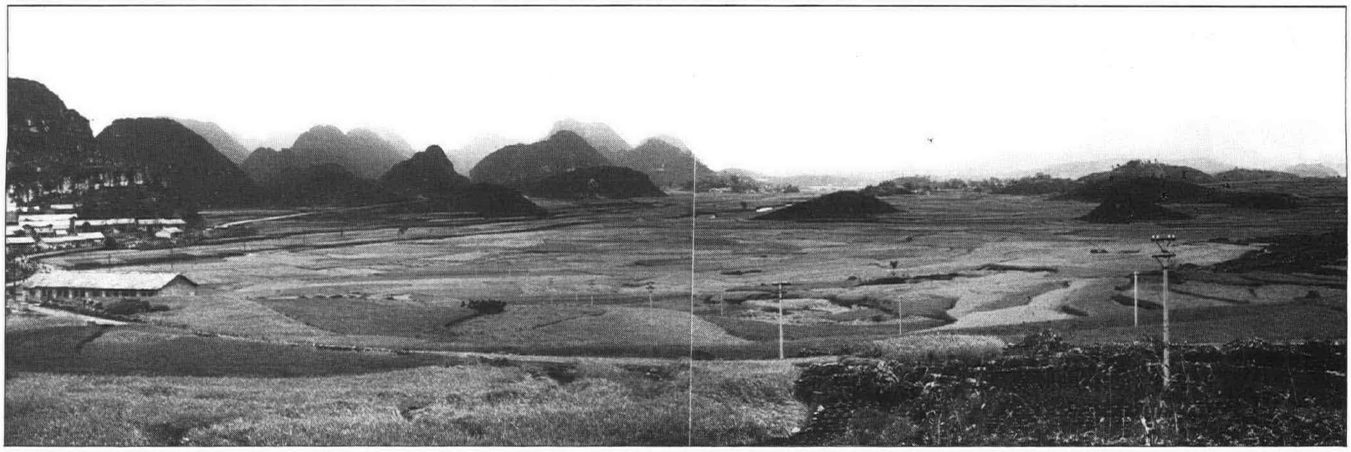
In classifying the karst style of whole landscapes or areas within them, Chinese geomorphologists use a combination of terms to describe the positive and negative elements of the landscape. The upland plateaus punctured by large and small dolines and uvalas which are so characteristic of much European karst would be described as Funnel and Depression landscapes. Combinations of Fenglin or Fengcong with depressions basins or valleys are indicated as Fenglin-depression, Fengcong-depression, Fenglin-basin etc. Where there are fluvial valleys originating within the karst, terms such as Fengcong-valley might be used to describe them. Many trunk river valleys in the Guizhou Plateau region have cut deep, precipitously-sided gorges or canyons. Where karst cones or towers have developed on their rims and sides the landscape is known as Fengcong-canyon (Fig.2 G).

In common with most Western geomorphologists, their Chinese colleagues believe that a freshly uplifted limestone area in which base level was subsequently stable would evolve along the following lines. Initially there might be fluvial development of valleys, especially if cover rocks were present. As the cover was stripped off and solution increased the permeability of the limestone, drainage would be diverted underground and Funnels would develop. Deepening and enlargement of some funnels at the expense of others would form depressions. The landscape would then consist of predominantly negative elements - closed hollows of different sizes and with the bases at various elevations, but all



Fengcong at Yangti, Guangxi. The Li River is visible at the foot of the cluster of peaks.

Fenglin towers rising from the level floor of a corridor valley, near Nantan, Guangxi.



Karst basin, Zhenning County, near Anshun, Guizhou. The left wall of the basin is a ridge of Fenglin cones in massive limestones whereas the right edge is more subdued karst topography on shaley limestones. The dip of the strata is c.10° from right to left. A river crosses the basin floor between the houses at left and the small residual cones in the middle ground.

above the water table. This is the Funnel-Depression stage illustrated schematically in Fig.3 A. As the depressions enlarge with time, so they will coalesce, modifying any remaining areas of original plateau surface between them into karst hills. If all the depressions are of roughly equal size and spacing, a cone karst type of Fenglin may result (such a karst style is seen in the Gunung Sewu region of Java: Lehmann, 1936; Waltham et al., 1983; Balazs, 1968). More often, however, the deeper depressions grow along major linear structural weaknesses such as faults and major fractures. Where this happens a Fengcong-depression landscape results, as illustrated in Fig.3 B, because the deeper the depressions eventually coalesce and isolate peak clusters containing smaller depressions and dolines between them.

Continuing downward erosion of the depression floors by solution eventually encounters the water table. Corrosion is then concentrated at the bases of the Fencong clusters. The walls of the Fengcong are steepened and the depressions broaden into basins. At this stage the landscape will consist of basins with ridges of Fengcong between them. Continued deepening of the depressions within the Fengcong clusters eventually reaches the water table also, and the Fengcong become broken up into closely spaced Fenglin towers. This stage of landscape development is known as the Fenglin-basin stage (Fig.3 C). The floors of basins are at or very close to the water table, and groundwater-fed streams frequently meander across them. Lateral corrosion at the edges of the basins eventually leads to the coalescence of neighbouring basins and the formation of a plain from which isolated and often spectacular Fenglin and/or major Fencong towers rise.

In south China, this sequence of development has been interrupted by rejuvenation due to marked uplift during the Quaternary. Major rivers have cut canyons into the uplifted karstified plateaux. Near the canyons, the water table has been drawn down and valley incision and/or fresh depression development occurred in the floors of former karst basins. Fenglin-basin areas have reverted to Fengcong-valley or Fengcong-depression styles as these new valleys and depressions have formed. Entirely new Fencong have developed on the upper walls of the deepest canyon valleys. These changes are well-displayed in the South Dushan area and are described later in this paper.

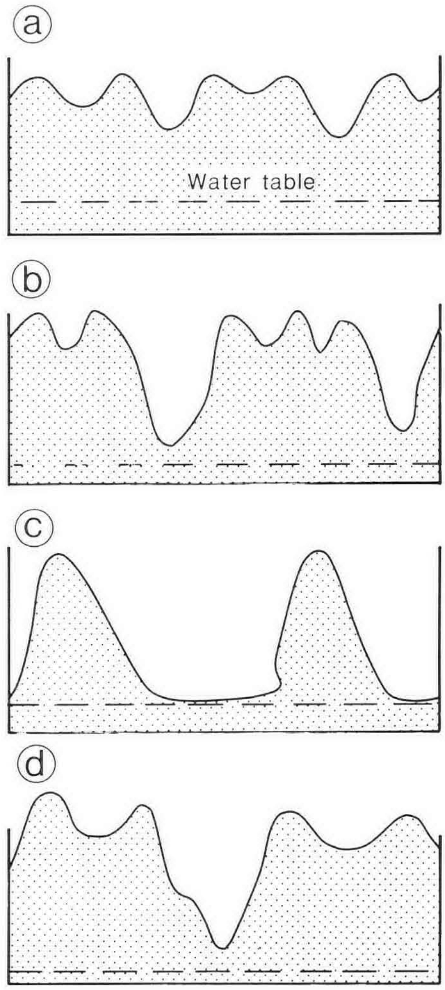


Fig.3 Diagramatic sections to show four stages of karst geomorphic evolution in South Dushan.

A. Funnel and depression stage
B. Fengcong-depression stage
C. Fenglin-basin stage
D. Rejuvenated Fengcong-depression, Fengcong-valley or Fengcong-canyon stage.

SURFACE GEOMORPHOLOGY OF SOUTH DUSHAN

Regional Geomorphic Setting

South China has experienced strong differential uplift during the late Tertiary and Quaternary, in response to the rising of the Himalayan mountain chain and the Xizang (Tibet) Plateau to the west and northwest. Uplift was least in the basin area of Guangxi, but much greater in the area to the north which is now the Guizhou Plateau. Thus, both regions have experienced some rejuvenation due to a relative fall in base level. In Guizhou, where the uplift was c.1000 m or more, rejuvenation has taken the form of downcutting by rivers to form canyons which partially dissect the karst plateau. In Guangxi, karstic erosion was apparently more

System	Formations (and symbol used in Figures)	Lithology	Texture	Chemical composition (%) CaO	MgO	CaO/MgO	R_2O_3	SiO_2	Degree of Solubility
Triassic	Falang Group (T_2f)	Limestone	Cryptocrystalline	52.01	0.54	96.31	0.77	1.99	middle
	Guanling Group (T_2g)	Limestone-dolomite	Cryptocrystalline fine grain texture	40.86	11.04	3.70	1.25	3.4	strong
Permian	Wujaping Group (P_2w)	Chert-limestone	Cryptocrystalline	45.59	0.51	89.93	0.27	13.54	middle
	Maukou Group (P_1m)	Limestone	Cryptocrystalline	55.04	0.39	141.12	0.09	0.31	strong
	Qixia Group (P_1q)	Limestone	Bioclastic	53.40	0.67	79.70	0.54	1.39	strong
Carboniferous	Maping Group (C_3mp)	Limestone	Bioclastic	55.34	0.29	190.83	0.30	0.99	strong
	Huanglong Group (C_2hn)	Limestone	Bioclastic	43.56	7.90	5.51	1.45	4.23	strong
	Shangsi Group (C_1d^2)	Limestone	Bioclastic	47.48	2.67	17.78	3.22	4.4	strong
	Yanguan Group (C_1y)	Limestone	Bioclastic	48.34	1.01	47.86	3.68	7.14	middle
Devonian	Yaosuo Group (D_3y)	Dolomite	Fine grained	34.95	14.89	2.34	1.25	2.77	middle
	Wangcheng Po Group (D_3w)	Dolomitic-limestone	Bioclastic	43.81	7.74	5.66	2.39	2.96	middle
	Dushan Group (D_2d)	Dolomitic-limestone	Bioclastic	38.09	10.67	3.56	2.65	6.30	middle

Table 1 Chemical composition and degree of solubility of carbonate rocks in South Dushan

nearly able to keep pace with uplift and so the karst forms, including the spectacular tower karst and plains between them, are preserved in a more or less active state of equilibrium.

South Dushan lies in the area between these two regions. Late Cenozoic uplift was greatest in the north of the area where the highest ground occurs. The study area itself lies between the canyon-like valleys of two consequent river systems flowing from north to south. Thus, it consists of rejuvenated canyons and the plateau area between them. In the west the study area is bounded by the Niu-he river, a tributary of the Hongshui-he, and in the east by the Daguo-he, one of the headwaters of the Longjiang river (Figs.1 and 4). All the subterranean drainage systems of the area are directed towards the canyons of these two rivers and run from the central part of the area towards the east (to Daguo-he) and the west (to Niu-he). The Jiaqiao, Yaohua, Bawan and Huanghe underground systems drain to the Daguo-he and the Magan, Yuzhai and Lalou systems feed the Niu-he (Fig.4).

There is a systematic arrangement of karst landforms, with the following sequence from drainage divide to canyon areas (see Figs.2, 3 and 4): Fenglin-basin landscape, mixed zone of Fenglin-basin and Fengcong-depressions, Fengcong-depression zone, and Fengcong-canyon zone. Exceptionally large depressions and linear, trough-like karst valleys occur in all of the first three zones. Dolines and larger funnel-shaped depressions occur mostly within the Fengcong zones.

Lithology and Geological Structure

Upper Devonian to Lower Triassic carbonate rocks cover most of South Dushan (Fig.4). Their total thickness is 3000 m and they were deposited in marine and neritic environments. The formation names, chemical compositions and textures of the various carbonate rocks are shown in Table 1. The $CaCo_3$ contents of the Huanglong, Maping, Qixia and Maokou limestones are the highest, and these are also the main formations for development of karst and subsurface drainage systems.

Type of aquifer	Geological formations included in each aquifer	Relative yield of aquifer	Hydrogeological Indices: discharge of springs (l/s)	groundwater flow coefficient (l/s km^2)	discharge of boreholes (m^3/d)	Subsurface stream: Total length km	density km/m^2
carbonate fissure-cavernous aquifer	D_3y	good	70-150	4.58		43.3	418
	$C_1d^2+C_2hn+C_3mp$	good	70-200	5.36-6.38	49	551.8	252.2
	$P_1q+P_1m+P_2$(yueli)	good	50-230	5.8	336	124.5	192.8
	$T_1^1dy + T_2g$	good	10			9	85.7
carbonate cavernous-fissure aquifer	$D_2d^{2-2}+D_3w+D_3y$ (Dushan, Jizhang)	good	35-70	2.33	970-2750	26.5	56
	D_3w+D_3y (Hezhai, Zhouqin)	moderate	10-50	3.49	52		
fissure cavernous aquifer of carbonate interbedded with sandstone and shale	$D_2d + D_2l$	moderate	5-30	3.06		14.2	26
	$C_1^2y + C_1^2d$	moderate	10-20			6	20
	P_2^1 (Pingtan and Lipo)	good	60-200	5.81		35	67.5
	T_2^2f	good	10-30	2.03		9	53.5
cavernous fissure aquifer of carbonate with sandstone and shale	O_1g	poor	0.6-1.5	0.1-1.2			
	€	poor	0.3-10	0.11-1			
	T_1	poor	0.2-8				
	E^1	poor	0.1-10				

Table 2 Characteristic values of carbonate aquifers in Dushan region,south Guizhou

Nie Yaoping (1984) has carried out dissolution experiments comparing different carbonate rocks with a standard marble. The results show that relative solubility in general decreases as MgO content increases. However, this is not the only control on dissolution since the solubilities of rocks with the same CaO/MgO ratio may differ greatly from each other. Apart from textural differences, the principal control is whether or not MgO occurs in the form of magnesian calcite or dolomite ($CaMg(CO_3)2$). Under normal conditions, $MgCO_3$ has a greater solubility in water than $CaCO_3$, and the solubility of dolomite is the lowest. Therefore carbonate rocks containing a high content of magnesite or high magnesian calcite will dissolve more quickly than those containing the same amount of MgO in form of dolomite. It is very important to determine the mineral form and concentration of $MgCO_3$ rather than simply expressing it as MgO, in order to estimate the effect of lithology on karst solution.

In the study area the most mature Fenglin-basin karst topography, with deep ponds, lakes and subsurface passages is mainly developed in the Middle Carboniferous Huanglong Formation which consists of limestone inter-bedded with several dolomite layers and crops out in the central part of the Dushan anticline. Table 2 gives typical values for various hydrological parameters which provide an indication of the degree of karstification of groundwater flow. Groundwater flow coefficients and subsurface stream densities are highest in the Permo-Carboniferous rocks.

South Dushan is situated in a zone of complex intersection between a north-south tectonic belt, an east-west tectonic belt and the Neocathaysian tectonic belt. Folds, faults and fracture systems are very well developed. Figure 4 shows the main outcrops of carbonate and non-carbonate rocks in the area, plus major faults. The major tectonic structures are described below with reference to this figure. The main north-south structure is the Dushan anticline. This is a box-fold whose axis runs from Shangsi to Dayuhe. To the east of the axis, there is a broad outcrop of limestone dipping gently eastwards, around fengdong, Yaoai and Yaobang. Further east, in the region of Jiaqiao and Baiyan, the dip steepens, giving rise to the narrow, north-south outcrops of sandstone and limestone there. The west limb of the anticline is broken up by a system of north-south faults parallel to the main fold axis, around Lawan, Magan and Xiasi, but again the dips are gentlest near the axis and steepen to the west. The Dushan anticline is truncated in the south, from Dayuhe to Yaohua, by a belt of strong east-west faulting and an important synclinal fold with its axis passing east-west through Bawan. Both the faults and the east-west strike of the folds in this area exert an important influence on the underground drainage.

The dip has an important influence on the development of karstic groundwater flow. Where the dip is gentle the thick, pure carbonate formations are exposed over a wide area and underground drainage systems are well-developed. Where the dip is steeper, interbeds of shale or sandstone from barriers to the regional groundwater flow, which is towards the east and west. Here subsurface drainage systems develop only on a small scale and with a simple pattern.

In the southern half of the Dushan anticline, the 250-400 m thick Huanlong Formation crops out over about 170 km² and dips at 10-20°. Fenglin cones and flat-floored basins are developed very well on the limestone parts of the Formation. The height of the Fenglin hills varies in the range 10-100 m, whereas the diameters are about 100-200 m. Several levels of caves are developed in the karst hills and in residual hills within basins. The karst basins are characterised by flat floors and large area. For example, the Xiasi basin is about 6 km long, 0.5-1.5 km wide and has an area of 8 km². There are many deep karst ponds and blue holes, such as the Datuan hole near Yaopang, which is 55 m deep. Negative topographic features occupy 35% of the total area. Because both north-south faults and sets of conjugate

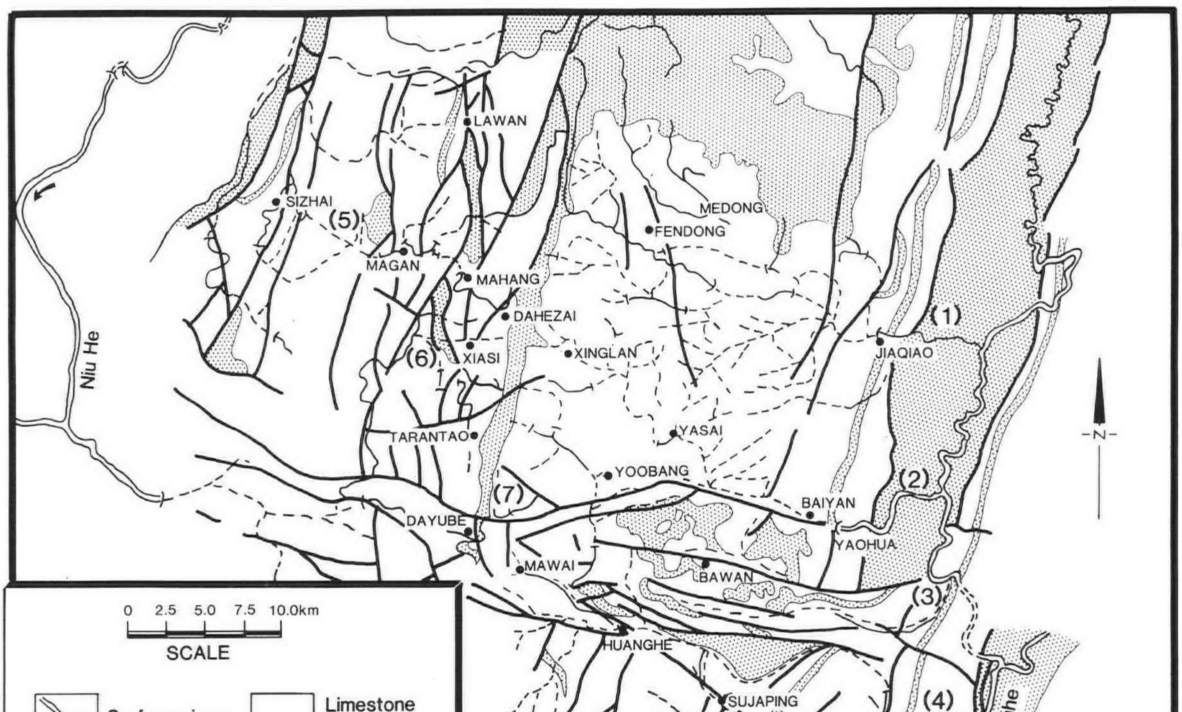
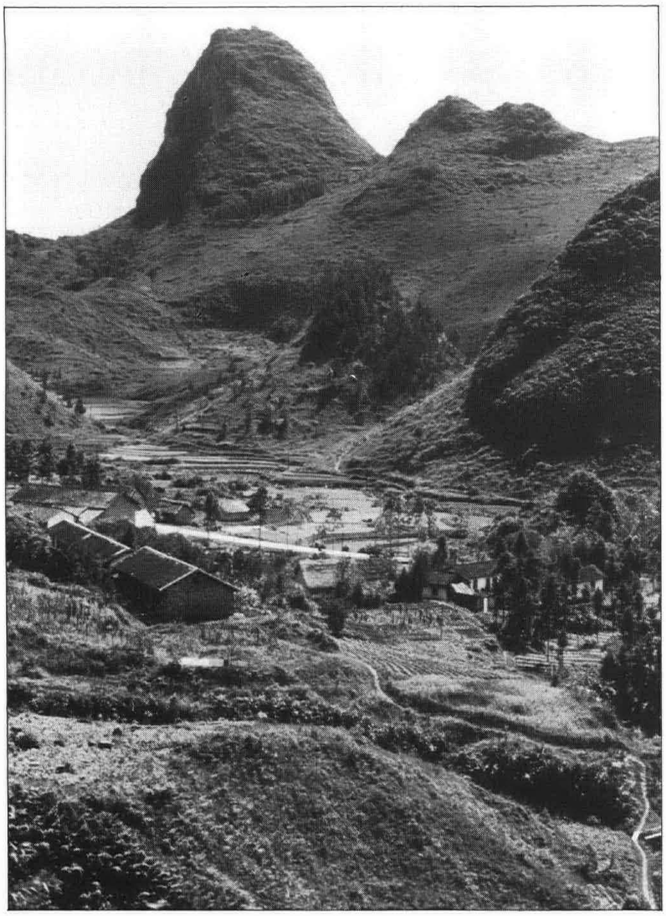


Fig 4. Subsurface drainage systems in South Dushan.



