Cave Science

The Transactions of the British Cave Research Association

BCRA

Volume 13 Number 3 December 1986

Karst geomorphology of Western Guizhou

Caves and limestones of Tonga

Evolution of the Castleton cave systems

Cave Science

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Cave Science

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

Volume 13 Number 3 December 1986

Contents

Cover: The fine Main Passage of the Peak Cavern at Squaws Junction, where the early phreatic tube is clearly seen on the controlling bedding plane, with the vadose canyon below it. The passage enters on the right and takes the sharp bend to go downstream on the left giving this fine view from the Main Stream Inlet ledge. By Paul Deakin.

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Karst Geomorphology of Western Guizhou, China

Peter SMART, Tony WALTHAM, YANG Mingde & ZHANG Ying-jun

Abstract: The Anshun and Shuicheng regions lie on the western part of the spectacular karst plateau of Guizhou. Cone karst of all types occurs, and is dissected by deeply incised fluvial canyons. The landscape types show a clear zonation from Fenglin Basin karst on the plateau interfluves, through Fenglin Valley and Fengong Valley, to Fengcong Depression karst close to the trunk rivers. Caves are mostly of phreatic origin, with both active and multiple high-level fossil systems, which indicate long histories of episodic uplift and rejuvenation. River capture, above and below ground, is a recurring feature in the karst, and is spectacularly developed along the incised Sancha River. Morphometric analysis of the karst cones reveals a remarkable uniformity and only limited geological control. The critical factor in the evolution of the karst is the rate of tectonic uplift: a model of evolution relates the contrasting types of karst landscapes to base level control and the relative rates of surface denudation, lateral planation and tectonic uplift.

INTRODUCTION

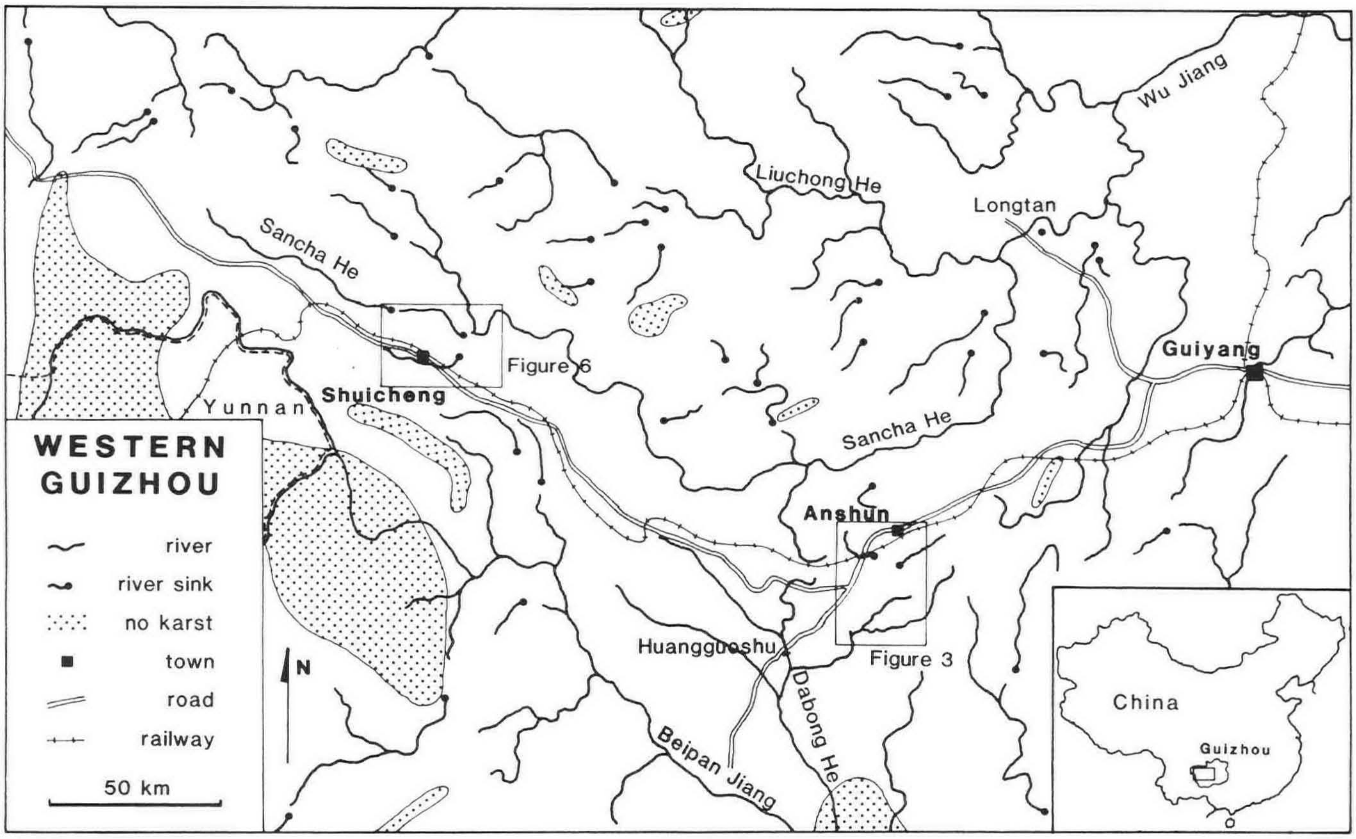
The Guizhou Plateau is a broad upland region separating the Yangtze and Pearl Rivers in southern China. It ranges in altitude from 1000 m to nearly 3000 m, and over 70% of its surface is limestone karst. The area has been studied by workers from Guizhou University, and additional work on both the caves and the surface karst was carried out during the joint co-operative project, "China Caves '85". This paper describes some aspects of the karst geomorphology of western Guizhou, particularly in the areas around Anshun and Shuicheng (figure 1), where carbonate rocks form over 90% of the surface outcrops, and the dominant landforms comprise cone karst of several different types. These areas lie over 200 km west of the Dushan karst, described by Song (1986), but readers will see many parallels in the landforms and their zonation.