Headwaters of a spring-fed valley in Fengcong area, near Siting, South Dushan, Guizhou. Valleys of this type are the tributaries of the deep canyons which dissect the Guizhou Plateau.

northeast-southwest and northwest-southeast fractures are well developed in the gently dipping limestones of the Dushan anticline, the underground drainage systems have been able to exploit them to form a markedly dendritic and networked pattern.

In the tightly folded Bawan syncline (which is aligned east-west through Bawan, Fig.4), the soluble Qixia and Maokou limestones (P1) are surrounded by the Liangshan sandstone and shale, and only a single conduit has developed along the fold axis in the Bawan subterranean drainage system, which has a catchment area of 62.5 km^2.

The locations of the main conduits in the underground drainage systems are controlled by fracture systems and faults. Conduits or caverns are always associated with fractures, especially large-scale and deep faults. For example, the Mawei tributary of the Huanghe drainage system and the main channel of the Yaohua system (Fig.4) are developed along the Mawei and Yaohua Faults respectively. (These faults are not named on Fig.4. They trend east from Mawei and west from Yaohua respectively). The upper reaches of the Jiaqiao underground drainage system are strongly influenced by conjugate fractures, giving rise to a multi-branched, dendritic drainage network (Fig.4).

Geomorphology and Neotectonics

Geomorphology controls the development of underground drainage systems by determining the base level of resurgences. The regional geomorphic characteristic of South Dushan is the slope between the Guizhou Plateau and Guangxi basin which determines the north-south direction of the principal rivers. The Niu-he and Daguo-he both flow from the plateau to the basin. As noted in section 3.1 above, the major surface landforms in South Dushan show a zonation from Fenglin-basin topography near the interfluve, through a mixed zone of Fenglin-basin and Fencong-depression topography, to purely Fencong-depression and Fencong-valley landscapes in a zone bordering the major rivers. The river valleys themselves are of Fencong-canyon type.

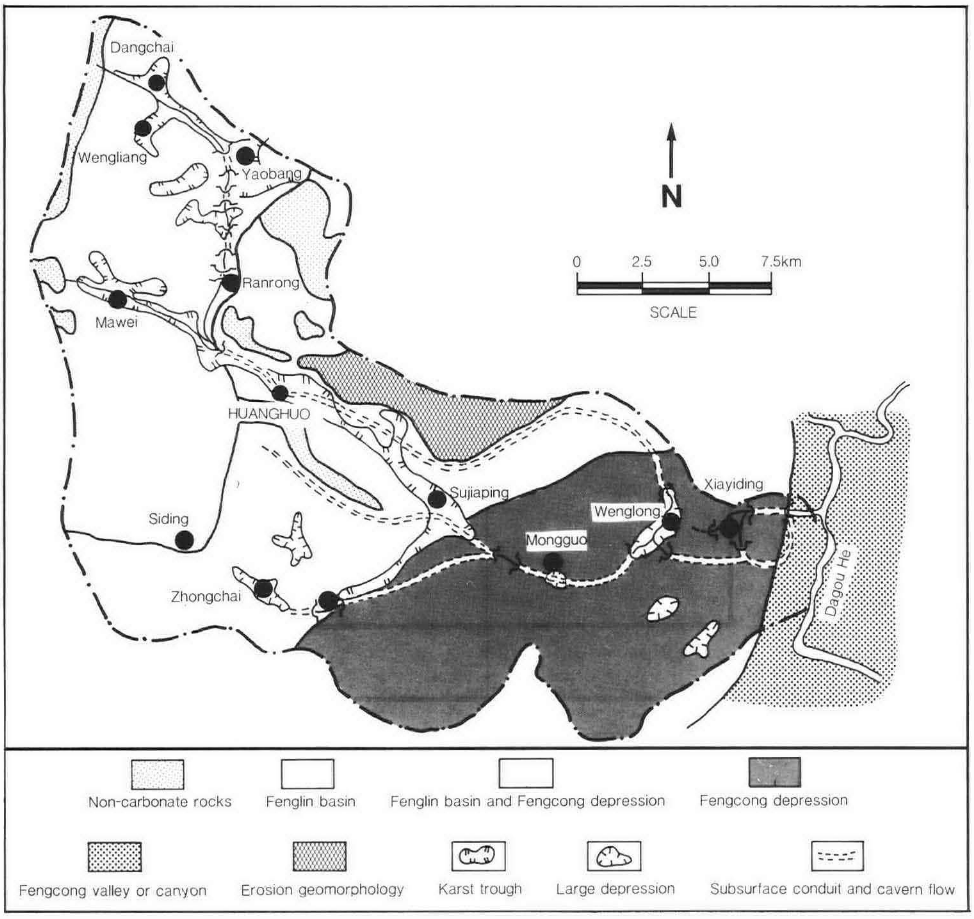


Fig. 5 Map of the main karst geomorphological zones in the catchment area of the Huanghe underground drainage system.

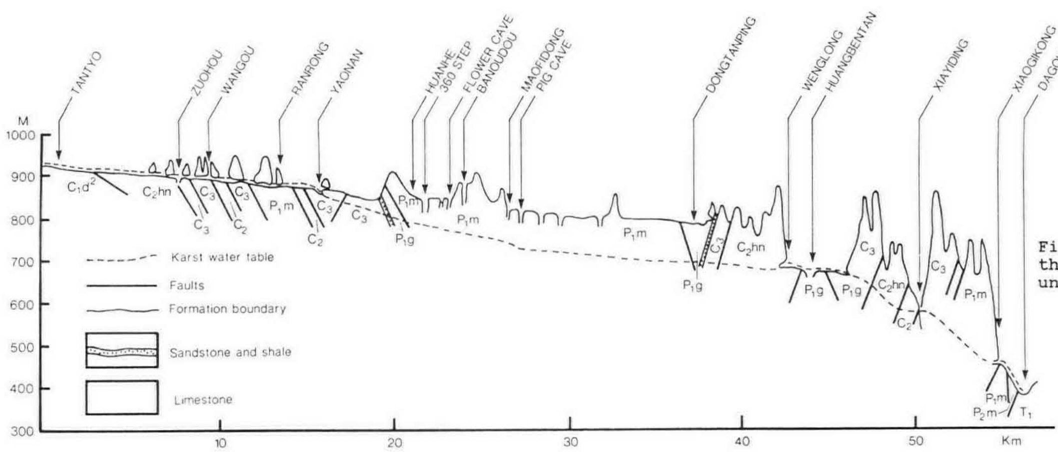


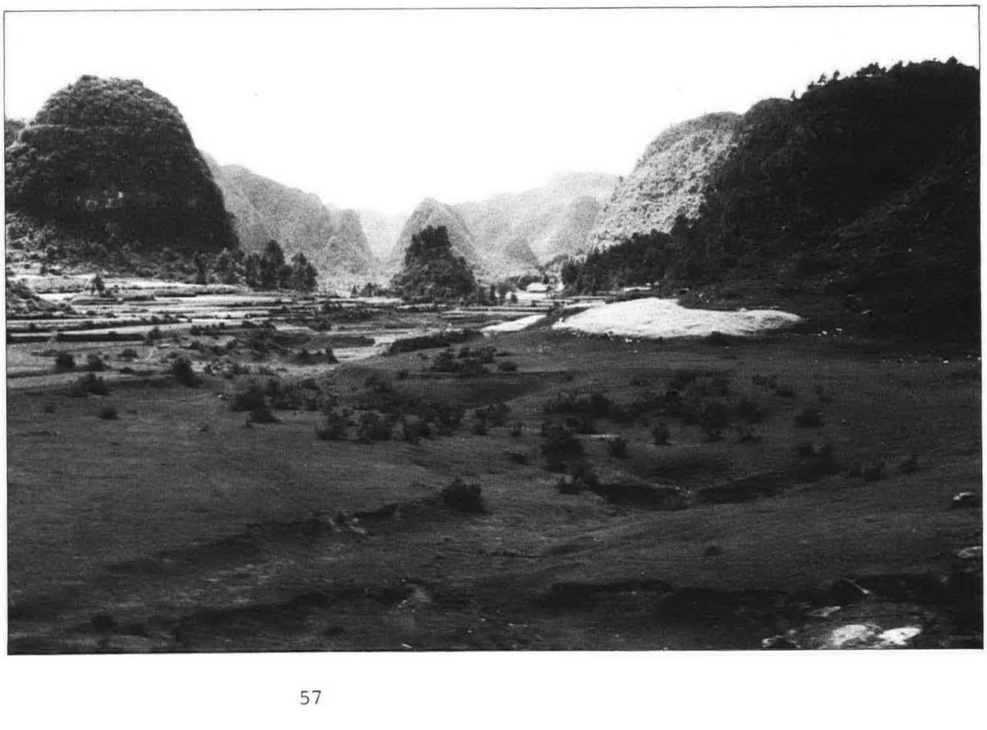
Fig. 6 Longitudinal profile of the main trunk of the Huanghe underground drainage system.

This geographic sequence of landforms is due to the geomorphic and neotectonic history of the region. The normal sequence of karst development under a humid tropical climate would be (a) funnels and dolines in the newly exposed limestone surface; (b) deepening and coalescing of funnels to form large, deep depressions - the funnel-depression stage in Fig.3; (c) coalescing of the deeper depressions to isolate clusters of rock hills in the Fencong-depression stage; (d) when the depression floors have eroded to the water table, they grow laterally instead of vertically, coalescing into basins. The peaks become isolated Fenglin towers, and a Fenglin-basin landscape results.

From this hypothetical sequence of development we would expect the parts of the landscape which are nearest to base level to reach the Fenglin-basin stage first, because the water table is shallowest there. So in a mature karst area, such as South Dushan, the Fenglin-basins should be in the lowest parts, with Fencong-depression or even funnel-depression types near the interfluves. The exact opposite is in fact observed! The key to this paradox lies in the neotectonic uplift of the area during the Quaternary period, during which the Guizhou Plateau just north of South Dushan was raised by 500-1000 m at least. As a result, vigorous headward erosion and downcutting by rivers formed deep canyons. In our area, the Dagou-he canyon is over 200 m deep. These canyons are the youngest features in the present day landscape, and they have not yet fully dissected the plateau. The interfluve areas, on the other hand, are composed of a pre-Quaternary karst landscape which had already reached the Fenglin-basin stage before neotectonic uplift raised it to its present elevation. On the margins of the canyons, and in their tributary valleys, underground hydraulic gradients were steepened by downcutting, new generations of dolines and depressions were formed, and the karst landforms were rejuvenated to forms a Fengcong-depression landscape. Completely fresh Fengcong developed on the canyon walls and rock-cut terraces formed as a result of pauses in uplift and downcutting. These give rise to the Fengcong-canyon landscape visible today.

This geomorphic history has had a profound influence on the character of the underground drainage network. In the plateau Fenglin-basin landscape (i.e. the upper reaches of the underground drainage systems) the water table is always shallow, a few metres below the basin floors, hydraulic gradients are low and karst conduits are large and mostly beneath the water table (Fig.6). Solutional development of fissures in the rock between conduits has formed a rather homogenous karst-fissure aquifer. In the Fengcong-depression region, the groundwater flow is much more concentrated into conduits, and hydraulic gradients are much steeper. The water table is deeper below the surface (50-100 m).

The size of the groundwater conduits is broadly related to the altitude of depression floors. The deeper the depression, and the lower the altitude of its floor, the larger the conduit beneath it. This principle has been used as a guideline in hydrogeological mapping of underground river systems which cannot be directly explored. It is assumed that trunk conduits tend to follow the lines joining the deepest and lowest



Karst rejuvenation in response to uplift and downcutting by canyons. The water table has been lowered beneath this basin floor and small dolines and blind valleys have formed (foreground and middle distance). Zone of mixed Fenglin and Fengcong, near Yaopang, South Dushan Guizhou.

depression floors. (Notwithstanding this, some of the depressions at lower altitude in South Dushan are shallower and less well developed than those at higher altitude: this is attributed to the effects of rejuvenation).

Successive pulses of uplift and consequent headward erosion of fluvial canyons into the plateau have created prominent knick-point waterfalls and rapids in surface streams. In the same way, knick-points occur in some underground drainage systems and appear to be migrating headwards from the system outlets. Underground drainage systems generally have a convex-upward longitudinal profile as a result (Fig.6).

Another effect of uplift has been to allow abandonment of old phreatic caves which are now preserved as remnants in the karst hills. Multiple levels of phreatic tubes can often be distinguished. For instance in the area around Shandao Fairy Cave there are four levels : the presently active water conduit near the basin surface ; Fairy Cavern (Shenxiandong) at 65 m above the basin surface ; Through Cave at 168 m ; and Fort Cave at 205-220 m. Likewise in the Yaobang area there are four levels of caves developed : within 5 m of the ground surface between the residual hills 30 m above the ground surface (e.g. Dadong Cave, Yaobang) ; 110 m (e.g. Xiafengdong Cave) and 160 m (e.g. Wandong Cave, Shangtou).

SUBTERRANEAN DRAINAGE SYSTEMS

There are seven subterranean drainage systems developed in South Dushan (Fig. 4). Each will be described briefly in turn.

Jiaqiao Drainage System

The Jiaqiao system (Figs. 4 and 7) originates near Shangsi and flows into the Deouda-he (a tributary of the Dagou-he) near Jiaqiao. It is about 40 km long and has a drainage area of 350 km². In the dry season the discharge of the resurgence is 0.67 m³/s. The system is mainly developed in the carboniferous limestones which dip at 5-10° on the eastern limb of the Dushan anticline. Northeast-southwest and southeast-northwest trending joints sets have an important influence on the dendritic network of tributaries to the underground river in this area.

The system can be divided into two sections. In the northern part of the catchment, surface and subsurface sections alternate along the tributaries. In contrast, in the south region, all the water channels are underground. The active conduit system gets deeper from north to south. For example, the Yangzhai branch is about 4-10 m below the ground surface, Dongda branch 10-15 m, Jianzhai branch 30-40 m. The longitudinal gradient of the system is the smallest in South Dushan averaging 0.25%.

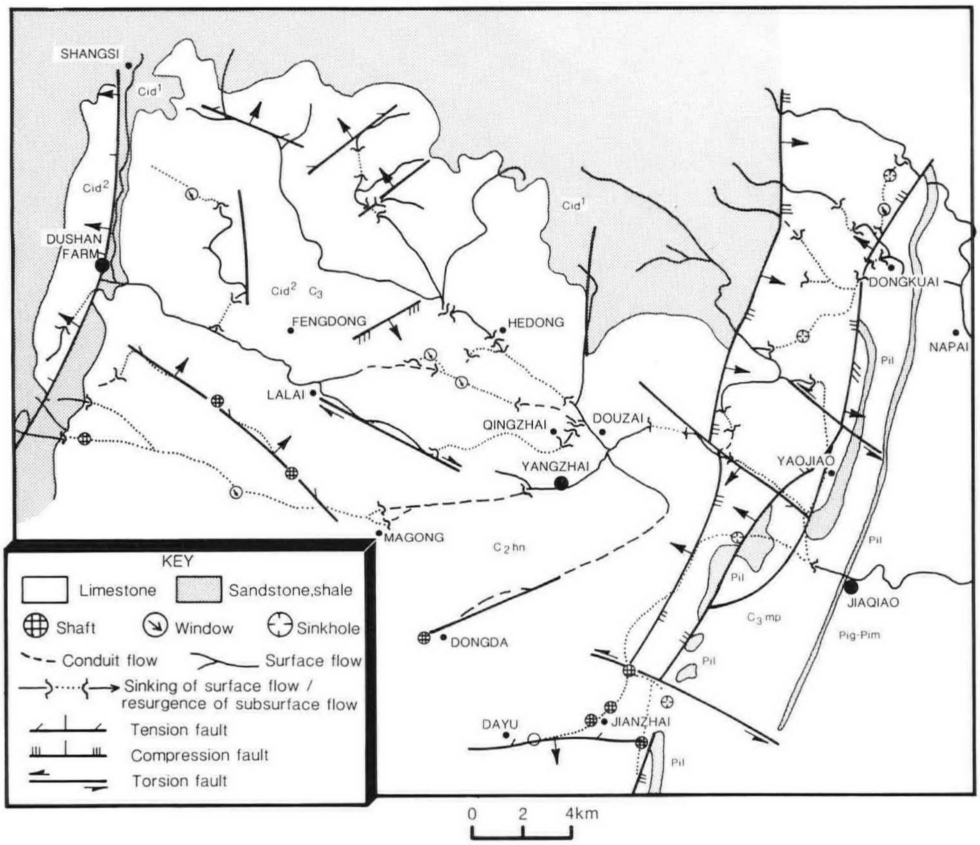
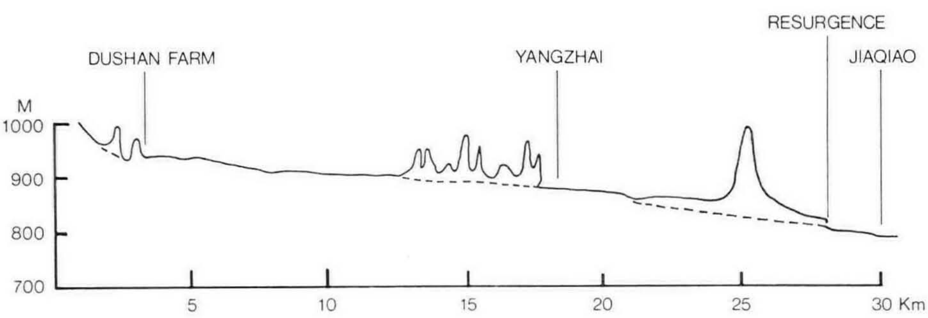


Fig. 7 The Jiaqiao underground drainage system.



Longitudinal profile.

Yaohua Drainage System

The Yaohua drainage system (Fig.8) lies to the south of the Jiaqiao system and is also developed in the Carboniferous limestones, especially in the Huanglong Formation, dipping at 5-10° east. The upper and middle reaches are influenced by shear-fractures aligned towards the southeast. The water of the lower reaches flows eastwards following compressional fractures and resurges at the contact between the Maping limestone (C3mp on Fig.7) and the Liangshan sandy shale, forming the Yaohua surface river. The altitude of the system head is 920 m a.s.l. and of the resurgence 830 m a.s.l.. The main course of the system is 39 km long with a mean gradient of 0.3% and a catchment area of 194 km². The dry season discharge is 0.8 m³/s. In the middle part of the system there are many deep karst ponds with water volumes of several tens to several hundreds of thousands of cubic metres and depths of 30-55 m (e.g. Datuan and Jatuan ponds). The hydraulic gradient of the longitudinal profile of the system is uneven and knick points obviously exist in the main passages (Table 3). Dendritic and trellised underground drainage is developed in the upper reaches of the Yaohua system as a result of control by northeast and northwest conjugate fracture sets. The lower part of the system consists of a single conduit parallel to a compressional fault which forms a barrier to groundwater flow. Water tracing experiments by local people suggest that the flow velocity in the middle reaches is 12 metres per hour.

Drainage system	Section	Distance (km)	Difference between upstream and downstream water levels	Gradient (o/oo)	Knick point
Yaohua drainage system	Naishie-Baya	4.6	10	2.1	
	Baya-Jiangji	3.9	17	4.3	
	Jiangji-Jiatan	7.5	9	1.02	
	Jiatan-Hegan	2.5	24	9.8	✓
	Hegan-Baiyan	6.5	12	1.8	
	Baiyan-Yaohua	3.5	35	10.0	✓
	Yaohua-Deoudahe	2.5	3	1.2	
Huanghe drainage system	Wangou-Yaonan	12	40	3.3	
	Yaonan-360 steps	4	62	15.5	✓
	360 steps-Flower Cave	1.8	10.6	5.9	
	Flower Cave-Banoudou	0.75	4.3	5.73	
	Banouduo-Maoqidong	2.18	28.6	13.5	
	Maoqidong-Pig Cave	0.4	9.5	23.75	✓
	Pig Cave-Wenglong resurgence	16	38	2.3	
	Wenglong resurgence-Wenglong	1.1	15	14	
	Wenglong-Huangbantang	1.5	4	2.67	
	Huangbantang-Xiayiding	4.4	58	13.2	
	Xiayiding-Xiaoqikong	4.4	234	53	✓

Table 3 Longitudinal gradient of Yaohua and Huanghe drainage systems in dry seasons

Bawan Drainage System

The Bawan drainage system (Fig.4) has its head near Yaomou. It is about 19 km long with a 62.5 km² collecting area. The resurgence flows at 0.24 m³/s in the dry season, the dry season runoff coefficient being about 3.9 l/s/km². The system is constrained to follow the Bawan syncline and consists of a single main conduit developed in the Qixia limestone along the Bawan fault.

Huanghe Drainage System

The Huanghe drainage system (Figs. 5, 6 and 9) originates in the Tantou basin near Xiasi and flows through Wangou, Ranrong, Yaonan, Huanghe, Wenglong and into the Dagou-he river near Xiaoqikong. It consists of the Wangou main course and nineteen tributaries such as the Mawei branch, Siting branch and Sujaping tributary. With a trunk course of 57 km and a catchment of 460 km², the system is the biggest in South Dushan and also one of the largest in the Guizhou Plateau.

The bedrock formations in the Huanghe area are the Lower Carboniferous Datan Limestone, the Huanglong Limestone (including several beds of dolomite), the Upper Carboniferous Maping Limestone, Lower Permian Qixia bituminous limestone and chert, and the Maokou cherty limestone. Above the Maokou limestone is the Upper Permian Wujaping Formation (coal, sandy shale with some silty limestone) and the Zhangxing Formation, a Lower Triassic silty limestone with shale. The total thickness of carbonate formations is about 2500 m.

The upper reaches of the Huanghe drainage

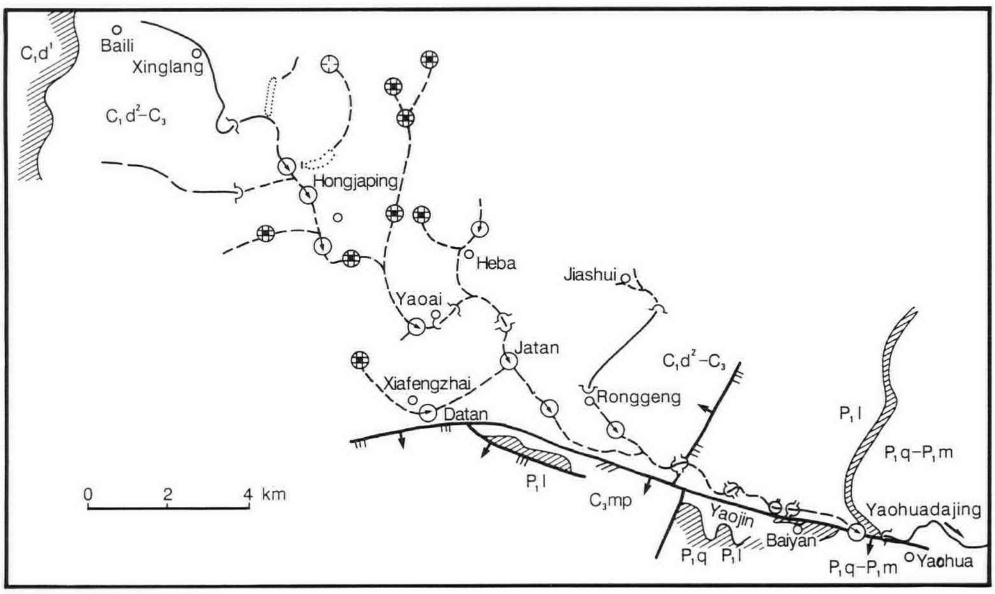
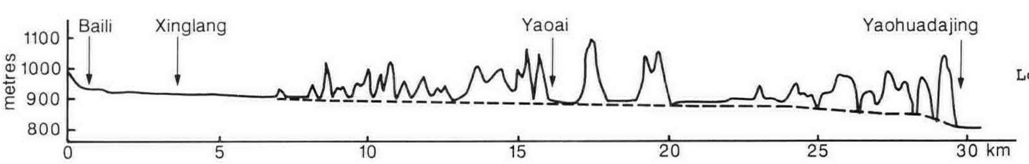


Fig.8 The Yaohua underground drainage system.



Longitudinal profile.

system are controlled by northwest- and northeast-trending fracture sets, while the middle reaches are affected by the large Huanghe Fault and the contacts between the Wujaping coal shales and the Permian limestones. The lower reaches are developed across the Wenglong Syncline, Xiayiding Anticline and Dagouhe Syncline.

Within the Huanghe drainage area the zonation of the karst landscape is well developed, with zones of Fenglin-basin, combined Fenglin-basin and Fencong-depression, Fencong-depression and Fencong canyon topography appearing in order from west to east (Fig.5). The underground drainage features are greatly controlled by the karst geomorphology. The upper reaches of the system are once again characterised by a shallow water table generally less than 10 m below the ground surface, many deep karst ponds such as the Wangou, Zouhou and Ranrong ponds, and an alternation of surface with subsurface drainage. The ratio between the length of surface with subsurface channels is 3.2 (surface/subsurface), and the average hydraulic gradient is 0.3%. Annual fluctuations of the water table are just a few metres.

In the middle reaches, the drainage is 100% underground. The groundwater velocity determined by fluorescent dye and Lycopodium tracing ranges up to 0.6-0.8 m/s. The highest value was found between 360 Step Window and Pig Cave (see Fig.5). The depth of the water table is 60-90 m or more below the ground surface in the dry season. The annual fluctuation between dry and rainy seasons is 60-100 m, with large variations following storms when water overflows out of the groundwater conduits and resurges from karst windows and caves. The hydraulic gradient is rather steeper than in the upper reaches (Figs.6 and Table 3).

In the lower reaches, because of the presence of more steeply-dipping beds with non-carbonates, surface streams appear, such as the Wenglong-he and Xiaoqigong streams. Both the surface and subsurface streams have high hydraulic gradients, up to 5% and have excavated canyons.

The discharge of the Huanghe system is 1.55 m^3/s in the dry season and up to 170 m^3/s in the rainy season. Thus, the annual discharge variability approaches 110 while the dry season runoff coefficient is 3.37 $l/s/km^2$.

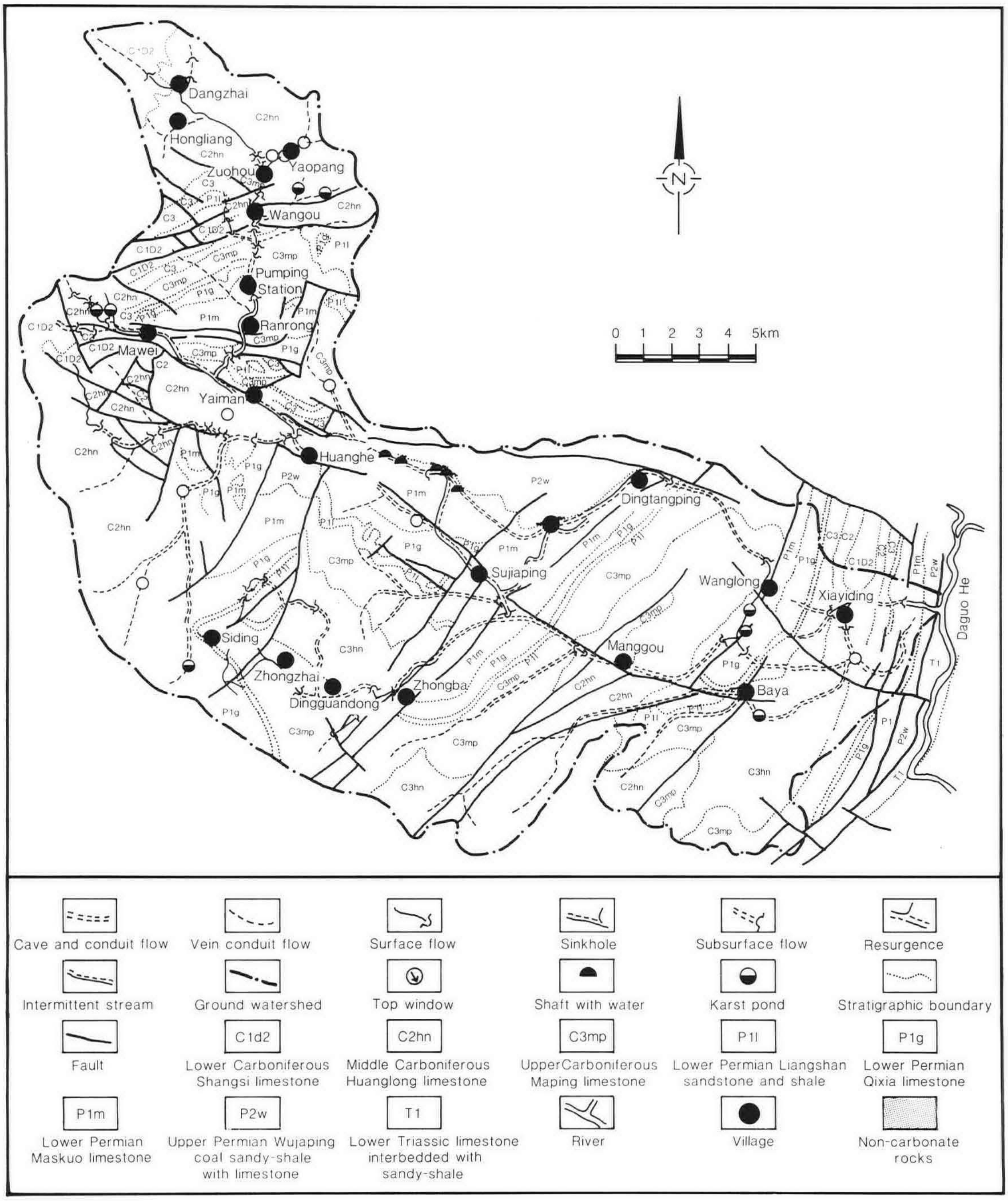


Fig.9 The Huanghe underground drainage system. (For longitudinal section see Fig.6)

Fenglin-basin topography, between Mawei and Siting, South Dushan, Guizhou. The sluggish stream in the foreground is fed by springs in the basin floor.

Magan Drainage System

The Magan system originates near Dahezhai reservoir and flows west through Mahong, Magan and then into the Sizhai river. It is 22 km long with a 100 km^2 catchment. The dry season runoff coefficient is 4.4 $l/s/km^2$.

The Magan drainage system is predominantly developed in Carboniferous Datan, Huanglong and Maping limestones in the western limb of the Dushan anticline. The longitudinal gradient is rather higher than in other systems. In the upper and middle reaches it averages 0.7%, whereas in the lower reaches it ranges up to 6%. The high gradient is related to steeper dips in the limestones and to deeper downcutting.

Yuzhai Drainage System

The Yuzhai drainage system (Fig.4) heads near Xiasi and Jarantan, then runs eastwards and northwards to Yuzhai, forming a tributary of the Malu-he river (a surface river which in turn sinks to become part of the Naba underground drainage system which is not described in detail in this paper). The main course of the Yuzhai system is about 10 km long and it covers 36 km^2. The annual lowest discharge is about 0.15 m^3/s, the dry season runoff coefficient being approximately 4.0 $l/s/km^2$.

The Yuzhai system is principally developed in the Upper Devonian Yaosou limestone and dolomite and in the Lower Carboniferous limestones. The distribution of the system is controlled by geological structure. Fenglin-basin topography occurs over the whole drainage area, each basin occupying about 7 km^2. The Fenglin hills between basins are generally 50-60 m high and residual hills scattered within basins are 20-25 m high. There are three levels of fossil caves, 5-7 m, 20-25 m and 50-60 m above basin floors. Many karst ponds up to 10 m deep, funnels and sinkholes are broadly distributed in the basins. The gradient of the drainage system is generally low, and sections of the surface streams frequently alternate with underground sections.

Dayuhe Drainage System

This small system is only 4.5 km long and 22 km^2 in catchment area. A surface stream occupies two thirds of its total length. The water table is about 3 m below the surface. Dry season discharge is 0.088 m^3/s and the mean hydraulic gradient is 1.16%. This drainage system is developed along the contact zone of Lower Carboniferous limestones with sandy shale.

SOME CHARACTERISTICS OF THE SUBTERRANEAN DRAINAGE SYSTEMS

Plan Shape

Plan forms of the subterranean drainage systems are affected by the lithology, geological structure, geomorphology, neotectonics, hydrodynamics and other factors. The various plan forms may be roughly divided into dendritic, network, comb and mono-conduit systems.

Dendritic underground drainage systems generally develop in terrain with gently dipping, well-fractured strata. They are chiefly found in the near-axial parts of the Dushan box-anticline. Their characteristics are a high ratio of surface to subsurface course, shallow groundwater table, good hydraulic connections between conduits and karst fissures, and multiple tributaries. The upper reaches of the Huanghe system (Fig.9) and the Magan system are good examples.

Network systems with shallow water table and low hydraulic gradients predominate in the core part of the Dushan anticline where dips are gentle and fractures well-developed and relatively closely spaced. Along these fractures, a network of conduits, fissures and surface streams is formed with good hydraulic connections and interaction between them. A typical pattern is found in the upper reaches of the Yaohua and Jiaqiao systems where a great number of deep karst ponds are developed.

Comb drainage systems commonly develop on one side of thrust faults or on the contact zone of limestones with insoluble rocks. The Huanghe compressive thrust constitutes a barrier to groundwater movement, resulting in the main channel of the Qingshuitan branch of the Huanghe system developing along the hanging wall of the fault. A lot of small conduit flows join the main course, giving a comb appearance in plan view.

Mono-conduit flow may result from dominant control by a single set of fractures, as in the lower part of the Yaohua drainage system. It is also developed when flow is guided along the axis of a syncline as in the Bawan drainage system.

Longitudinal Profiles

There are two kinds of longitudinal profiles among underground drainage systems in South Dushan.

Drainage systems with a low hydraulic gradient (such as the Yaohua and Jiaqiao) are developed mainly in the east limb of the Dushan anticline. This limb is drained by the Deouda-he river, a tributary of the Dagou-he. The Deoudahe is less affected by headward erosion than its trunk stream, the Dagou-he. Thus, downcutting has been much less in the surface valleys into which the underground rivers of Yaohua and Jiaqiao drain. As a result these underground rivers have evolved under very stable base-level conditions and retain all the features of a plateau river with low gradients throughout their courses. The systems feeding the Deouda-he have average gradients of only 0.2-0.3% (Figs.7 B and 8 B).

Strong downcutting in canyons lowers the base level for underground drainage and results in a steepening hydraulic gradient as resurgence levels shift downwards to keep pace with canyon flows. A typical example is the Huanghe drainage system which originates at 920 m a.s.l. and resurges at 386 m a.s.l.. The average gradient is 0.92%, but the maximum is 5.3% in the lower reaches (Fig.6). The longitudinal profile is strongly convex-upward.

Hydraulic Aspects

Hydraulic features of the South Dushan underground systems are determined by the evolution of the karst geomorphology (Song, 1984).

With the evolution of karst geomorphology from funnel-depression through Fengcong-depression to Fenglin-basin stages, the bottoms of depressions and basins gradually approach the karst groundwater level. Corrosion of the limestone is greatest near the surface (Smith and Atkinson, 1976) and expands and interconnects the fissures in the limestone beneath basin floors to form homogenous aquifer made up of a network of fissures. The water table beneath basins is only a few metres below the surface, sometimes as little as 1 m, as in the Zhongzhai basin in the upper reaches of the Huanghe drainage system. Local people have dug numerous wells to reach this shallow ground water. The hydraulic gradient in this basin is 0.45%.

Conduit flow is the main form of underground flow in South Dushan. The conduit systems are most continuous in the middle and lower reaches of the various underground drainage systems.

In Fenglin-basin areas, where there is a homogenous fissure-network aquifer beneath the basin floors, conduit flows always develop in the limestone blocks between adjacent basins, especially where these are on different levels (Song, 1984). The higher the elevation differences of two neighbouring basins, the better is the development of conduit flow. For example, karst conduit flow is developed beneath the block of limestone hills between Zhonghai and Zhongba

Location	Thickness of sandstone and shale (m)	Notes
1.3 km east of Dongtanping	110	Trunk conduit
Baha	110	Trunk conduit
1.4 km west of Xiayiding	130	Xiayiding branch
1.5 km west Xiaoqikong	80	Xiayiding branch
3.5 km southeast of Sujaping	90	Sujaping branch

Table 4 The thickness of sandstone and shale cut through by the conduit flow of Huanghe Drainage System

(Fig.9) and resurges in the Dingguandong cave on the boundary of Zhongba basin. The conduit flow is now artificially diverted to the village of Sujaping as a water and irrigation supply. Dushan County has built 28 underground reservoirs and 10 subsurface hydro-electric power stations on conduit flows.

Scouring Erosion

Conduit flow in the middle and lower reaches of the underground drainage systems has a high gradient and flow velocity and consequently exerts a strong shear stress on the conduit bed, given by

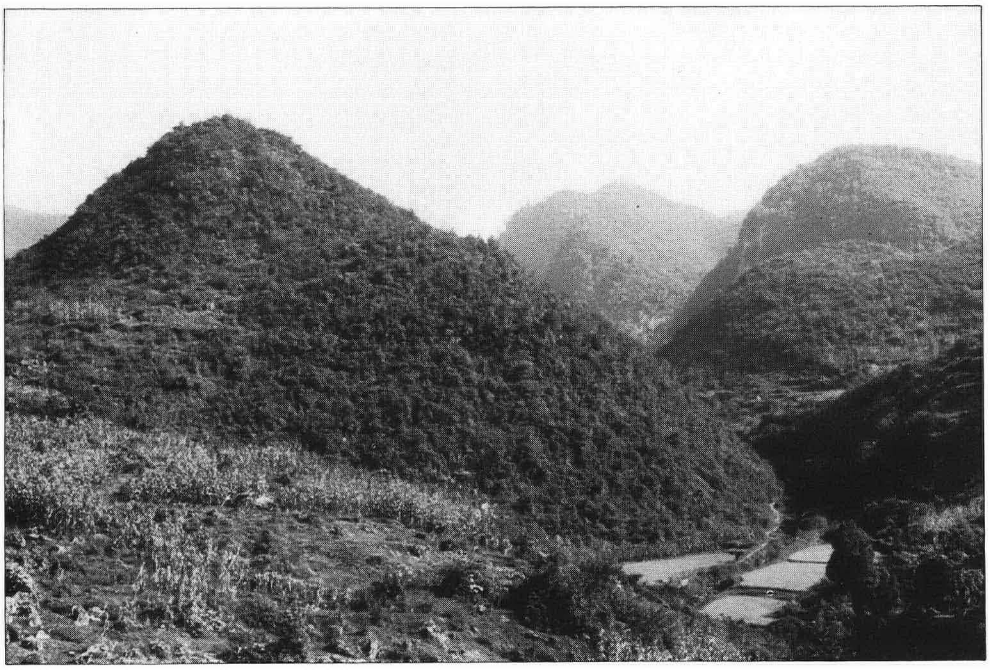
$$\tau = \rho . g . d . s$$

for uniform, steady, open-channel flow, where τ = bed shear stress, ρ = water density, g = gravitational acceleration, d = flow depth and s = water surface and bed slope. This equation indicates that when the hydraulic gradient, s, is high there will be considerable scour force on the bed. In parts of the Huanghe drainage system, conduits carrying discharge of about 1 m^3/s pass through up to 100 m thickness of sandstones, coal and shale (Table 4). Mechanical erosion of these rocks along an initial fracture path seems to be responsible for the development of these conduits.

SUMMARY AND CONCLUSIONS

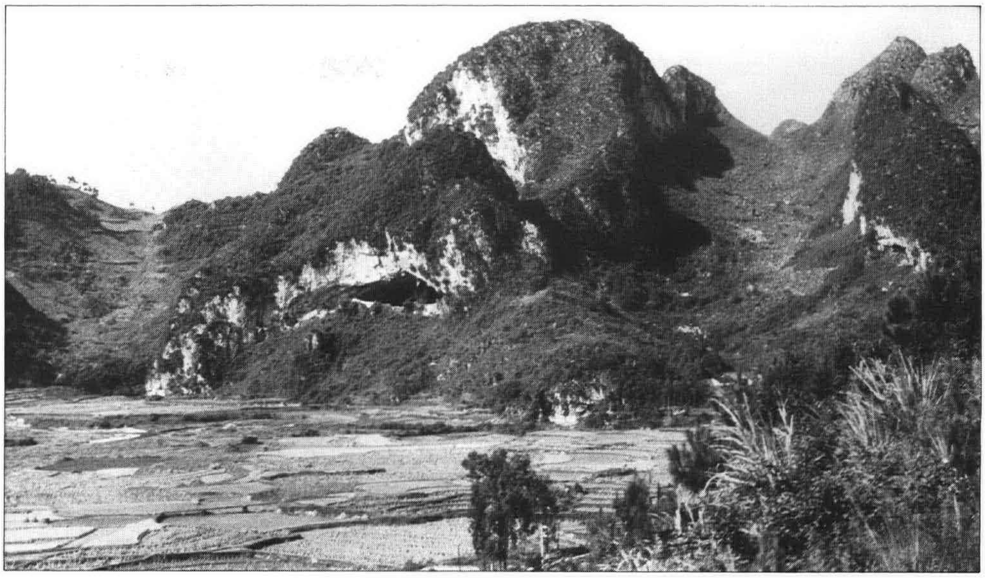
The development of karst geomorphology and underground drainage systems in South Dushan is closely controlled by lithology, geological structure, neotectonics and hydrology.

The karst geomorphology has undergone four stages of development : doline-depression, Fengcong-depression, Fenglin-depression, and karst rejuvenation to Fengcong-depression and Fencong-canyon, caused by strong neotectonic



Small karst depression among conical hills on the Guizhou Plateau near Duyun. This feature is typical of the term "depression" as used in this paper, i.e. a closed hollow larger than a doline, often with a flat floor, but at an altitude above the local water table.

Fengcong hills containing inactive phreatic caves. The valley in the foreground contains a stream (visible on extreme left). Typical Fengcong-valley topography (see Fig.3 D), near Nantan, Guangxi.



uplift. Correspondingly, the evolution of the karst hydrology has followed a developmental sequence of intergranual and fracture flow in solutionally unmodified rock, flow in solutionally-widened fissures, conduit flow, flow in homogenous fissure networks, and conduit flow with high gradients produced by karst rejuvenation.