Anshun and Shuicheng both lie on the plateau divide between the two drainage basins of the Wu Jiang (flowing north into the Chang Jiang, or Yangtze) and the Beipan Jiang (flowing south into the Zhu Jiang, or Pearl). These rivers and their major tributaries have cut deep into the plateau to form valleys and canyons with steep sides. Adjacent to these trunk valleys, the local relief is at a maximum (commonly up to 700 m), while on the plateau interfluves it is much less (in many areas less than 200 m).

Because of the greater uplift of the Guizhou Plateau in the west, the Shuicheng area is both higher and more dissected than the Anshun area (Table 1). Rainfall originates from the southeast, and therefore declines towards the northwest, despite the increase in altitude.

Carbonate rocks supporting the karst in these parts of western Guizhou include limestones and dolomites of Carboniferous, Permian and Triassic age. Clastic rocks, and some volcanics, form only

Figure 1. Location map and regional drainage pattern.



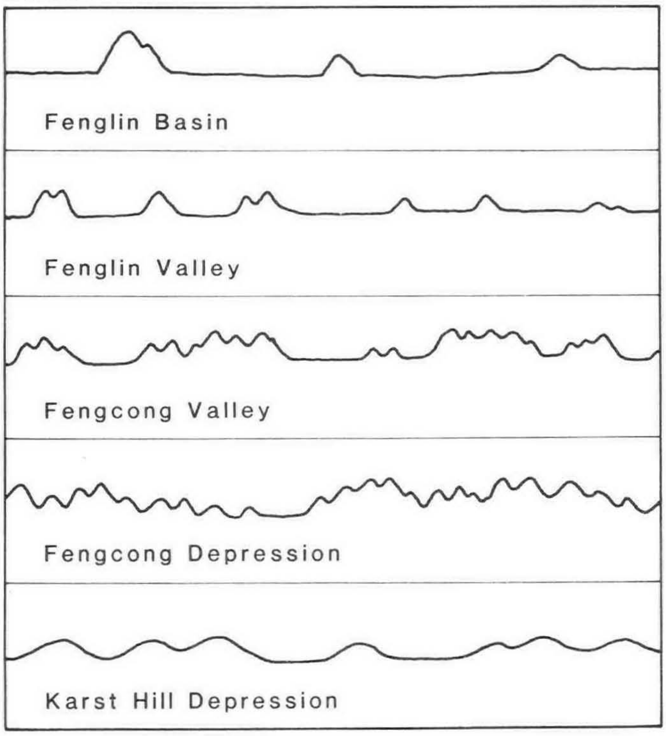
a small proportion of a very thick carbonate sequence. The geological structure is complex, and limestone bedding locally assumes all dips from horizontal to vertical. Strong intermittent uplift has affected the whole Plateau through the last 50 million years, and differential movement on fault blocks has continued into the Quaternary; this has been especially important in the Shuicheng area where it has influenced the patterns of plateaus and gorges and also the landforms evolution within the karst.