The seven underground drainage systems in South Dushan have been studied since 1976. Their karst hydrological characteristics are very closely related to their geomorphological evolution, as follows. In the Fenglin-basin areas, network aquifers jointly composed of solutional fissures and conduits are very well developed. The bigger the basins, the higher the density of fissures beneath their floors, and the more homogenous the spatial distribution of groundwater flow in the fissure network. The block of limestone hills between the two basin floors with different levels usually constitutes a geomorphological knick point. Here conduit flow develops along favourable routes within the block. The conduit flow is better developed when the difference in height between the two basins is large.

In the zone of mixed Fenglin-basin and Fencong-depression topography, underground flow changes in type from fissure networks to predominantly conduit flow. These conduits form the principal discharge outlets for the network aqifers which occur beneath the Fenglin-basins of this mixed zone.

In the Fencong-depression zone, with its high hydraulic gradients, conduit flow is well developed. This conduit flow commonly resurges as hanging springs on valley sides in the Fencong-canyon belt.

In each of the different geomorphological zones there is a different mixture of groundwater flow types. In the Fenglin-basin, flow types alternate between fissure-network flow beneath basin floors, and conduit flows between basins. In the Fencong-depression areas conduit flow is recharged by fissure network flow, while in the Fencong-canyon belt, conduit flow is fed by diffuse flow in fractures and fissures.

The development of karst water resources is very different in the different geomorphological units. In the network flow areas of Fenglin-basins, the water table is shallow and the distribution of groundwater is relatively homogenous. Therefore it is easy to dig shallow wells or set pumping stations on karst ponds and surface stream sections for water supply and irrigation. The ideal sites for constructing small dams are on the conduit flow sections within the rock hills between two basins at different levels. Such dams are used to form underground reservoirs and small hydro-electric generators. In the mixed zone of Fenglin-basin and Fengcong-depression, because of the greater depth of the water table and the high groundwater gradient, it is necessary to use methods of cave survey and hydrology, water tracing experiments etc., to locate the conduit flows and to drill boreholes for water supply and irrigation. In the Fengcong-canyon area, steep conduit flows with high velocities and water heads are ideal for developing hydro-electric power which may be used for pumping water supplies.

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RECENT WORKS ON THE DEPOSITS IN CHARTERHOUSE WARREN FARM SWALLET MENDIP HILLS

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Exploration and excavation of Charterhouse Warren Farm Swallet, Mendip began in the early 1970's subsequent to the floods of the 1960's when it was noted that water was sinking at this point. It was not until 1984, however, and after an hiatus of over ten years, that further work led to discovery of the cave system. The two upper chambers of the system are of great archaeological importance due to the presence of a rich and varied bone deposit. The paper will describe the discovery of this deposit and discuss the methods employed in the recording, analysis and conservation of the assemblage, with emphasis being placed upon the interpretation of the nature and age of the deposit.

Some time will be given to a description of the recording methodology since the survey employed archaeological rather than purely caving techniques to produce more detailed records than normally required, in particular a 1:25 scale plan of the main area of bone deposits. Such detail is necessary, not only to aid the analysis of the deposit using distribution plans, but to provide an accurate record of the material. The latter has been lacking in the case of earlier discoveries on the Mendips.

It will be shown that there are at least two zones of input to the assemblage, and that they are possibly contemporary. One of these occupies its primary location, but the major portion of the deposit is in a secondary location, and ideas about its origin and movement - via debris flows - will be discussed. Evidence for this comes from the examination of the distribution of the cave sediments as well as the distribution of the bones.

The nature of the deposit is undoubtedly archaeological. Although there are no cultural artefacts within the cave, a rich assemblage was found during the earlier work. Furthermore the bones within the cave include the remains of domestic animals and humans as well as wild animals. The assemblage is especially important and intriguing due to the presence of aurochs, *Bos primigenius*, and finds of this species from the earlier work have been dated as the latest known aurochs from Britain.

Dating the assemblage is problematic since the usual methods may not provide dates which correspond to the emplacement of the assemblage for reasons which will be discussed, but, tentatively, the deposits are thought to be late Neolithic or early Bronze Age - that is about 3000 - 2500 BP. Conservation of the cave and its contents is also important. Whilst the caving fraternity needs no persuasion concerning conservation of cave formation, the importance of bone (and similar) deposits is sometimes less well understood. This aspect will be discussed with reference to the present deposit since the actions of the cavers in this case can be seen as a model of cave conservation.

GROUNDWATER FLOW ALONG A BANK MARGINAL FRACTURE ON SOUTH ANDROS, BAHAMAS : A PROGRESS REPORT

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Numerous blue holes formed along the bank marginal fracture allow direct access to groundwater flowing in the fracture system. Conductivity profiles and waterlevel measurements provide evidence of significant trends in the distribution of water types and of flow in a southerly direction along the fracture.

Conductance of surface water increases southwards along the fracture in association with a reduction in thickness of the brackish lens. This is attributed to progressive intermixing of the brackish lens with underlying saline groundwater. Major controls on the generation of mixing include: a) Nature of passages ; especially the dispersive effect of flow through boulder chokes; b) Presence of an open water surface; determining the extent of wind and thermally induced mixing; c) Water-level variations resulting from semi-diurnal ocean tides.

Flow along the fracture is clearly visible in caves both at the surface and at depth near the saline interface. It is suggested that ocean tides, which are lagged down the Tongue of the Ocean, produce a north/south head differential which drives this flow.

Limestones in the mixing zone are soft and extremely corroded, and a study relating water chemistry to wallrock solution is in progress. The observations imply that bank marginal fractures are subject to strong solutional development, and may be sites of enhanced porosity development in ancient carbonate platforms.

APPLICATIONS OF MAGNETIC FABRIC MEASUREMENTS TO CAVE SEDIMENT STUDIES

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Measurements of magnetic susceptibility anisotropy (magnetic fabric) provide a rapid means for estimating the degree of preferred orientation of non-spherical particles in a sediment. This fabric can be described in terms of a lineation and a foliation whose orientations and strengths are related to the environment and deposition and consolidation history. By combining data from magnetic fabric and remanence measurements it is possible to deduce the direction and velocity of water flow in a cave passage and to infer an accurate palaeomagnetic field direction. The magnetic fabric can also provide evidence for postdepositional diagenetic or mechanical changes to the sediment, such as slumping or burrowing, which may not be apparent in the field.

SPELEOTHEM DATING AND THE GEOMORPHIC HISTORY OF G.B. CAVE, MENDIP HILLS

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With the advent of speleothem dating techniques in the 1970's, we decided to date selected speleothems from G.B. Cave, in order to put a timescale onto D.C. Ford's published account of its origin and development (Proc. Univ. Bristol Spelaeol. Soc., 1964, 10, 149-88). The deposits and morphology of the cave were re-examined between 1975 and 1980 and a total of 70 speleothem dates obtained in our own laboratories and with with help of R.S. Harmon and D.C. Ford.

Throughout its altitudinal range (250 m to 117 m a.s.l.) G.B. Cave contains speleothems older than 35,000 years which is the limit of the U/Th dating method. Some of these speleothems are younger than 1.25 million years, as shown by disequilibrium in their U234/U238 activity ratios. Thus the whole of the known cave originated at least 350,000 years ago, but is probably younger than 1.25 million years, at least in part.

Ford recognised morphological evidence for palaeo-water tables at c.120 m and c.135 a.s.l. The oldest dripstone speleothem found between these altitudes is c.350,000 years old, indicating that the 135 m palaeo-water table had been abandoned before that time, probably in response to base-level lowering of the outlet at Cheddar.

The main clastic sediments are (i) boulder piles formed by roof collapse, (ii) silty muds formed locally under ponded or backwater conditions, (iii) unsorted gravelly debris flows entering via passages which connect with the surface, and (iv) sands and pebble gravels laid by streams. The deposits are highly variable laterally, and only the very youngest can be confidently traced through long lengths of passage.

With the aid of dates on speleothems which are interbedded with or included in the clastic deposits, we can reconstruct the sedimentary history of the last 130,000 years in some detail. Before that, there is evidence of several earlier episodes of infilling and re-excavation of sediments, but it is too fragmentary for a detailed reconstruction to be made.

In the Ladder Dig there were episodes of gravel deposition before c.130,000 and at c.100,000 years B.P., separated by flowstones in Helictite Chamber. The second gravel underwent some re-working at c.60,000 B.P., as evidenced by broken speleothems included in it. The collapse which produced the Great Chamber post-dates all of these deposits, but occurred before the deposition of Holocene stalagmites which are growing on the collapsed boulders. In the Gorge there are two gravel layers, separated by flowstone at the Bridge. This flowstone is 55-60,000 years old. The younger gravel above it was deposited after that date but before 10,000 (perhaps before 20,000) years ago. Most of the gravel has since been removed by the stream and this removal was at least half completed by 8,700 years B.P. as indicated by a stalagmite growing on the cut face of the deposits. Much of the collapse which produced the Main Chamber occurred before 60,000 B.P.

Overall, deposition of gravels seems to have occurred before 130,000 B.P., or just before 100,000 B.P., before 60,000 B.P. and between c.45,000 and 10,000 B.P. The last period is also recognised at Rhino Rift nearby, and includes the coldest part of the Last Glacial. All of the gravels coincide with known periods of cold climate. They presumably reflect greater sediment supply due to frost shattering of exposed bedrock at the surface, combined perhaps with large annual snowmelt floods which transported the coarse sediment into the cave. Re-excavation must also have required high stream discharges, but a diminished sediment supply, and the dating evidence suggests that this may have occurred during the late stages of the Last Glacial Period or in the earliest part of the present Interglacial.

The speleothem dating demonstrates that the history of G.B. Cave was much longer and more complex than originally suggested by D.C. Ford. This study highlights the limitations of caves as "geological repositories" of information about the Pleistocene, in that the sedimentary record is discontinuous, fragmentary and often poorly preserved. On the other hand, it demonstrates what can be achieved by a detailed and systematic study of cave geomorphology, combined with speleothem dating.

CAVE DEVELOPMENT ON THE ISLAND OF 'EUA, TONGA

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The island of 'Eua is the second largest in the Tongatapu Group which is the most southerly part of the Kingdom of Tonga. The island is almost 20km long (north-south) and has a maximum width of 7.5km near the middle. By Tongan standards it has high relief, reaching 312m above sea level and it is also geologically more complex than other Tongan islands.

Speleological investigations in a 6km² area east of Petani and Kolomaile settlements near the centre of the island have identified four distinct groups of caves:

(1) Essentially vertical caves up to 120m deep entered at the base of solution dolines in the Eocene Limestone. The dolines contain well developed centripetal drainage channels which converge on the cave entrances and although no surface flow was observed during the visit it is clear that the caves function as depression drains. Remnant phreatic roof tubes provide evidence of the caves' origins but most passage development has taken place by vadose incision during or following uplift and there is clear evidence of joint/fault guidance. Typically the caves consist of a series of 5-25m shafts leading to a modern active streamway up to 2m in height which terminates in a sump.

(2) Caves entered via vertical shafts which have developed where surface streams flowing on late Middle Miocene or early Pliocene calcareous volcanic arenite have cut down to the underlying Eocene limestone. Only two such caves were explored, one active and one abandoned, and both were essentially vertical vadose slots with clear joint/fault guidance.

(3) Caves which originated under phreatic conditions at the base of the Pliocene limestone and which have subsequently cut canyons down into the underlying calcareous volcanic arenite by a combination of mechanical and solutional erosion. All of the caves entered were linear streamways which form part of an integrated underground drainage network. They are up to 500m long and up to 45m deep but none contains significant shafts.

(4) Short, relatively recent caves situated where streams which rise at the edge of the sandstone outcrop sink into the altitudinally lower but stratigraphically younger fringing reef limestones.

THE UNITED KINGDOM SPELEOTHEM RECORD

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During the past two decades over five hundred speleothems have been dated from British caves. Although most researchers have considered that some relationship existed between speleothem growth and the prevailing climatic conditions outside the cave, statistical analysis of the data on speleothem growth was too crude to establish any clear correlations. In the past five years attempts have been made by several researchers to analyse the data more rigorously; unfortunately all these attempts have been flawed. However a modified version of the error weighted frequency curve method of Gordon and Smart (1984) has been used to analyse 520 uranium series analyses from U.K. speleothems and has yielded results consistent with our knowledge of Quaternary climatic change. This makes possible the placing of the Upper Pleistocene stratigraphy of the U.K. into an absolute chronological framework. An ill-defined warm period occurs in the record between 160 and 200 ka. The last interglacial period appears to be composite with three separate warm phases, while up to six separate Mid-Devensian interstadials are inferred by the presence of small but significant peaks in the frequency of speleothem growth. The Holocene, while somewhat over-represented in the sample, is again a period when speleothem growth is abundant.

HABITAT ZONATION IN UNDERWATER CAVES IN THE BAHAMAS

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Underwater caves in the Bahamas and elsewhere contain a distinctive biota, which changes with increasing distance into the cave. Four major habitat zones within such underwater caves can be recognised, and are defined by both physical and biological criteria, including light availability, position within the cave environment, and source of food supply. The underwater cave environment is compared to the terrestial cave environment in terms of biotic structure and terminology. The following terminology is proposed for underwater cave biotic zones: Arena, Vestibule, Transition Zone and Deep Cave.

CHARACTERISATION OF CARBONATE AQUIFERS : A CONCEPTUAL BASE

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The three fundamental attributes governing the behaviour of carbonate aquifers are recharge, storage and transmission. Failure to recognise their independent nature has resulted in considerable confusion in the literature. We propose a model in which all three attributes are ranged between end members giving a 3-dimensional field into which carbonate aquifers may be plotted. For recharge, the end members considered are concentrated and dispersed inputs; for transmission, conduit and diffuse flow; and for storage, unsaturated and permanently saturated stores. The implications of this model are considered with respect to water resources development and protection.

THE IMPACT OF GLACIATION ON DRAINAGE DEVELOPMENT IN ALPINE KARST

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The effects of glacial processes on drainage development in alpine karst terrains may be considered under three heading, those of erosion, deposition and hydrology. Erosive effects include the removal of any pre-existing cover of non-carbonate materials, deranging preglacial (sensu lato) drainage and giving rise to diffuse postglacial recharge. Glacial scour may truncate preglacial cave systems, leaving them as either non-functioning remnants or conduits for invasion waters. Intense localised glacial erosion may dissect previously-integrated aquifers. The entrenchment of glacial troughs may result in the progressive lowering of resurgence levels, causing the development of a vertical series of successively-abandoned, laterally-developed phreatic cave systems and subsequent deep vadose tributaries. At the same time, however, the rapid rates of valley incision may leave resurgences perched above valley floors.

Glacial sedimentation may result in the abandonment and bypassing of cave passages by postglacial flows, it may plug inlets to the karstic system, or it may block or bury aquifer outlets. The consequence of these depositional effects is likely to be one of aquifer reorganisation, however, rather than to put the aquifer totally out of action.

Although glacial meltwaters possess low solutional potential, this appears to be compensated by the high total discharge from glacial systems. More importantly from the point of view of aquifer development, it would appear that under bare, alpine karst conditions the bulk of the solution takes place at depth within the aquifer rather than close to the surface. Thus, aquifer development may actually be accelerated where glacial drainage is superimposed on the karst. Interaction between the glaciohydrological system and the karst hydrological system can take place in three main situations: first, where concentrated proglacial drainage enters the aquifer; secondly, where ice marginal streams develop caves parallel to the valley walls; and thirdly, where subglacial channel flow develops vadose invasion shafts beneath the ice surface.

RELATIONSHIPS BETWEEN SURFACE GEOMORPHOLOGY AND SPELEOGENESIS IN SOUTH WALES

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Due to the relatively simple structrue of the limestone of the South Wales Coalfield, the geomorphology-speleogenesis connection is more visible than in other regions. Division of the geological time scale into periods of erosion or deposition shows the small proportion of erosional periods during which cave passages can be enlarged. The change of gradient of the Far North passages in Dan yr Ogof, from bedding controlled to horizontal at a level of 285 metres, coincides with a Cretaceous peneplain level and points to development at this period. The many deep canyon passages in Ogof Ffynnon Ddu could have been formed during the post-Cretaceous tectonic uplift. The cliffs of Craig y Cilau are ascribed to an incised meander of the proto Wye, the filtering of water through the extensive fracture systems at tramroad level providing the erosional tool for the formation of the parallel systems of Ogof y Daren Cilau, Ogof Craig a Ffynnon and the more recent sections of Agen Allwedd.

CALCIUM AND MAGNESIUM BUDGETS OF TROPICAL KARST OUTCROPS, PENINSULAR MALAYSIA

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It is well established that in non-carbonate terrain in the humid tropics nutrients are cycled very actively by rainforests, with annual fluxes of elements such as Ca and Mg often far exceeding chemical denudation losses, Hitherto, comparable data have been lacking from tropical karst terrain. The present study encompasses three limestone regions of Peninsular Malaysia: Selangor, the Kinta valley (both areas of tower karst) and the Setul Boundary Range. Over a 1-year period 217 underground seepages, cave streams and springs were monitored, and rainfall interception, rainfall and throughfall composition and 'fine' litterfall (i.e. including branches <2 cm diameter) were measured in six, 30-40° forest plots. Additionally, soil throughflow waters were collected from the soil-rock interface at three sites. This paper outlines the main findings and examines the overall Ca and Mg budgets of the karst outcrops.

Ca concentration in groundwaters average 51.3 mg/l. The soil cover in the Setul Boundary Range is generally deeper and more continuous than in the steeper and more rugged tower karsts, As a consequence, recharge waters in the former area are more aggressive and the resulting groundwaters contain an average of 82.5 mg/l Ca, compared with 44.6 mg/l in the towers. Soil throughflow samples, which contained 49.6-70.0 mg/l Ca, indicate that much of the weathering/leaching potential of recharge waters is expended within the soil or at the soil-rock interface. Mg concentrations average 4.80 mg/l and the mean molar Mg:Ca+Mg ratio is 12.8%. The close similarity of the latter figure to that of 13.3% recorded for 187 rock samples indicates that solutional losses of Ca and Mg are broadly congruent. Gross outputs of Ca and Mg from the karst outcrops range from 545-651 and 16.7-85.7 kg/ha/yr, respectively. Expressed as $CaCO_3$+$MgCO_3$, this is equivalent to a gross karst denudation rate of 57.1-71.5 m³/km²/yr.

In the six forest plots, the total fluxes of Ca and Mg in the form of fine litterfall and canopy leaching alone average 345 (range, 297-475) kg/ha/yr and 45 (range, 34-66) kg/ha/yr, respectively. Clearly the actual rate of uptake by plant roots will be considerably greater than this, since the 'large' litterfall component was not assessed. Plant uptake and, hence, the weathering potential of plant roots are thus similar in magnitude to, and may well exceed, groundwater losses. Since the soil cover, even in the Boundary Range, is generally less than 50 cm deep, tree roots are in direct contact with bedrock for much of their length and it seems likely that they absorb appreciable amounts of Ca and Mg directly from the limestone. Much of the weathering activity is thus confined to bedrock in immediate contact with plant roots or soil. Indeed, in extreme cases tree roots may be the principal agents of primary rock weathering, with percolating soil waters serving largely to leach previously-cycled Ca and Mg from the soil, and groundwater flow functioning chiefly as a conveyor of soil leachates through the main body of bedrock. Under such circumstances rates of speleogenesis would be particularly slow, despite the large volume of water passing through the outcrops.

UNDERGROUND DAMS - PROBLEMS AND FAILURES OF DAMS BUILT ON CAVE RIVERS

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Recent observations of a number of failed cave dams have promoted a short review of this challenging aspect of civil engineering. The most severe problems are posed where a dam plugs a cave passage in order to divert the flow, and this creates high water pressures. Two such dams in Xizhen Yan, Guangxi, China both failed because they were built on unrecognised sediment floors, as did another in Gua Ngobaran, Java, built merely on breakdown. All three were undermined and have never retained water. On the other hand Chinese engineers successfully dammed the cave rivers of Lutoa, in Hunan, and Jijiao, in Guangxi, to raise water levels by respectively 36 m and 30 m and so create new springs for local water supply. Reference should also be made to the Obod cave river in southern Yugoslavia which was dammed, so causing local water levels to rise by 120 m; this did however create new springs, promote landslides and cause general chaos.

Simply wiers on cave rivers do not create such high heads, and therefore are more likely to succeed. Successful wiers impound substantial reservoirs in Gua Bribin, Java, and in Guan Yan, Guangxi, but another in Xizhen Yan, Guangxi, loses water from its reservoir into a long ox-bow passage. A variation on this theme is the completely submerged dam inside the Port Miou resurgence in southern France, which successfully prevents salt water intrusion up the cave passage.

Low wiers at cave resurgences, intended to raise outlet water levels by a few metres, are commonly devoid of problems. Well known examples include those at Planina Jama, Yugoslavia, and a Wookey Hole. A similar wier on the Xiaoheli Yan resurgence, in Guangxi, caused a dramatic blow-out and the creation of a new resurgence beside the dam; a short sediment-filled distributary passage below the impounded water level was easily washed out to bypass the dam.

Dams around the sinkhole entrances are more likely to pose problems when they impound reservoirs which may lie at levels well above local water tables. A dam at the Rhar Chiker, in Morocco, does impound seasonal water in the polje which drains into the cave. A similar dam around the shaft entrance of Luweng Puleireng, in Java, retains no water. On the first filling of the intended reservoir, the water escaped into new sinkholes in the sediment of the valley floor. The process of this failure is the same as that whereby so many reservoirs, worldwide, have failed through sinkhole drainage into sediment-covered limestone.

The major single cause of failure of dams and impounded reservoirs in caves is unconsolidated sediment. In this respect, cave dams are similar to surface structures in limestone regions, but the problems are exacerbated by the practical difficulties of site investigation in the cave environment. Failure to identify, or design to accommodate, sediments of the cave floor is normally fatal; serious errors have arisen through the site engineer's lack of experience of cave geomorphology. Complete passages obscured by sediment may be much more difficult to identify. As is characteristic of any civil engineering on limestone, site investigation for cave dams has little alternative to painstaking fieldwork, backed up by specific experience in karst, and hopefully aided by a modicum of sheer good luck.

WATER TRACING AND MODELLING, A PROGRESS REPORT WITH PARTICULAR REFERENCE TO THE PEAK CAVERN SYSTEM

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Techniques for water tracing are reviewed. Postulated dowsing results, including a possible 6km of flooded cave passage in the Mossdale/Black Keld system and northwards towards Kettlewell in Upper Wharfedale, are presented. Similar work in the Peak Cavern system is claimed to have detected a master cave in the swallet area, with feeders to Slop Moll/Russet Well and to Coalpithole Vein, including possible detection of the lost Peakshill Sough south from Odin Mine to the Giant's Hole valley. Other detections claimed are Oxlow Cavern to Bottomless Pit and to Speedwell Whirlpool Rising, and New Rake to Speedwell Main Rising. It is claimed that the use of dowsing, a time-honoured but nevertheless uproven method, is justified as a hypothesis when all conventional tracing methods, such as dyes, chemical analysis and flood pulses, have been exhausted, as is the case for the systems mentioned. This is particularly appropriate where the majority of the flooded passages may never be entered by cavers.

The paper continues with a review of previous chemical and statistical analysis work in the Derbyshire region by Christopher and Wilcock, including classification of karst waters by chemical fingerprinting. The hydrology of the Derbyshire area is more complex than some other karst regions because of the presence of volcanic rocks, lead and copper mines, and mineral veins (rakes), and many cave systems are affected by drainage of mines, soughs (drainage levels) and natural vein cavities, the Peak Cavern system being the most important example.

After 40 years of cave exploration, perhaps only 10% of the passages of the system have been entered by cavers. Recently-gathered data from an automatic weather station, rain gauges, instrumentation of the sinks P6 and P9 and the resurgences at Peak Cavern now holds out the possibility of black-box modelling of the system. It is postulated, as previous flood pulse and dye-tracing work suggests, that there are three, perhaps four flow-routes from the sinks to the Peak Cavern and Speedwell risings. Time will tell whether a plausible computer model can be contructed which simulates the observed characteristics.

As an ancillary study, the determination of the proportion of allogenic (swallet) and autogenic (percolation) water in a given rising is being attempted. This has already been studied by Newson (1971) in the Mendip region. It is hoped that a theoretical numerical technique using multivariate statistics can be developed on a computer to estimate the proportions of allogenic and autogenic waters in a given rising, with particular reference to the karst waters of the Derbyshire region.

LIMESTONE QUARRIES : AN EVOLVING LANDFORM?

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Quarrying of limestone may result in the destruction of certain landforms such as caves, dolines and in some cases entire hills; and the substantial modification of other landforms, particularly valley systems. However, quarrying also creates new landforms, notably rock basins. These comprise an assemblage of rock slopes which exhibit a variety of post-excavational forms relating to the method of excavation practised immediately prior to their abandonment. Under present environmental conditions natural rock slopes are often regarded as essentially stable landforms which have reached a characteristic equilibrium form. However, quarried rock slopes are evolving with the rapidity characteristic of young landforms which are out of equilibrium with their surrounding environment. This study examines the processes involved and the form changes which result on rock faces within working and abandoned limestone quarries in the White Peak, Derbyshire. This will have applied value in facilitating the prediction of the ways in which quarried rock slopes with differing abandonment-forms evolve over time; thereby enabling quarry operators to modify the end-form of quarry rock slopes in order to achieve an equilibrium landform in the shortest possible time and enhance the success of current restoration practises.

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The Caves and Blue Holes of Cat Island, Bahamas

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Abstract: A description of 18 cave sites and 7 Blue Hole sites on Cat Island, Bahamas, is given, together with information on their biology and geological structure.

In January 1985, a team of 28 members of Operation Raleigh spent three weeks on Cat Island, exploring and surveying cave and Blue Hole sites. As far as can be ascertained, this was the first comprehensive scientific examination of these Cat Island features, although they have long been known to the islanders, both as a source of "cave dirt" (guano), used as fertilizer, and as goat shelters or village refuges in times of hurricane. A total of 18 cave and 7 Blue Hole sites were visited, though it is believed that further sites exist on the island. A lack of time in the field, coupled with logistical and access difficulties, precluded a more complete examination. Not the least of problems was the difficulty of movement in the thick scrub bush that covers most of the upland areas of the island.

Cat Island itself is one of the most easterly of the Bahamas, a long thin island formed from the remains of calcarenite dunes of Pleistocene age, raised during a period of eustatic exposure of the Bahama Banks. The eroded Pleistocene surface is fringed by later Holocene sediments. The caves lie entirely in Pleistocene aeolian limestone.

The island is about 80 km long and between 2 and 16 km wide, and rises to 60m at Mt. Alvernia (Comer Hill), the highest point in the Bahamas, though most of the upland dunes are considerably lower than this, averaging perhaps 15-30 metres in height. Unusually for the Bahamas, the economic emphasis is on agriculture rather than fishing, a fact that has not always been to the good of the cave fauna. The removal of rich guano beds has undoubtedly had a negative effect on the development or maintenance of troglobitic and troglophilic fauna.

Much assistance was given by the islanders with direction to sites, and with information regarding their social and economic history. Though one of the original aspects of the project had been to search for archaeological sites of Arawak age, there was no obvious indication of cave use by these early island inhabitants, despite stories of cave paintings in local folklore. Guano extraction may well have destroyed much evidence of pre-Columbian usage. Local folklore also inhabits several of the Blue Hole sites with both mermaids and water monsters, though the mermaid stories bore suspicious similarities to European and Asian legends on the same theme, and may well be a cultural import. These stories are collated in an appendix to this paper.

THE INLAND CAVES

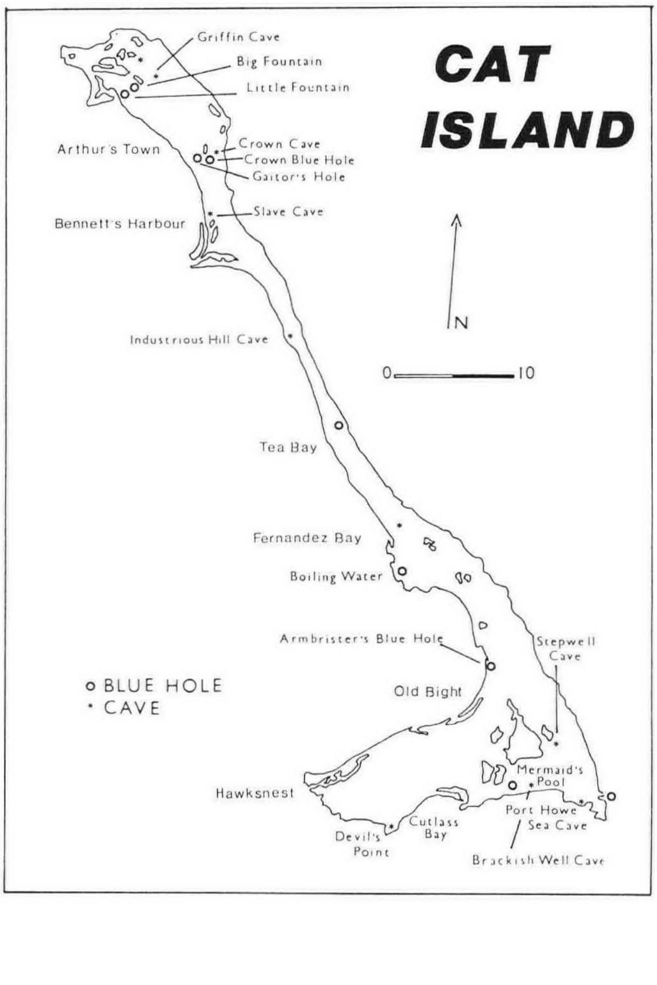
The dry caves of Cat Island are described, together with relevant notes on their geology and exploration history. Grid references where available from the Bahamas 1:25000 Second Series O.S. Maps.

GRIFFIN CAVE, Orange Creek. NGR: VC 297272
The cave entrance is located on the dirt road east of Orange Creek, south of the track and distinguished by the remains of a gate and wall at the mouth of the cave.

The 2m x 3m entrance leads to a low tunnel, which rapidly bifurcates. Both routes enter a large, low chamber, from where a number of short, blind passages radiate on the left side. Like the nearby Crown Cave, the cave is a high sea-stance phreatic cavern. It contains one of the richest guano-associated and bat faunas seen on the island. As such, it represents a prime conservation site, and close controls on "cave dirt" (guano) extraction should be made.

JAMES CISTERN CAVE, Orange Creek. VC.284284.
The cave is located on the north-east side of James Cistern Lake, 6m above the lakeshore. A low crawl leads to a chamber from which a phreatic maze radiates. Almost all of the passages become too low after 20-40m, their floors being bare rock. One passage on the right leads to a small chamber after 35m, from which a single exit continues for 10m to a bat chamber, 10m long, 5m wide and 4.5m high, thickly-floored by guano, and containing over a thousand bats.

CROWN CAVE, Dumfries. VC353216
The cave is reached by taking the dirt track east from Dumfries. It is possible to take a four-wheel drive vehicle one kilometre along the track to a distinct fork. A further 250m walk along the right hand branch leads to a junction with a track heading north into the forest. After 300m, the blue hole is 100m on the left and the cave entrance is up a short path on the right.

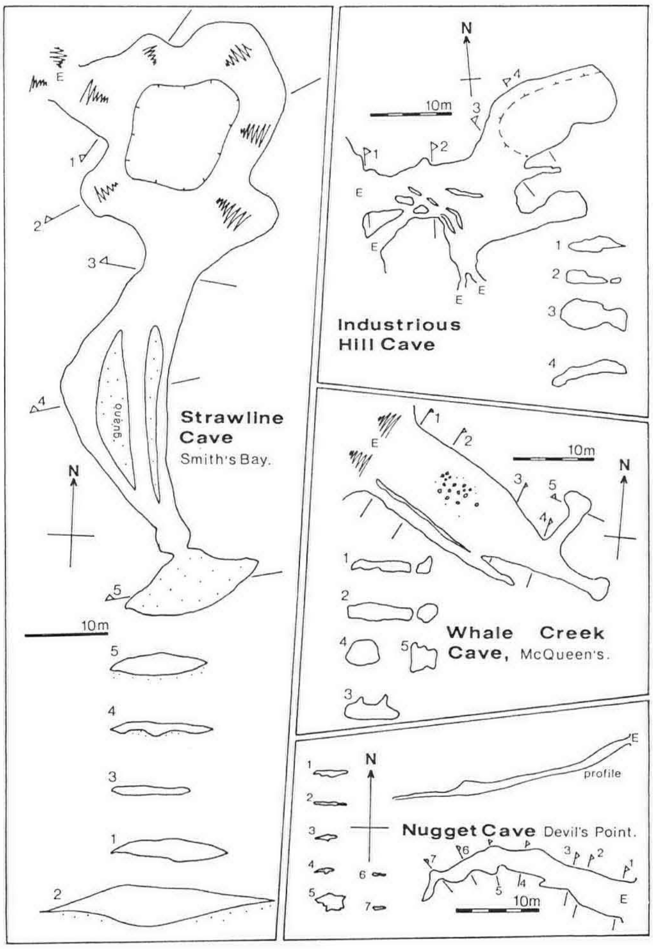


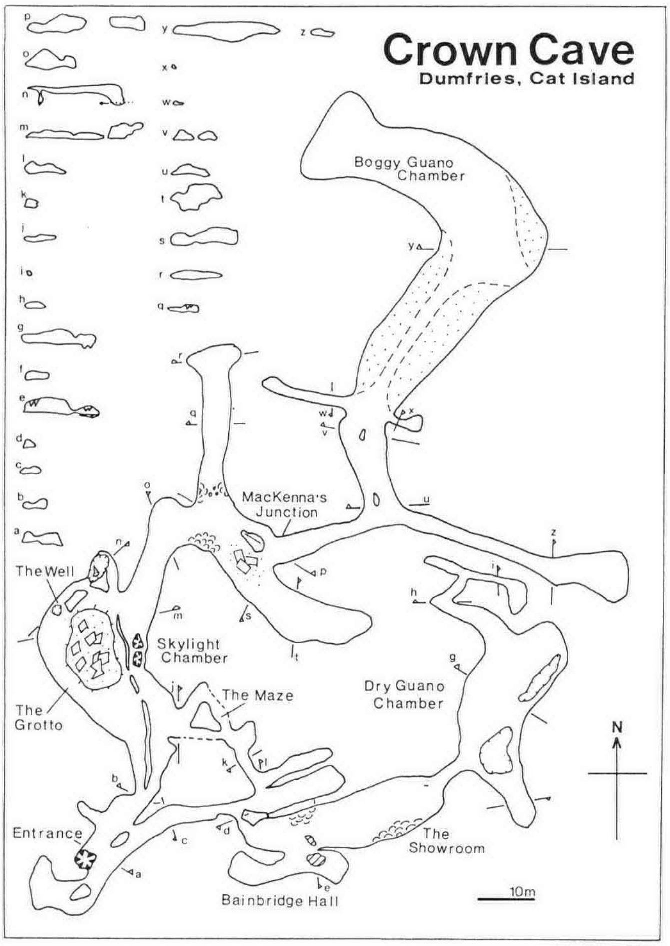
The cave represents the most interesting exploration of the Raleigh project. The entrance is a one metre diameter pit in the forest floor, where an easy 3m climb down drops into a sizable entrance chamber; this is the only easy entrance.

The majority of the passages are phreatic tubes. From the entrance left leads to a breakdown chamber via a small phreatic maze. Skylight Chamber owes its name to two man sized solution holes in the roof; much of the cave lies close to the surface. A 4m climb down the nearby Well reaches a mud floor, from which a bedding plane gives visual contact with a sluggish, shallow, muddy stream. The water may be at the local water-table level or it may be a small vadose development in the cave.

To the left of the entrance to Well Chamber, a larger passage leads to MacKenna's Junction, with large phreatic tunnels to right and left. Straight across MacKenna's Junction, the passage continues to a fork. Right is a large passage ending in a low chamber close to the end of Dry Guano Chamber (see below). Left at the fork leads to Boggy Guano Chamber, the largest and most impressive passage in Crown Cave. It consists of a large phreatic tunnel with domed roof and parallel walls, is some 60m long by 15m wide, and ends suddenly at a blank wall. Boggy Guano Chamber harbours an enormous bat population, and has a layer of guano over a metre thick; it is saturated with percolation water, and so represents the only known boggy guano habitat seen on the island.

Back at the entrance chamber, the right-hand passage leads to a small crossroads, and via a low crawl, into an impressive cavern, 30m long and 10m wide, called The Showroom. This contains a number of large and attractive formations, now inactive. The right-hand exit from The Showroom is into Bainbridge Hall and a low, wide bedding chamber. This area is well-decorated, by inactive formations, and the roof of the bedding bears an ancient inscription, reading "J.A. Bainbridge HOHMS". The bedding cave has three pools fed by percolation water, and containing ostracods. The Showroom ends in a short tunnel that leads to to Dry Guano Chamber, with thick deposits of partially-mined guano. This chamber terminates in a large round room containing a huge bat population.





SLAVE CAVE, Bennett's Harbour. VC406109
This is located about one kilometre east of the coast road, just before the Z-bend at Bennett's Harbour. It consists of a small cavern within a large depression, possibly formed by the collapse of a much larger cave. It is much used by feral goats and is devoid of guano. The cave is so named because of the presence of a human skull, rumoured by locals to be the remains of a runaway slave.

BASKETBALL CAVE, Bennett's Harbour. VC356163
A small blind phreatic passage located on the track between the roadside basketball posts and the church in Bennett's Harbour.

GOAT CAVE, Bennett's Harbour
A small phreatic chamber behind the goat corral in Bennett's Harbour, rumoured to connect with Basketball Cave nearby, though the passage is now blocked.

STRAWLINE CAVE, Smiths Bay. VB522923
The cave is reached by taking the path behind the Deveaux House in Smith's Bay; it lies in the bush beyond the Strawline Fields, on an overgrown track used to bring guano from the cave.

There is one entrance (4m wide by 1m high) leading to a handsome chamber excavated for guano. A low crawl leads out of the chamber in to a wide bedding cave fringed by low phreatic passages, all of which are blocked; the inner chambers retain a thick layer of guano, maintained by the resident bat population. The cave exhibits typical phreatic features - wide low chambers with horizontal maze development at the perimeter - and probably represents a fossil phreatic level from a high glacio-eustatic sea level; it may typify the type of cave to be found by further exploration of the virgin bush in the island interior.

The cave has a dense bat population and a rich fauna associated with the undisturbed guano. It may be one of the most important refuges for bats in this part of the island, and this bat population probably makes a very important contribution to the local agro-economy in terms of pest control.

BLUFF CAVES, Bluff Settlement. VC 406109.
The entrances are located 500m seaward of the road at Bluff Settlement. The large entrance on the landward side is in a hollow, part-covered by retreating roof collapse. It widens into a central chamber and a maze of passages, which exit on a wave cut platform 3m above sea level. It may be an old sea cave, or it may be a fossil phreatic cave which marine erosion has exposed. It exhibits typical phreatic features, with eroded pillars between maze-like passages, with much solutional fretting on the walls. A small population of bats is present in the main chamber, but the guano beds have been extensively mined.

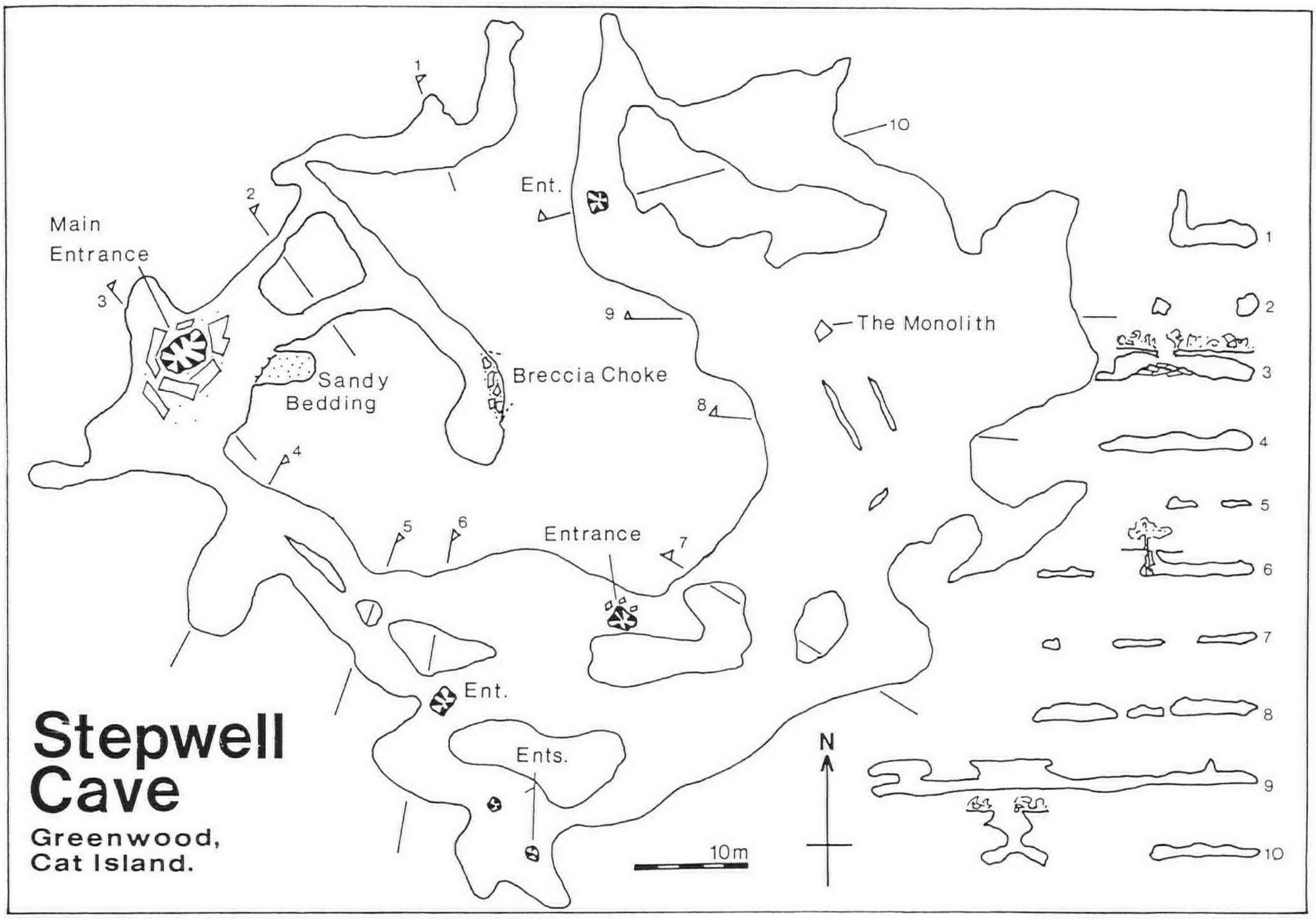
INDUSTRIOUS HILL CAVE, Industrious Hill. VC439054.
This is one of the best known caves on the island, lying only a few metres from the main road at Industrious Hill, in a Pleistocene dune. The main passage runs for20m and ends in a breakdown chamber, divided into upper and lower levels by a sloping ramp. Several much smaller entrances pocket the southern margin of the dune, and connect to the main cave via a small phreatic maze. The cave has been much modified by marine erosion; it may be simply a sea cave, although it is more likely that it is a fossil phreatic system.