KARST LANDFORMS

Within the Anshun and Shuicheng regions there is a spectacular range of karst landforms, including all types of cone karst, dolines, sinkholes and shafts, karst basins and poljes, dry and blind valleys, active and fossil caves, natural bridges and underground rivers. The landscape is described in terms of the density and pattern of karst hills and the proportional areas of depressions and valleys. In Chinese karst studies the prime descriptive factor is the hill morphology. Consquently the main landscape types recognised in Guizhou are the isolated hills of fenglin and the clustered hills of fengcong. (Though fenglin and fengcong have mostly appeared in the Western literature in reference to the tower karst of Guangxi, they are applied equally in Chinese literature to the cone karst of Guizhou).

The two main karst types are then sub-divided according to the morphology and lateral extent of the negative landforms separating the hills. Depressions are generally small and have floors, with nil or minimal alluviation, which are above the level of the regional water table. Valleys are generally larger and intersect the water table; in many instances they have surface streams on their floors and may be elongated along the lines of geologically weaker structures. Basins have extensive flat floors, which may be both mantled in sediment or exposed bedrock, and have perennial surface drainage. (Some Chinese workers use the alternative term karst plain, though this can lead to confusion with a plain having no hills at all).

Figure 2. Diagrammatic profiles of the main karst types in western Guizhou.



Fencong Depression karst east of Shuicheng.
(Photos by Tony Waltham, except where otherwise credited)

Five major landscape types are recognised in these regions of western Guizhou, (and are shown diagrammatically in figure 2):-

Fenglin Basin: large karst basin or polje, with isolated towers or cones (fenglin) spread thinly across the basin or near its margins. The flat area greatly exceeds the hill area, and surface streams normally flow on an alluviated floor.

Fenglin Valley: isolated karst cones (fenglin) combined with open valleys containing surface streams. Cone summits are generally 80-150 m above the valley floors. This is only a transitional type between Fenglin Basin and Fengcong Valley.

Fengcong Valley: combination of clustered cones on a common base (fengcong) and valleys. The area of fengcong is normally greater than that of the valleys.

Fengcong Depression: combination of clustered cones (fengcong) and closed depressions which may be of great depth. The depressions are drained by sinkholes and commonly lie 100-200 m, or more, below the cone summits. The area of fengcong is greater than that of the depressions.

Karst Hill Depression: combination of low karst hills and closed depressions. The hills are rather dome-shaped with slope angles of generally less than 38°. In these parts of western Guizhou, this landform is mostly developed in dolomites, or impure, or thin-bedded limestones.

This landscape classification is broadly similar to the groupings described by Atkinson and Song (Song, 1986) with reference to Guizhou and Guangxi. It should also be noted that the karst cones of Guizhou are mostly steep; only in the Karst Hill Depression landscapes do the cones resemble the gently rounded forms of the classical Gunung Sewu type (Waltham et al, 1983). The cone

Location	Altitude	Regional relief	Mean temperature	Mean rainfall
Anshun	1300 m	1100-1500 m	14.2 °C	1350 mm
Shuicheng	1800 m	1200-2600 m	12.2 °C	1225 mm

Table 1. Relief and climate of Anshun and Shuicheng.

morphometry is discussed in more detail later in this paper.