GEORGELAND CAVE, Old Bight.
The entrance is located in Georgeland Hill, overlooking the Bridge Inn tourist development. The large entrance is in an area of bare limestone at the top of the hill, with wire fencing for goat shelters. Inside there is just a series of small chambers. The cave may well be one the highest on the island, and lies in the remnants of the oldest Pleistocene sand dunes.

OLD BIGHT SHAFTS, Old Bight.
Two kilometres into the bush from Old Bight along the old plantation road is an area of vertical solution pits. Of the ten shafts descended, all were blocked, generally at around 10m.

STEPWELL CAVE, Greenwood. NGR: VB663748
The cave lies in the thin bush, 10 minutes walk from the Port Howe road to Greenwood. Its main entrance is a collapse, with roots running down into the cave providing convenient handholds. The cave is the most significant find in the south of the island, consisting of a maze of phreatic passages developed just below the surface. The pattern of the maze is best followed from the survey, the only notable chamber being Monolith Hall with its many bats but only minimal guano deposits. There are several skylight entrances containing tree roots and inwashed piles of organic debris.

The cave is highly complex in its morphology, and shows phreatic solutional fretting and rock scallops. The numerous collapses allow the profile of the overlying rock to be seen. The whole series of rocks in the section are characterised by their structural weakness. The uppermost layer is a thin section of fairly hard surface rock, calcrete, beneath which is a layer of loosely-compacted beach-sand. It is this which forms the bulk of the sand piles within the cave. The next layer is one of thinly-bedded limestone, possibly calcrete, prone to fracturing under

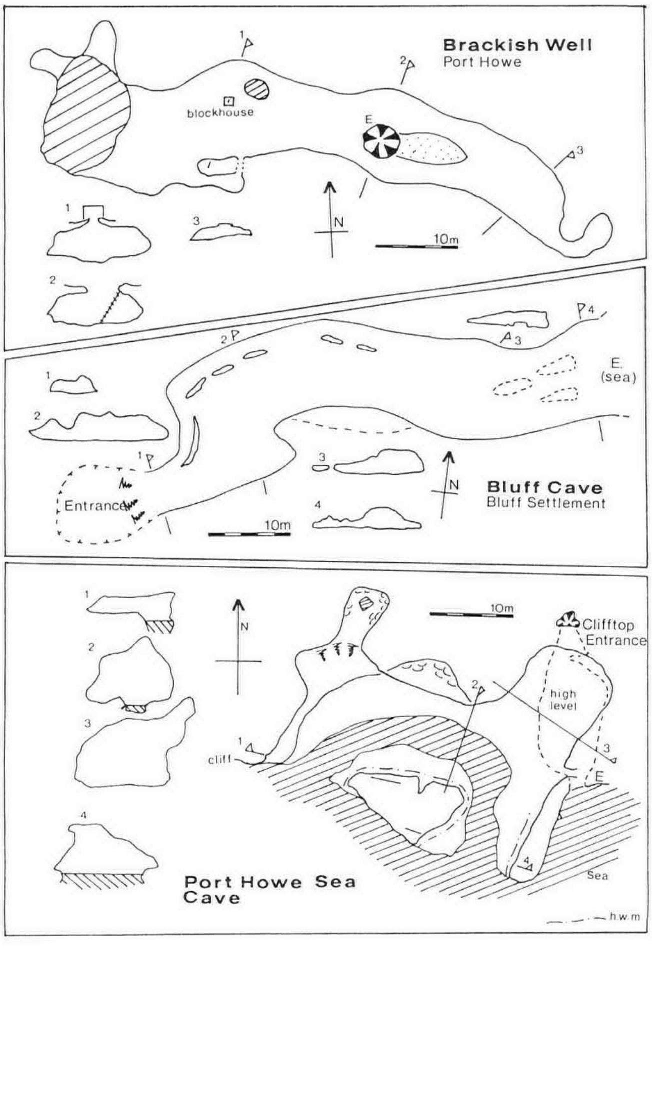


stress. The main cave roof in many areas is formed below a conglomerate of large cobbles in a sandy matrix.

This sequence of overlying rocks suggests that the cave may have been formed prior to the final stage of dune deposition, and possibly before the last eustatic high sea stand. A possible sequence of events is as follows:
a) Primary dune formation during the early stages of a period of Bank submergence. caves form almost syngenetically at the base of a shallow mixing zone.
b) Sea levels fall, and the calcarenite dune surface is eroded. Collapse of the cave roof allows windblown sands and sharp limestone fragments to accumulate beneath such openings.
c) A further rise in sea level triggers a secondary period of dune formation, and wears the sharp, broken limestones of the surface calcretes into rounded cobbles. This forms the layer immediately above the earlier calcretes of the cave roof.
d) Recent erosion of the secondary dune surface has again opened collapse entrances to the cave. The primary collapse entrances of stage b) can be recognised by the presence of brecciated fragments of limestone and sandy infill. Later collapse entrances contain rounded, water-worn cobbles within the accumulated collapse debris.

Dating rocks within the overburden and collapse debris would be necessary to authenticate this sequence of events, and may yield a more precise chronology for high sea-stand cave development in the Bahamas.

ZONICLE HILL CAVES, Zonicle. VB621718
The cave lies in a bluff overlooking a salt lake, 30m above lake level. The main entrance is a 2m wide solution tube into a large, low phreatic chamber floored with guano and mud. Low bedding planes run off at each end. At one side it is possible to drop into a solution pocket and through the second entrance. The cave has been extensively mined for guano and bats are still present in the cave.



WILLIAMS HILL CAVES, Port Howe. NGR. VB668725
The caves are located in a hill overlooking the road between Port Howe and Green wood. There are two main entrances, each 2m in diameter; the western has a small passage and chamber, and the eastern has a series of maze-like passages associated with it. The caves are formed in relatively soft and steeply-bedded dune limestone. The overall passage length is small, but represents a high fossil phreatic system.

PORT HOWE SEA CAVE. Winding Cove. VB673073
The caves lie in the sea cliffs between Baintown and Winding Cave. The main chamber of the cave is 30m long and 20m wide, and has a vaulted roof 25m high. The south side is open to the sea through two massive arched entrances, and much of the cave floor is flooded at high tide. The roof contains many solution pockets, which are home to a large bat population. The upper cave is very well decorated with massive stalagmites and stalactites, now covered in green algae due to exposure to the daylight. These are unusual features for the generally sparsely-decorated Cat Island caves. On the north (landward) side of the chamber, a steep 10 metre scramble leads to a small chamber well decorated with flowstone. This has a guano floor, out of reach of the sea, and is home to a sizeable bat colony.

Although much of the cave's present morphology is due to marine erosion, the fossil formations and the high level passages suggest that it might be the remains of a high sea level, phreatic system that has been truncated and vertically enlarged by marine action. The cliffs on the south coast of the island have been formed by the truncation of old dunes by marine erosion, and this and many other caves high on the cliffs may represent a fossil phreas.

BRACKISH WELL CAVE. Baintown. VB609704
The cave is located within Baintown village, between the square and the sea. The cave consists of one large passage, 80m long. The cave roof lies only a couple of metres below the surface for most of its length. The seaward end becomes low and is choked with sand, although small roof tubes produce a powerful draught. Midway along the main passage is a muddy pool, below a hole in the roof. The pool is reputed to be tidal, and has been used as a well. The landward end of the passage terminates in a large guano polluted pool; the cave supports a large bat population.

WHALE CREEK CAVE. McQueens. VB 545752
The cave is reached across Whale Creek after a walk from McQueens. Its entrance is located 30m inland, by two large pine trees; is partially walled, and was once used as a shelter. The cave consists of one phreatic passage 40m long, with one side passage leading to a small chamber. There are no signs of bats or guano. The cave is wave-scoured, and appears to be an old sea cave.

DEVIL'S POINT CAVES. Devil's Point.
There are a number of entrances along the coastline near Devil's Point. Nugget Cave has a single passage, and a few solution pits are up to 10m deep and blind.

There are undoubtedly many more caves on Cat Island than those listed above. Many of these, however, probably lie in areas of thick thorn scrub and access to them will be extremely difficult. Further explorers would do well to seek local knowledge in conjunction with aerial survey. Caves in less accessible areas might well yield not only more established bat and guano fauna populations, but might prove more archaeologically interesting. Despite rumours of Arawak remains and paintings, none was found on this occasion, and it is likely that extraction of guano for agricultural purposes will have destroyed many good archaeological sites.

Deposits in more remote caves may be less disturbed. It was felt that the larger dune systems in the north of the island might prove most rewarding in terms of future study.

THE BLUE HOLES

Blue Holes appear to be less common on Cat Island than on other Bahamian islands, possibly as a result of the greater relief of the island, which rises to a maximum of 60m. Inland Blue Holes appear to be more frequent in the north of the island, where there are well-developed fossil phreatic cave systems within the Pleistocene calcarenite dunes. The presence of more than a few marine Blue Holes is uncertain: those explored on the 1985 Operation Raleigh expedition are described below.

BIG FOUNTAIN, Orange Creek. VC292.266
This large inland hole is 1500m east of Little Fountain, and lies a few metres north of the same access track. The hole is surrounded by an area of lush surface growth. The freshwater lens is very shallow, despite the distance from the coast, and there is a marked halocline and thermocline, commencing at -3m. The temperature difference is distinct, rising from 22.2°C to 25.5°C within a metre. There is an evident H_2S content in the water to -15m, below which there is a distinct improvement in visibility, and a slight cooling of temperature. A ledge at -12m shelves steeply down towards the south-east corner of the lake, reaching a vertical cliff at -20m. The bottom of the entrance lake is reached at -33m in the south-east corner. At the base of the shaft, in clear saltwater, a descending passage leads off to the south-east, with speleothems evident in increasing profusion. This quickly opens out into an enormous rift chamber ("The Well at the Edge of the World"), where the downward continuation of the rift was descended to a depth of -63m, reaching an area of sharp and broken boulders, fresher-looking breakdown than that of the main chamber above. The rocks were covered with fine brown silt and the rift continued downwards out of sight.

At the -35m level, in the main chamber, a large passage 20m across was followed for a further 75m horizontally. Twisted speleothems were evident on the roof and walls, with some fine stalagmite grottos on the sloping northern floor. The passage appears to have formed along a hading rift. At one point, an ascent was made to -20m. The water at this level was sulphurous in taste, and gray, organic fronds were observed floating free in the water. The cave continued beyond the furthest point reached.

Freshwater growth was much lusher here compared with the nearby Little Fountain, and the walls to a depth of 3m were coated with algae, and grazed by large shoals of Gambusia. The H_2S layer has a zone of bacterial growth on walls and floor. There was a distinct cave fauna, with 2 species of Remipedia, amphipods, thermosbanaceans, ostracods and shrimps observed. At the -20m level in the main cave passage, an area of colonial bacterial growth was associated with the sulphurous zone. These bacteria, growing in complete darkness, may provide one of the primary food sources of the cave.

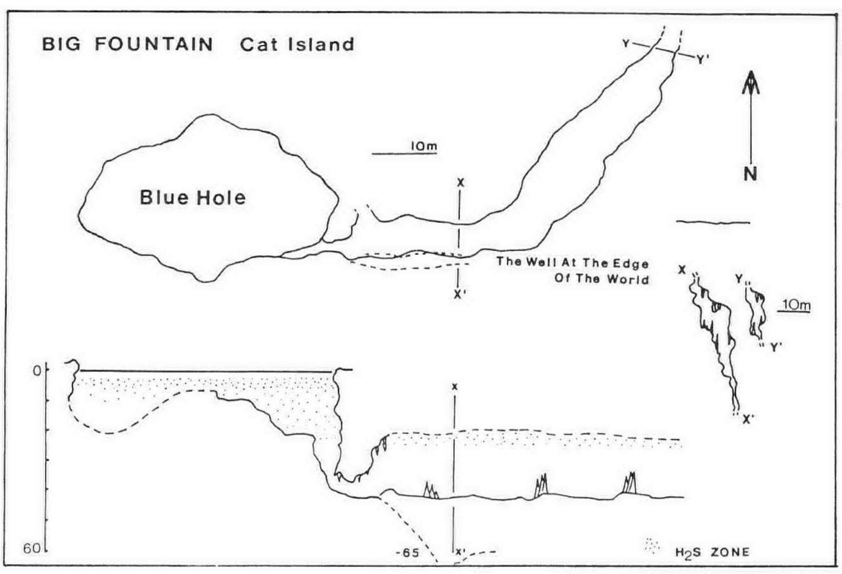
LITTLE FOUNTAIN, Orange Creek. VC286.254
This inland hole lies 1500m from the west coast at Orange Creek. The pool is 12m in diameter, with freshwater to a depth of 7m, where an indistinct halocline is met. Below this to a depth of -15m is brackish water, with H_2S present. The sloping floor is of fine organic silt and algal detritus. Below the halocline, there is bacterial growth on the walls. The pool is frequently used for washing clothes by local villagers, and the water is regularly contaminated by high levels of household bleach.

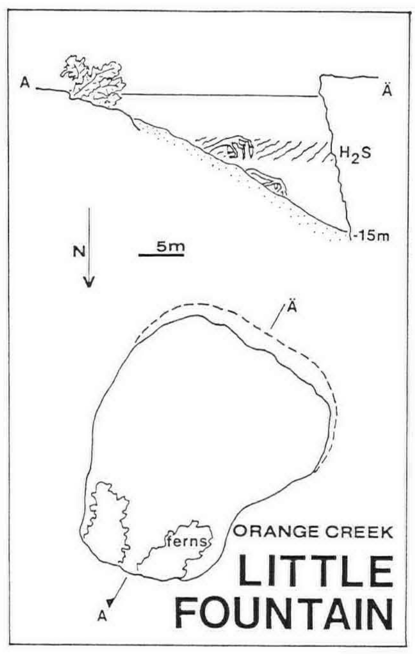
It is not surprising that there is little in the way of an established fauna in this Blue Hole. A frog, a duck and a very few Gambusia and mosquito larvae were the only creatures observed.

CROWN BLUE HOLE, Dumfries. VC352.217
This large collapse entrance is by the side of a large mangrove fringed depression that contains an undived inland Blue Hole. Nearby is the extensive dry cave system of Crown Cave.

The entire Crown Blue Hole collapse is filled with a dense growth of mangrove and fig trees, their roots reaching down into the freshwater lake that floors much of the Hole. At the south end, a semi-collapsed arch leads out over shallow muds to the main mangrove depression. There is a tidal fluctuation of almost 1m in this Hole, considerable if compared to other inland sites. At the opposite end, the passage drops steeply down over organic sediments to a detritus-floored bedding at -25m, of unknown width, heading north-west towards the large mangrove depression containing the undived Blue Hole. The passage has less than 0.5m of vertical water space, and contains a distinct H_2S layer, overlain by tannic, brackish water. This mixing zone passage may well be in the primary stage of formation. The passage was entered for less than 10m before being considered too dangerous to explore.

Several other caves were discovered in the immediate area, generally vertical shafts leading to water. Crown Blue Hole appears to have formed





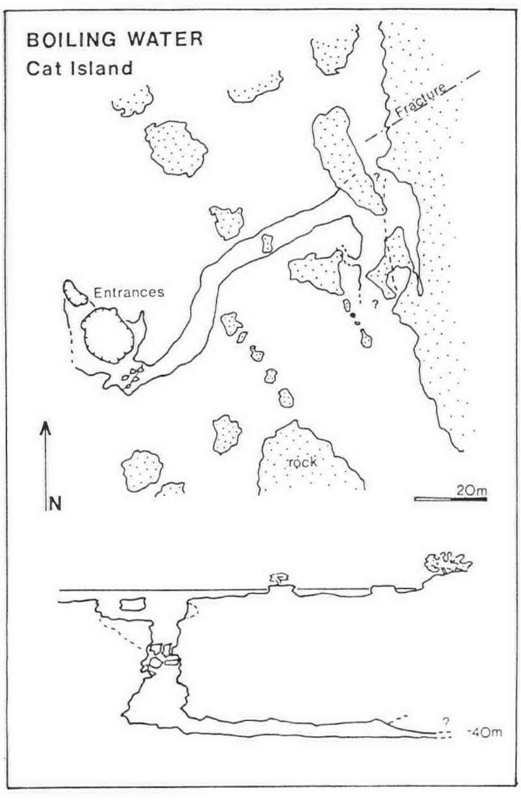
along a north/south fracture, and bedding patterns on the walls suggest it follows the dip of an old dune slope, and that collapse along this has been the cause of the present shape.

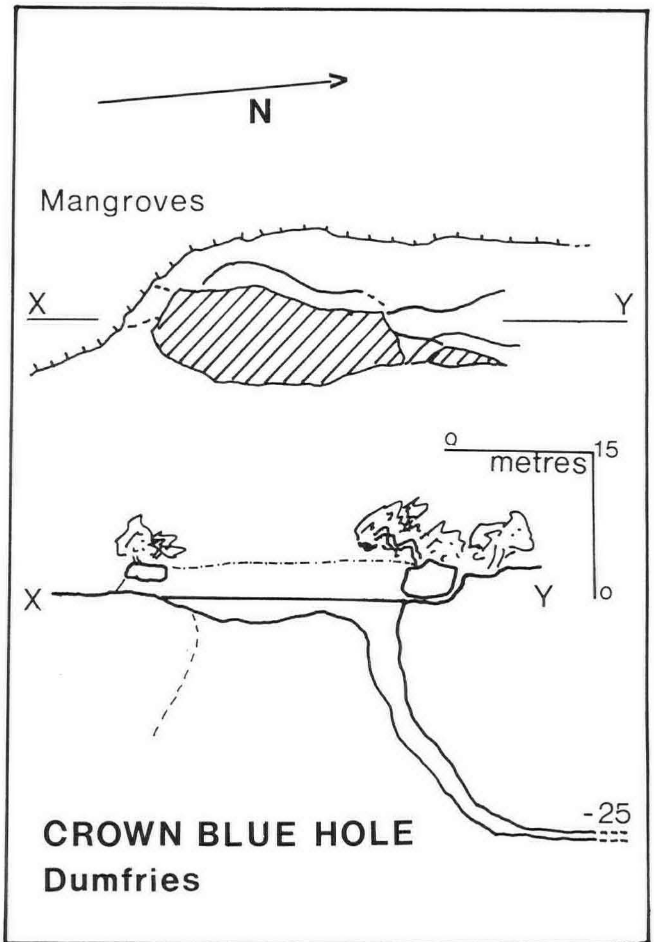
The cave is inhabited by a profuse population of shrimp (Barbouria cubensis) which appear to graze on the wall flora. Generally, the walls in this freshwater zone were clean rock, with no algal covering (perhaps not surprising in view of the numbers of shrimp) though a freshwater sponge was common in small, encrusting mats, and a lacy growth form. Some Gambusia were present. There appeared to be a khaki-coloured sponge on the roof of the underwater passage at -25m.

GAITER'S HOLE, Dumfries. VC 286.254
A large inland Blue Hole is reached by a rough track to the east of Dumfries settlement. Of two possible entry points, that to the north-east is more convenient. The Hole has an unusually thick H_2S layer, deep purple in colour (Sulphur-reducing bacteria) and 1-2m thick at -6m depth. Passing through this creates a temporary "hole" through which daylight can be seen dimly. Otherwise, all light is blocked by the density of the layer. A less dense H_2S zone continues to a thermocline at -12m. Much of the floor of the hole appears to lie between -6 and -12m, sloping gently to s deep shaft on the northern side of the hole (the south was not investigated). The shaft descends in vertical steps past sheer rock faces, where stratification marks on the otherwise clean surfaces suggest that sediments piled up against them have fallen abruptly away at some time. At -29m, the silt floor slopes in to the base of a vertical wall, with no apparent continuation visible in the by now crystal-clear saltwater. A deep undercut was present at -6m on the northern side of the hole, corresponding to the surface of the dense bacterial layer.

Gambusia swam in shoals in the freshwater zone, and were noticed at the furthest point of the undercut, within the sulphurous zone. The deep saltwater cave (below -20m) was inhabited by remipedes, of which three specimens were collected and several other observed. No other cave fauna was seen.

BOILING WATER, Fernandez Creek. VB 528.887
The twin entrances to this cave lie in a tidal mangrove creek 1 km west of the main island road.

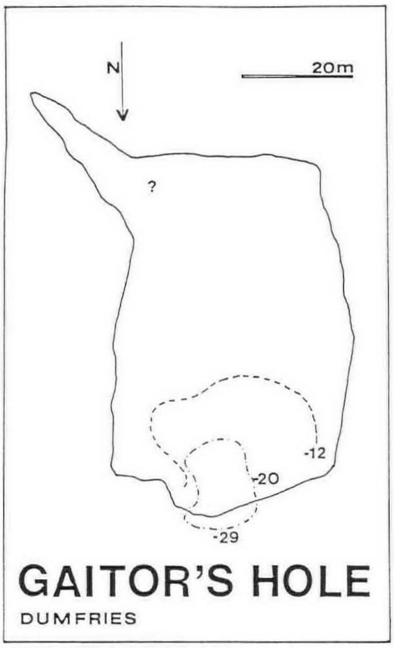


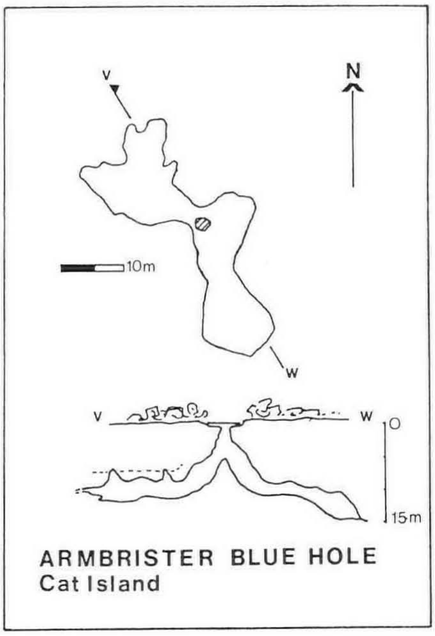


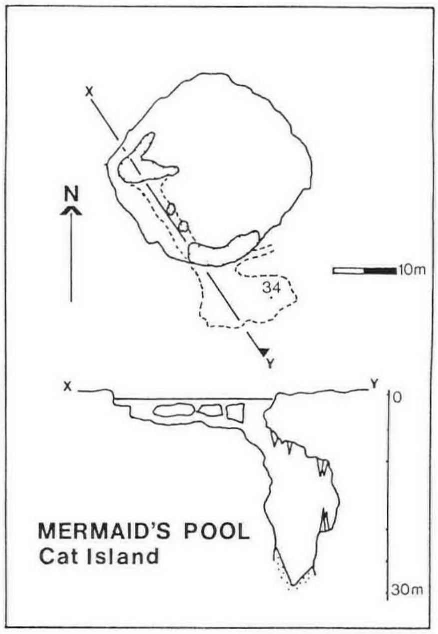
The entrances appear to form one side of an aston collapse, and the holes are linked by a connecting bedding passage, where collapse has not yet occurred. The inflowing current is extremely strong, while the outflow is unusually weak by comparison. Slack water in the cave occurs just before local slack water in the creek (75 minutes after high tide at Old Bight).

The entrance to the main cave passage is on the south side of the hole, where a sponge encrusted bedding slopes down to -6m. Ten metres in, a vertical shaft descends among boulders to a large horizontal half tube at a depth of 30m. After 100m, the cave splits, with the main continuation possibly lying unexplored on the left. To the right a sedimented bedding, 10m wide, with a distinct current flow, reaches 131m from the entrance, and then divides again. The main bedding continues lower and a tube heads south on the right. There are no obvious speleothems. The passage orientation appears to relate to a distinct surface fracture visible in the bedrock above the cave, and at the end runs parallel to fossil dune ridges on the surface.

The cave entrance forms a densely-populated marine enclave within the shallow tidal creek, with an unusual abundance of sponge and algal growth. Algae were present in dense patches in the sunlit areas of the entrance, whilst sponges became dominant in shaded and darker areas. The Blue Hole algae appeared to be a more robust species than the typical creek flora of the immediate surface environment. "Knitting" sponge growths and globular white calcarous forms were common, with a grey/white sponge growing in large mats on the floor and roof of the cave entrance, often to a thickness of several centimetres. This species may also form the white, pendulous growth-forms on the cave roof further into the dark zone. Within and around the sponges grew polychaete tube worms, bryozoans, hydroids and occasional anemones and ascidians, the latter two on shaded walls and roof only, free from sediment cover. Hydroids were common on all surfaces,







though in greatest abundance on the floor. Light levels and position in relation to current are obviously important in local and species zonation. The growth forms of individual species of sponges appear to relate to cave variables such as light, gravity, food availability, current and sedimentation patterns. There were no evident corals.

Fish life was typical of similar Blue Hole entrances, with snapper, blue and french striped grunts, Nassau grouper, bar jacks and blue-striped wrasse being common. There were few crustacea, other than large white spider-crabs being extremely common in and amongst sponges up to 100m inside the cave. Several small crayfish (Paulinus argus) inhabited the vertical shaft. Snappers were observed up to 100m inside the cave.

The blow cycle still contained much detritus, and there was little evidence of organisms being orientated with regard to direction of available food-supply within the cave. Sponges were common to the explored end of the cave, on both "upstream" and "downstream" sides of the rock surfaces. Growth forms became smaller and more encrusting with increasing distance into the cave. The floor of the deep cave was composed of shell sand and skeletal algal remains.

ARMBRISTER BLUE HOLE, Armbrister Creek. VB462.816
This has a small entrance in a tiny side creek off Armbrister Creek. The shaft opens into a large isolated chamber,choked at both ends by silt banks. A halocline was evident in one high roof pocket at a depth of 8.5m, accompanied by a distinct temperature change. The wall fauna ceased abruptly at this point, and small speleothems above were white, and free from overgrowth. This suggests a shallow fresh or brackish lens overlying the saline cave water at this point, although this is not evident at the entrance. The cave appears to be undergoing a stage of major infill, with no obvious water outlets other than the entrance. The floor consists of soft organic muds and polychaete tube fragments.

Algae and large sponges grow near the entrance, with matted growth-forms on the floor sediments. In the twilight and dark zones, polychaete tube worms form the dominant wall fauna, interspersed with knitted or pendulous sponges and sclerosponges. Tubes grown thickly and in clusters, occasionally extending for tens of centimetres in length from walls and speleothems. Crustacea were uncommon, with one small crawfish (Paulinus) and one crab, dwelling within a large entrance sponge, being recorded. Other than transient visitors (snappers, jacks, pipefish) in the entrance and surface creek, the only fish were two spiny cheeked gobies which are commonly found within Bahamian caves, often at considerable distances into the dark zones. Funnels in the floor sediments may be indicative of burrowing animals. The estimated percentage of species cover on the walls was as follows: Polychaete Tubes: 50% Sponges: 20-25% Rock/sediment: 25%.

MERMAID'S POOL, Baintown. VB609.713
The 20m diameter pool is set in thick scrub, growing from a dissected limestone pavement. To the north and east extends a complex chain of solution pits, some of which reach the water table. Four openings in the floor of the 3m deep surface lake lead down into a large underwater chamber, 34m deep on the south side. At 8m depth there is a halocline, with an associated thermocline (2.8°C increase) and H_2S layer. The water remains sulphurous to -15m, and is accompanied by a luxuriant and very delicate bacterial growth on the walls of the chamber. The floor, sloping from -20 to -34m, is of soft grey lime muds and algal fragments. The mud appears to be formed from precipitated calcites and shell fragments.

The walls of the entrance pool were covered with a dense population of algae, polychaete tubeworms, bivalves and encrusting sponges. By the cave entrance on the south side of the pool, faunal and floral density declined with depth, ceasing abruptly at -7m. Shoals of Gambusia manni inhabited the surface pool, and individual fish were occasionally observed below the upper halocline at -8m though never lower than -10m. Below there, the walls were carpeted with a thick growth of colonial bacteria, growing in strands up to 1m long below overhangs, with a shorter mat-like growth form on vertical and inclined surfaces. This bacterial growth was present to the base of the cave at -34m. Mermaid's Pool holds one of the most interesting and varied biotic communities of the inland Blue Holes explored on the island.

Other Blue Hole sites are known on the island, notably a large Blue Hole near Crown Blue Hole, an inland hole east of Tea Bay, and an uninvestigated ocean hole near Winding Bay in the south-east corner of the island. The vertical range of cave development - over 70m - makes Cat Island one of the most interesting islands in the Bahamas group with respect to Pleistocene speleogenesis in response to changing sea-levels.

Further studies on the island will undoubtedly reveal more of the complex saga of cave development in the phreatic zone of Bahamian groundwaters.

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APPENDIX. MERMAIDS, MONSTERS AND BAHAMIAN FOLKLORE

The Bahamas are a relatively recently established society, and the diverse anthropological background of the Bahamian people has lead to a lack of established folklore, although festivals such as the Christmas/New Year Junkanoo are emerging, together with a more indigenous folklore in the Family Islands.

Blue Holes are a favourite source of intrigue, and an established folklore has already developed with respect to these underwater caves on several of the islands. One Blue Hole on Cat Island is reputed to be the home of a horse-eating water monster, and stories on Andros (one of the more superstitious of the islands) tell of a mythical creature called the "Lusca", said to inhabit ocean Blue Holes, and whose breathing is reputed to be the cause of the fierce currents that surge in and out of the Holes, occasionally creating whirlpools on the surface. Whilst scientific exploration has shown these current to be caused by tidal differences on opposite sides of the islands, stories still tell of men and boats being sucked down into the maw of the caves by the monsters inside.

Until recently, certain marine and intertidal Blue Holes may have been frequented by manatees, seals and crocodiles, though all these are now extinct in the Bahamas. Folk memories of these, frequently linked with mermaid stories elsewhere in the world, may form the background to many of the Blue Hole folk tales of the islands. European storybooks, and colourful imaginations, might (a little more cynically) form much of the rest. Blue Holes do, however, have the habit of producing peculiar species previously unknown to science - perhaps the mermaids, the Lusca, and the water-beasts still lurk somewhere in the caves, awaiting discovery?

Mermaid stories form the most common theme, and three of these, from Cat Island and Grand Bahama, are recorded below:

i) Mermaid's Pool, Baintown, Cat Island.
Our guide cautioned us to be quiet, as we stumbled through the thick bush that surrounded the Blue Hole. He wanted, he told us, to see the mermaid that lived in the lake, and who would flee at the first sound of human approach. We crept to the water's edge, but despite our care, saw no trace of such an exotic creature. Our young local guide swore that his father and a friend had been here shooting duck many years before, and had actually seen and shot a mermaid. The body was half-man and half-fish, just like in the stories. His father had taken it to Nassau in his boat, but the boy had no idea what had happened to the corpse after that.

ii) Gaitor's Blue Hole, Dumfries, Cat Island.
Ishmael Gaitor. the old Cat Islander who owned the land around the Blue Hole, told us this story. Long ago, Gaitor's Blue Hole was used by a young Cat Island girl for washing her family's clothes, and each week the girl would make the three kilometre trek into the bush to the deep freshwater lake. One day, she made the journey there, but did not come back in the evening. Despite a long search by her family and friends, she could not be found.

Several weeks later, and very pregnant, she reappeared. It seems she had encountered a young merman at the lake, immediately fallen in love, and spent the intervening months living with him in his splendid home beneath the waters of the lake. At length, homesickness for family and friends had become too much a draw, and as her time approached, she left her aquatic lover to return to her terrestial home.

Her father and brother were less broadminded than she. Plantation owners were one thing, mermen another. Taking their guns to the Blue Hole, they trapped the merman and shot him dead. Several weeks later, the heartbroken girl gave birth to a baby merman, with a tail just like a fish. Legend again said nothing of its fate.

iii) The Bight, Cat Island and Sweeting's Cay, Grand Bahama.
Village girls playing near Blue Holes occasionally had the fortune (or misfortune!) to be greeted by a mermaid, who would coyly ask the girl whether or not she liked the taste of fish. An affirmative answer was a mistake, and resulted in a one-way underwater trip, to drown in the depths. Those who honestly (or cleverly) said "no" would be taken on a different underwater tour, through the crystal palaces (an odd co-incidence) below the lake, and would there be presented with a lock of the mermaid's hair. If they kept their visit secret, and told no-one, a good marriage, wealth and happiness would follow. Tell the tale, and quite the reverse would occur - the gossip would lead a most unfortunate life.

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Preliminary Studies of Speleogenesis on Cat Island, Bahamas

R J PALMER

Abstract: Cat Island, in the Bahamas group, contains three major cave types: sea caves, fossil high-level phreatic caves, and Blue Holes. The processes of formation of these and their position in the development of cave systems during fluctuating sea-levels of the Pleistocene are outlined.

Cat Island lies on the eastern fringe of the Bahamas group, on the Atlantic edge of the Great Bahama Bank. This limestone Bank is a tectonically stable region, with extremely slow subsidence, probably at variable rates and averaging about 1 cm per 250 years (Mullins and Lynts, 1977). The island is composed of calcarenite dunes of Pleistocene and Halocene age, backed by low-lying areas of marine carbonates. Halocene dunes are of comparatively recent age, generally poorly-consolidated (Lind 1969) and are found only along the island coast. They play little part in cavern development at present. Pleistocene dunes of less certain age form the main north-south spine of the island, rising to heights of 60 metres, the highest points of the Bahamas. Mylroie and Carew (1985a) have used amino-acid racetemization to date similar dunes in nearby San Salvador, an island separate from the main Great Bahama Bank at circa 85,000 years BP, and more recent work (Mylroie & Carew 1985b) on palaeomagnetic orientation of paleosols on San Salvador takes formational dates for associated surface calcrete back as far as 700,000 years BP, the oldest rock exposed at the surface so far known from the Bahamas

The island is fringed by active coral reefs to south and east, beyond which the sea floor drops away to depths in excess of 1000m. To the west, a shallow bank 10 to 15m deep extends for 15km to the 600m deep Exuma Sound. Cat Island forms a narrow peninsula of the Great Bahama Bank, linked to the main bank by an 18m deep neck of shallow sea at the north-west corner of the island. Its climate is sub-tropical, with mean annual temperatures of 25°C and a rainfall of approximately 85cm a year. The surface has been extensively plantation-farmed in recent centuries, though agriculture has reverted to a slash-and-burn technique. Where land has not been so cleared for farming, it is covered by a dense coppice shrub, rendering access to many inland areas difficult in the extreme.

The Pleistocene limestones of the island exhibit well-developed karst features, including solution-pits, dolines, limestone pavements, small poljes and underground cavern development. During the 1985 Bahamas phase of Operation Raleigh, a three-week study was made of the terrestial caves and Blue Holes (under-water caves) of Cat Island. Three distinct cave types were recognised: fossil high-level phreatic systems, Blue Holes and sea caves. All appear to relate to past or present eustatic sea levels, and most appear to have been formed under phreatic conditions at the base of a freshwater lens (Palmer and Williams 1984). Cave development was observed to have occurred at several distinct levels, at approximately 5 metres ASL (above present day sea level), 2m ASL and to depths of 63m below sea level. At the present time, the island supports a series of irregular freshwater lenses of varying thickness from 1m to over 20m deep.

CAVE TYPES

Sea Caves

Sea Caves have been formed in exposed cliff faces by marine erosion. The cliffs are the result of truncation of the dune formations, the best examples of which can be found along the south-eastern coast of the island from Cutlass Bay to Port Howe, where the coastline is currently being eroded by marine action.

The two levels of development are found here (McHale et al, this volume) one at present sea-level, and the other approximately 5/6 metres above this. This higher level may correspond to the +6m level of Pleistocene seas at circa 125,000 years BP, and if so, it indicates that primary dune formation took place at or before this high sea-stand.

Caves of this type are typically small, but a 100m long-system at Industrious Hill on the west coast (where marine action appears to have modified a pre-existing phreatic system), and the large cavern of Port Howe Sea Cave (which contains extensive speleothem deposits) are unusually

The main chamber of Port Howe Sea Cave, a two-level system joined and enlarged by marine action following dune truncation.

complex. The Industrious Hill cave lies approximately +2m above present sea level, as does Brackish Well cave near Baintown on the south coast, and these, if marine in origin and/or modification, may correspond to a Holocene +2m sea stance, for which Lind (1969) found additional evidence along the Exuma Sound coast of the island. The complete absence of speleothems in these systems might be indicative of such recent formation or modification. The Port Howe cave is a greater anomaly. It links the +5/6 metre level and lower present level to the top of the dune, with another possible development level at approximately +20m. Though this could be the product of extensive collapse within the cave, it could also be that the present cave is a marine enlargement of one or more earlier phreatic systems within the dune, exposed by its truncation Generally, however, sea caves on the island are only a few metres long and hold little interest for the speleologist.

Fossil Phreatic Caves

Fossil high-level phreatic caves are found within the oldest Pleistocene dunes, and form horizontal mazes often several hundred metres in extent. There is no evidence of directional flow within these systems, and entrance is only possible where the collapse of overlying rock has opened chambers to the surface. There are no sink or resurgence features: large passages which might have been thought to have a conduit role simply end in blank walls of rock, sculptured with solutional hollows. It appears that the caves have formed as enclosed solutional cavities within the dune rock. The close similarity of these cave systems with underwater cave networks reported from elsewhere in the Bahamas, notably Grand Bahama (Palmer 1983) suggest that they have formed under similar phreatic conditions at the base of a high sea-stance freshwater lens (Palmer and Williams 1984). Solutional features in the roof and walls of the Cat Island caves, such as scalloping, solutionally-enlarged upward joints and phreatic mazes, support this theory, as does the complete lack of vadose features within the caves (with one possible minor exception), despite the steeply-dipping dune limestone across which they form. Exposed bedding planes in the wall of Crown Cave dip at angles of up to 30°, whilst the passages within the system are entirely horizontal. The one vadose anomaly is within Crown Cave where a small and immature secondary streamway was found at the bottom of a phreatic rift, though this appears to flow only in the wettest of weather. The whole Crown Cave area is an unusually complex area of cavern development, and warrants further study.

The altitude of most of these caves above present sea-level appears to correspond to two discrete sea-levels, a +6m level (Crown Cave and other northern caves) and a +2m level (Industrious Hill and coastal fragments). Without more concrete evidence, any attempt to relate these levels of development to particular sea-level stands must be largely conjectural, but the higher +6m caves appear to be older, often containing extensive speleothem deposits (Crown Cave, Port Howe Sea Cave), and the lower undecorated +2m caves more recent. The +6m caves would have needed a sea-level of at least 5-6m above present levels to form, even assuming an extremely thin lens and highly-aggressive brackish mixing zone at which such caves might form. The most recent accepted time that this is known to have occurred is around 125,000 years BP (Neumann and Moore, 1975). This would assume that the primary dunes were in existence during this time, and that they were raised during an earlier stage of eustatic exposure, with the caves forming in them once they had consolidated, and been inundated by the rising sea. Mylroie and Carew (1985 a) discuss similar cave development in Lighthouse Cave on the nearby island of San Salvador, which also exhibits phreatic features to +7m ASL, in dunes dated at 85,000 years BP, and give evidence for their formational period being between 85,000 years and 50,000 years BP.

Stepwell Cave (Palmer et al, 1986) is peculiar in that the Pleistocene calcarenites in which the cave has formed appear to have been largely removed at the surface to leave only a thin rock roof above the cave. Later sediments (late Pleistocene?) have formed a secondary eolianite layer above these which appears to post-date the period of cave formation. These sediments have entered the cave through former entrances, blocking these to form banks of unconsolidated or poorly-consolidated sandy limestones and pebble conglomerates within the cave passages, although the same sediments have become more completely cemented where they overlie the pre-existing dune rock at the surface. Where upward migration of the cave roof has encountered these less-consolidated secondary deposits, the younger beds can be differentiated from the older underlying rocks by their softer, sandier consistency. This is most evident at the main entrance to the cave, where the boundary between the two rock types is clearly visible as an unconformity in the north wall.

Fragments of cave passages entered but not

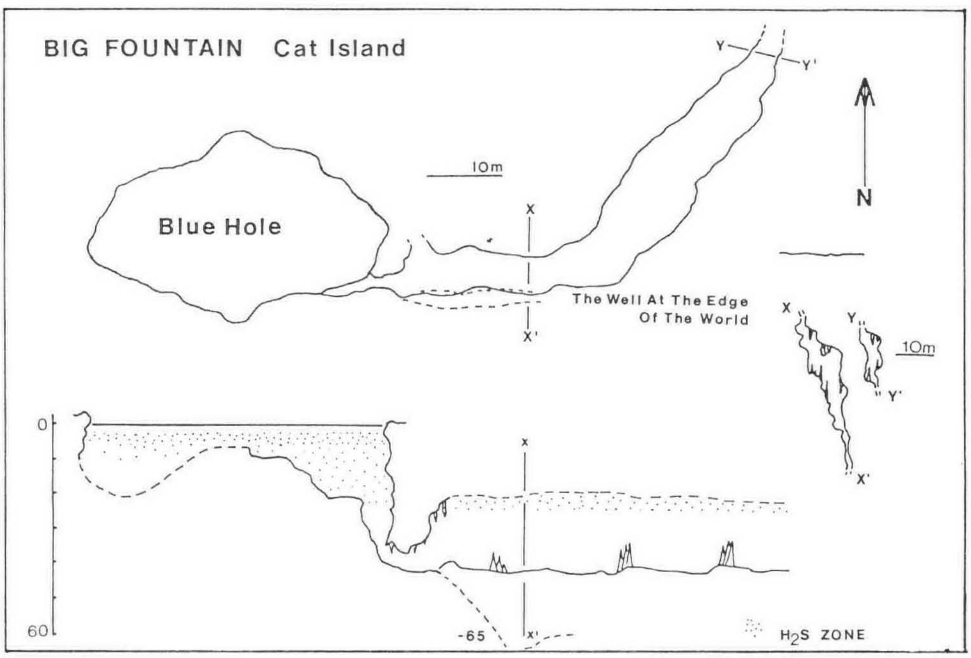
Steeply-dipping dune bedding exposed in Crown Cave. This phreatic system formed horizontally across the dune during a high sea-stance. The darker rock at the base of the passage indicates the depth of guano prior to removal.

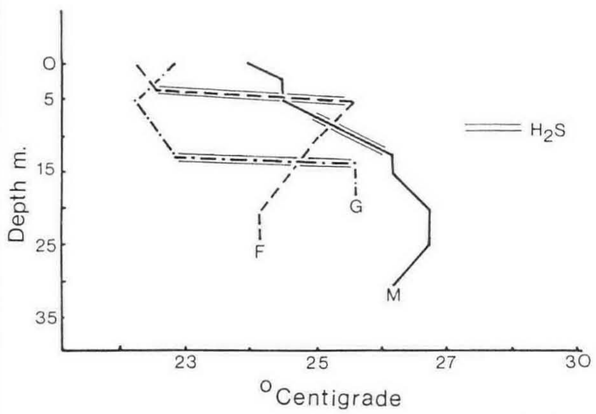
The entrance to Industrious Hill Cave, set on the seaward side of a Pleistocene dune.

surveyed in the hills to the north east of Old Bight may date from the same period as the +5m caves, and may have been formed in the same way. Unfortunately, the original Pleistocene topography has been much obscured by later removal through solution, and it is difficult to relate these fragments to any overall area structure.

Blue Holes

Blue Holes are typically entered through large water-filled openings in the limestone bedrock, either between dunes or in the lower-lying areas of marine carbonates to the west of the dune ridges. Most of the Blue Holes entered in 1985 were of the cenote type where successive collapse of the original cavern roof has opened a vertical shaft to the surface. Four of these cenote Blue Holes were explored in 1985. Of these, three had entrance shafts around 30m in depth, the fourth being shallower at -15m. All were floored by collapse material covered with thick organic silt. One site, Big Fountain (Palmer et al 1986) opened out at one corner of the entrance shaft to enter a large passage on an inclined fracture, which was explored for 70m horizontally without reaching the end. The passage had a maximum gained depth of 63m, and a minimum of -20m. This was a significant discovery, it being unusual in such Bahamian cenote features to be able to enter the pre-existing passages. In this case, the cross-section of the cavern may give some indication of how such cenote Blue Holes form. From the 3m wide roof at -20m, the passage opened rapidly to an estimated 15-20m in cross-section at a depth of 35-40m, below which it narrowed to a 2-3m wide fissure below -60m. The water in the upper zone (above 25m) was less clear than below, and had an increasingly sulphorous taste with decreasing depth. Water in the outside cenote is brackish at this depth, and this fresh/saline intermixture is related directly to the solution of limestone at such levels (Bogli, 1971). If the fracture has been thus enlarged by chemical solution at the -20 to -40m level, followed by subsequent collapse of wall rock and overlying rock beds due to solutional weakening of the rock (enhanced by the removal of buoyant support of the water during periods of low sea-level), it would result in the formation of a cenote in the manner





Temperature profiles for Big Fountain (F). Gaitor's Hole (G). and Mermaid's Pool (M).

described by Palmer and Williams (1984).

Evidence for a current -20/25m deep solutional horizon in the Crown Cave area comes from Crown Blue Hole, where a low, wide and perfectly horizontal passage was entered by diving at a depth of -24m. The floor was obscured by a thin layer of decaying organic/bacterial sediment and the roof was actively in a state of corrosion. The halocline was clearly visible in the centre of the 0.75m high passage. At Boiling Water Blue Hole, near Fernandez Bay there is evidence for a -30 to -40m fossil horizon, where aston collapse (Jimenez 1967; Palmer and Williams 1984) provides entry to a horizontal phreatic passage at that depth. The large cavern at Big Fountain, and other local cenote Holes could well have begun forming when the solutional horizon was at a lower 30-40m level, and continued to enlarge through solution and collapse as the horizon rose with eustatic sea-levels during an interglacial. The presence of speleothems in Big Fountain precludes this having happened in the final Holocene rise. These must have formed during a low sea-level stance following the primary formation of the chamber, and are evident to depths of at least 40m. The current level of enlargement would appear to be around -20m. Sulphur-reducing bacteria are found on the walls of the cave at this depth, and the weak H_2S solution produced by such bacterial activity would have a solutional influence on the surrounding limestone. The present day variation in the depth of localised freshwater lenses suggests that for current sea-levels at least, the concept of solutional horizons must also of necessity be localised.

Only two of the Blue Holes examined were marine-influenced, of which one, Armbrister Blue Hole, proved to be a single isolated chamber, possibly a remnant of a larger system now infilled with sediments. Boiling Water, however, was actively carrying a reversing tidal flow (Williams, 1978) of especial interest in that the inflow was considerably stronger than the outflow. This could be the result of a greater net head of water at the site of the Blue Hole than on the eastern coast of the island, caused by a combination of tidal lag over the 15km wide bank on the west of the island, and the position of the Blue Hole at the head of a tidal creek, thus never allowing the tide to be fully "out" at this site.

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Preliminary Biological Investigations in the Terrestial Caves of Cat Island, Bahamas

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Abstract: The dry caves of Cat Island include roosts for four species of bat, some of which appear to be under threat from human disturbance. Preliminary studies of the invertebrate faunas shows impoverishment owing to guano removal and lack of input of other detrital food sources. The short dry caves, with considerable penetration of daylight, appear to have given little chance for the evolution of cavernicolous species.

This paper presents the initial results of biological collections made by Operation Raleigh venturers under the supervision of the author during December 1984 to January 1985.

Identification of many of the specimens is still at an early stage and a full species list is therefore not given. Some observations on the ecology of the caves are presented.

Full descriptions of the caves together with localities and maps are given elsewhere in this volume. (Palmer 1986). Biological specimens were collected from virtually every site. Bats are the most obvious inhabitants of the caves and support a number of invertebrate species on their guano. An assortment of non-cavernicolous species were also present in the caves.

THE BATS

Bats were present in the majority of caves examined, often in prodigious numbers (2000+ estimated in Strawline Cave); however, exhaustive searches for bat roosts in scrubland and buildings outside proved unproductive.

Methods of Collection

Bats were collected by hand with relative ease; they were then given a lethal dose of anaesthetic, tagged and preserved in formalin. A minimum of specimens were collected, just sufficient to establish an identification series, minimising our impact on the population.

A total of 86 specimens were collected representing four taxa as identified by J.E. Hill (BMNH). These were Macrotus waterhousii compressus (Big eared bat) Natalus lepidus (Gervais funnel-eared bat) Tadarida brasiliensis bahamensis (Brazilian Freetailed bat) Erophylla sezekorniplanifrons (Buffy flower bat).

Discussion

Bats have been collected from Cat Island by previous workers (Allen and Sanborn, 1937), but only a limited series is held in the British Museum (Natural History) collections. The bats of the Bahamas were discussed in some detail by Koopman et al. (1957). They are of general interest as they are the only indigenious land mammal in the islands with the exception of the hutia, Geocapromys ingrahami. Specifically, the bat fauna is of zoological interest since the series represent an assemblage of basically Neotropical origin. It is an impoverished fauna, of special note because of its northern distribution, the Bahamas being the only part of the West Indies to extend into temperate zones (J.E. Hill pers comm.). The four species collected are found throughout the Bahamas, but Tadarida brasiliensis is a new record for Cat Island.

Cat Island lacks the montane forest, which is the chief habitat of bats on the Antillian islands, so our observations confirm the important influence of caves on the distribution and density of the bats.

Bats are important to the cave ecosystem in that they provide a food-energy input in the form of guano. Guano is also utilised by the human inhabitants of the island as a source of nitrogenous fertilizer to supplement the meagre soils of the limestone. Bat Guano is known colloqually as cavedirt and its producers are universally called ratbats. Local sources suggest that, at one time, the excavation of cavedirt represented a major industry on the island. This has declined presumably alongside the demise of the cotton and pineapple plantations and the advent of chemical fertilizers; and also perhaps as a consequence of many caves being exhausted of

Bats in Crown Cave.

supplies of both guano and bats.

It is rather surprising to observe that the bat populations are treated with little respect by the local population. Evidence was found that repeated human disturbance had driven populations out of some caves e.g. Whale Creek cave. It is also probable that repeated guano excavation (in some cases a 2m depth had been removed over $50m^2$) has destroyed the habitat of guano dwelling invertebrates. In some cave sites bat populations had been extirpated and existing guano deposits had been removed by mining, leaving behind only dry sterile substrates, e.g. entrances of Strawline and Industrious Hill Caves. In cave sites away from centres of population, or in those rarely visited by locals, bats were more plentiful and often fresh guano was present with an associated community of invertebrates, e.g. Crown and Griffin Caves.

Some of the antipathy towards bats was based on fears of bat-borne rabies and resentment of bats as pests of fruit crops. In his report to Operations Raleigh J.E. Hill refuted both these suspicions as follows:-

"Firstly the vampire bats, Desmodus, Didemus and Diphylla do not occur in the Bahamas. Thus the major vector of bat-borne rabies is absent. The rabies virus has been found in a number of other species but these do not attack humans unless provoked. There is little basis for fear of bat-borne rabies in the Bahamas, any risk being further reduced by taking the commonsense precaution of not handling dead or moribound bats".

A more real health risk associated with bats is that of histoplasmosis. Any large bat roost in the tropics or semi-tropics that contain large quantities of guano may also harbour the spores of histoplasmosis. As some cavers well know, these spores, if inhaled, can produce a pneumonia-like chest infection which can prove fatal in a minority of cases. During the Cat Island Expedition personnel were advised to avoid areas of very dry dusty guano which histoplasmosis favours. Not withstanding these precautions one member of the bat team did suffer symptons similar to those seen in histoplasmosis. However, the infection has not yet been confirmed as histoplasmosis.

An interesting study would have been to test all expedition members for histoplasmosis infection before and after the expedition to assess the presence of the disease on the island. Since most of the personnel were non-cavers, it would have been unlikely that they would have been exposed to the disease prior to visiting Cat Island Caves. The question of histoplasmosis is certainly worthy of further study especially in view of the suggestion by some Cat Islanders that Crown Cave be developed as a tourist attraction; histoplasmosis could carry a remote but possible hazard that visitors might wish to avoid.

On the question of bats as pests of fruit crops, J.E. Hill made the following comments on the species collected.

"Macrotus and Erophylla are pollen, nectar or fruit eaters with some insects. The species Natalus and Tadaria feed exclusively on insects. Insect remains, fruit stones and seed cases often form a loose litter over guano beds. Although some ripe fruits may be taken by frugivorous species, the nectarivores and frugivores make an important contribution to agriculture as polinators of many economically important plants and as dispersers of their seeds. In addition all of the species function as insect predators reducing the population of insect pests on the island. Thus any reduction of bat populations by direct disturbance or by uncontrolled use of their roosts could result in damage to the economic health of the island. Another vitally important reason to conserve and protect the bats of the Bahamas, wherever they may be, lies in their taxonomic status. The genera Monophyllus and Erophylla are endemic to the West Indies and belong to a small group of bats, the Phyllonycterinae, that is itself unique to the West Indies and is therefore of great intrinsic interest".

Conservation measures in the Bahamas might well take the form of education to stress the value and harmless nature of the ratbats. Our expedition attempted this on a small scale by encouraging local children to help in the biological survey of the caves and also by giving short talks in local schools to try to demystify the children's concept of the ratbats as frightening spirits.

A further strategy to conserve the bats would be to encourage the preservation of the cave environment that houses the bats from the disturbance generated by guano digging and tourist development. In the case of the former it would be unfair and probably impossible to limit guano excavation; however, the people should be made aware that without bats there would be no guano.

On the second threat, tourist development, there are already plans on Middle Caicos Island to make bat roosts into tourist caves, (Miss M. Reid pers comm.) On Cat Island, as already stated, some islanders wish to see Crown Cave developed as a tourist attraction which would be disastrous for this important biological site. For the moment financial contraints make such development highly unlikely, but it is a factor to be considered in any future study/planning.

In order to avoid drawing too pessimistic a picture of bat disturbance on the Cat Island, it is important to realise that many more cave sites other than those explored probably exist in the interior of the island. The investigation of such sites would provide a more accurate assessment of the status of bat populations on the island and their current conservation status.

THE INVERTEBRATES

Methods and Introduction

Collections were made by hand from all substrates in each cave, often by the inexperienced venturers who rapidly became adept at obtaining the material. In addition pitfall traps were set in two caves (Crown and Brackish Well) and bread and meat baits placed in several other sites. Temperatur readings were taken in a number of caves.

All specimens collected were preserved in alcohol and have been forwarded to the relevant experts for identification. As the identification of this collection is not yet complete, it is premature here to present a full species list for the caves. Instead there follows a general account of the ecology of the various Cat Island cave habitats based on observations made in the field. In general, the fauna of the caves was depauperate when compared to the fauna in the overlying forest scrub and soil. In addition very few of the invertebrates were seen to exhibit cavernicolous characteristics, in contrast to the varied and obviously cave-adapted Blue Hole fauna, observed elsewhere on the island. The following sections proposes some explanation for the dearth of hypogean invertebrates and also describes the type of habitat to be encountered in the caves of Cat Island.

The Habitats and their Fauna

1. The majority of the cave sites examined had dry sandy substrates near cave entrances or in such close proximity to secondary entrances, that they represent a threshold zone (Jefferson 1976) throughout their length. The walls and roofs of such sites had numerous solution pockets and fissures which were home to a variety of epigean species, principally the ubiquitous cockroach (Periplaneta sp.). Examples of this habitat were Whale Creek Cave, Williams Hill Cave and Zonicle Hill Cave.

2. The second principal habitat was formed by disturbed guano beds. Such beds had either been excavated by the island people for cave dirt or sometimes trampled by domestic goats sheltering within the cave. In a number of these sites the local bat population had evacuated or retreated to

Dry guano floor in Crown Cave.

inner passages. (e.g. Strawline and Brackish Well Caves.)

Both habitats 1 and 2 were utilised by an array of surface-dwelling species, ranging from land crabs and crickets to soil inhabitants such as pseudo-scorpions, centipedes, woodlice and a variety of spiders. All these species are likely to be accidental or, in the case of the Arachnids, possible trogloxenes.

3a. The third and most interesting cave habitat encountered on Cat Island was that provided by undisturbed fresh guano. Guano is likely to be the major food energy source in the caves. The specialised nature of guanobious species is well documented elsewhere in the tropics. (Decou 1981, Chapman 1981). Thus it was likely that such substrates would yeild our most interesting finds.

It is somewhat surprising, that given the large numbers of bats in the caves and their wide distribution, that only three caves had large deposits of fresh guano, of more than a few square metres in area. These sites were Strawline, Griffin and Crown Caves - deposits up to 700 m^2 were seen in the latter site. It is also significant that none of these sites were exploited for cave-dirt by local people.

As predicted, the guano yielded a small but fascinating array of species capitalising on the rich bacterial and fungal content of the guano (Oruport 1964). The guano was covered with the seed-like egg cases of tineid moths, many containing pupae. Adult moths were also abundant above the guano. The substrate was also utilised by various mites and collembola. More interesting, was a species of 'isopod-like' beetle or beetle larva which was extremely abundant, all over the guano and able to dig into the substrate to evade capture; these measured 1 cm in length.

A species of opilinid was also common, and this may prey on the other inhabitants, as may the numerous psuedo-scorpions observed in the guano. These are the same species of psuedo-scorpion seen in the dry and disturbed guano habitat.

3b. In Crown Cave much of the fresh guano was inundated by percolation water producing a wet guano in contact with a saturated atmosphere. Elsewhere (Chapman 1981) such boggy guano has yielded its own specialised fauna. Surprisingly, despite repeated observation and baiting, no guanobious species were collected from the site. It was populated only by cockroaches of a species seen in the cave entrance zone.

4. The final habitat described on Cat Island was that of standing water. As already stated, the majority of the island caves were arid with minimal percolation water entering. However, Crown Cave possessed a number of 2m^2 shallow (5cm) pools of fresh water. These were formed on a solid calcite floor and fed by the overlying palmetto (Sabal bahamensis) forest. It was difficult to establish whether further pools are formed during the rains of May, June and October, but no evidence was found for this supposition in the form of dried-up ponds etc.

The Crown Cave pools were of interest in that they contained a large population of Ostracods (Chamydotheca unispinosa). This is a first record for Cat Island, though they have been collected from fresh water wells on the other islands. The ostracods may be indicative of an interstitial fauna living in the microfissures and cavities above the fresh water lens.

Discussion

It is useful to consider the surface environment of the island, to gain an understanding of the conditions present in its' caves. Like the other Bahamian islands, Cat Island is composed of Pleistocene and Holocene limestones which are largely a product of coral growth influenced by glacio-eustatic sea level fluctuations (Lind 1969). Because of this Karst development there is no concentrated surface run off in the form of rivers and streams. Precipitation rapidly disappears underground leaving the surface dry.

In terms of its climax-ecotype Cat Island may be classified as a 'tropical dry forest' environment with potential evapotranspiration exceeding precipitation (Holdridge 1964). Soil development under these conditions is not pronounced, resulting in thin soils of low organic content.

How then do these conditions affect the cave ecosystem? The complexity of a cave fauna is limited by the available niches in the cave ecosystem. Caves which receive significant energy input in the form of stream-borne detritus, trogloxene bodies and organically-rich sediments washed vertically down open joints from the surface are likely to have diverse faunas as many different niches are available (Chapman1983).

The xerophytic conditions on the surface of the island results in a relatively low biomass, further reduced by grazing and cropping. Soil cover is thin and so it is probable that little organic matter enters the cave systems through vertical seepage. The high surface temperatures probably result in rapid oxidation of organic material in the soil bacteria furhter reducing the energy content of sediments entering the cave. In addition the caves lack the streams and rivers found in many temperate and tropical caves which are the main agents reponsible for introducing detritus. This leaves only one important source of energy entering the cave, namely guano; this must therefore represent one of the most important factors, controlling the invertebrate ecology of the caves.

It is also difficult to envisage how cavernicolous faunas could have evolved in the Cat Island caves, given the paleoclimatic history of the islands, which has been dominated by glacio-eustatic sea level changes in which the caves may have been partially or wholly submerged for long periods in their history. Barr (1968) statedthat troglobitic evolution is created when surface conditions remove surface fauna, isolating troglophiles in caves, and only then if a diverse and adequate food supply is maintained to the troglophiles during the surface change. It is unlikely that non-aquatic cavernicoles could have survived the traumatic sea level changes punctuating the islands' recent geological history.

A third environmental factor on Cat Island is the microclimate with in the caves. As described elsewhere in this paper the caves are all relatively short and shallow, often with many entrances. Thus, the occurrence of a true deep-cave environment with stable air temperatures and saturated atmosphere was very rare in the sites visited. Indeed many of the caves lacked even a true dark zone (Jefferson 1976) due to the presence of numerous entrances and skylights formed by roof collapse, allowing light to penetrate. It is unlikely, that even the true dark zone habitats in these caves would provide a suitable habitat for the evolution of troglobitic species. Howarth (1980) and Chapman (1982) both argued that troglobites are adapted to cope with near-saturated atmospheres and favour draught-free habitats. In all the caves visited, much of the substrate was dry sand or, where water was present, draughting entrances were in close proximity. Thus humidity levels in the sites are far from favourable to specialised terrestrial cavernicoles.

CONCLUSION

The mostly short, dry caves of Cat Island have little biospeleological interest. However, the undisturbed guano of some of the caves is undoubtedly an important habitat for some cavernicolous species. It is possible that some guano dwelling species may prove to be troglophilic or even troglobitic, when identification is complete.

The occurrence of terrestrial troglobites would raise some interesting evolutionary and biogeographical questions. For example would any such species be the recent descendants of native epigean species which have become increasingly cave adapted or might they represent an outlying remnant fauna, formerly widespread in the Antilles and recently isolated by changes in sea level?

This brief study raises important conservation issues in that the guano dwelling fauna is sensitive to and has already been significantly affected by human activity, specifically cave-dirt excavation. Any future collectors would do well to locate a bat cave as yet undisturbed by the islanders, if they wish to examine a truely authentic Cat Island cave fauna.

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