The spatial zonation of these landscape types is clearly seen in the Anshun region, where the karst of the Longgong Dong drainage basin contains a transect from Fenglin Basin to Fengcong Depression.

THE KARST OF LONGGONG

The Longgong Dong underground river system feeds into the upper reaches of the Wanger He, which is a mjaor tributary of the Dabong He and thence the Beipan Jiang. It traverses and drains a spectacular region of cone karst between the high-level, interfluve basin of Anshun and the incised Wanger He valley (figure 3). The catchment area is around 250 sq.km. and the mean flow from the Longgong resurgence ranges from 480 L/s in the dry season to 5500 L/s in the wet season. The river system consists of two major branches, the Youcai He in the east with its longest arm extending 31 km upstream of the resurgence,and the Alang He in the west; both have their headwaters in the southern part of the Anshun basin. They converge in the Xuantang polje before flowing mainly underground to the Longgong resurgence.

The geological structure of the Longgong area is dominated by faults and folds oriented SW-NE, which give a noticeable grain to the landscape. This is particularly conspicuous in the central area of Fengcong Valley karst, where roughly parallel valleys along fault lines or zones of weaker limestone are separated by lines of cones forming serrated ridges in the stronger bands of rock. The result of this is a trellised drainage pattern, with the longer sections of surface river orientated SW-NE, and numerous instances of river capture.

The main rivers have many alternating sections of underground and surface flow, and underground river capture is a significant feature in this maturing karst landscape. Underground capture is demonstrated by the Ninggu He, southeast of Anshun (figure 3), which at its first sink now goes underground to the southeast, abandonning a fault-guided valley with an underfit stream towards the southwest.

Zoning of the karst landscapes

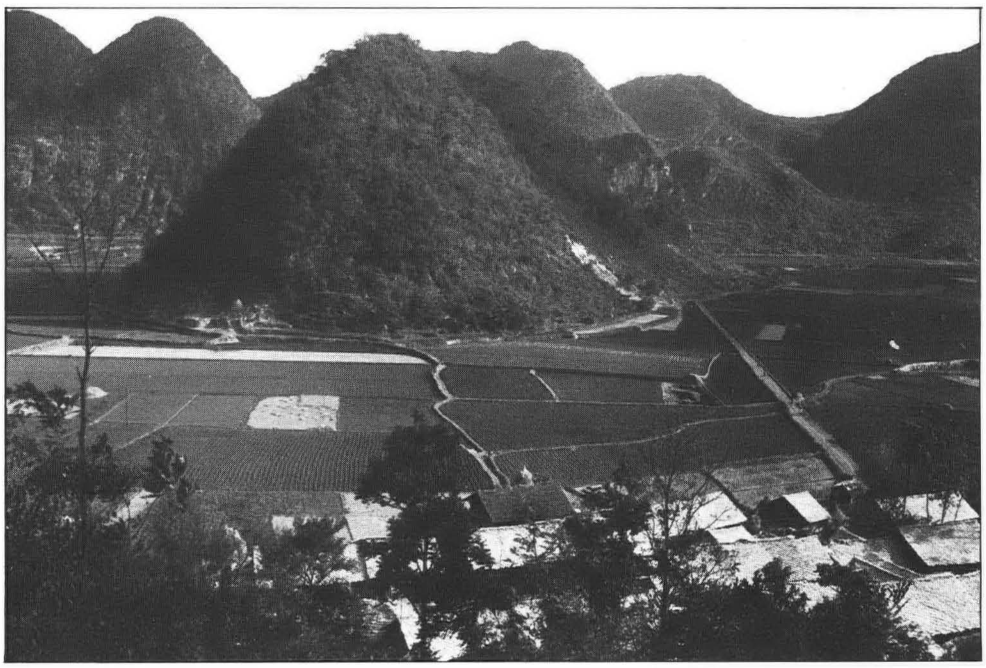
The landscape in this karst area is dominantly of steep-sided fenglin and fengcong cones. The spatial distribution of the sub-types is related primarily to the distance from the incised course of the Wanger He (figure 3).

SHORT GLOSSARY

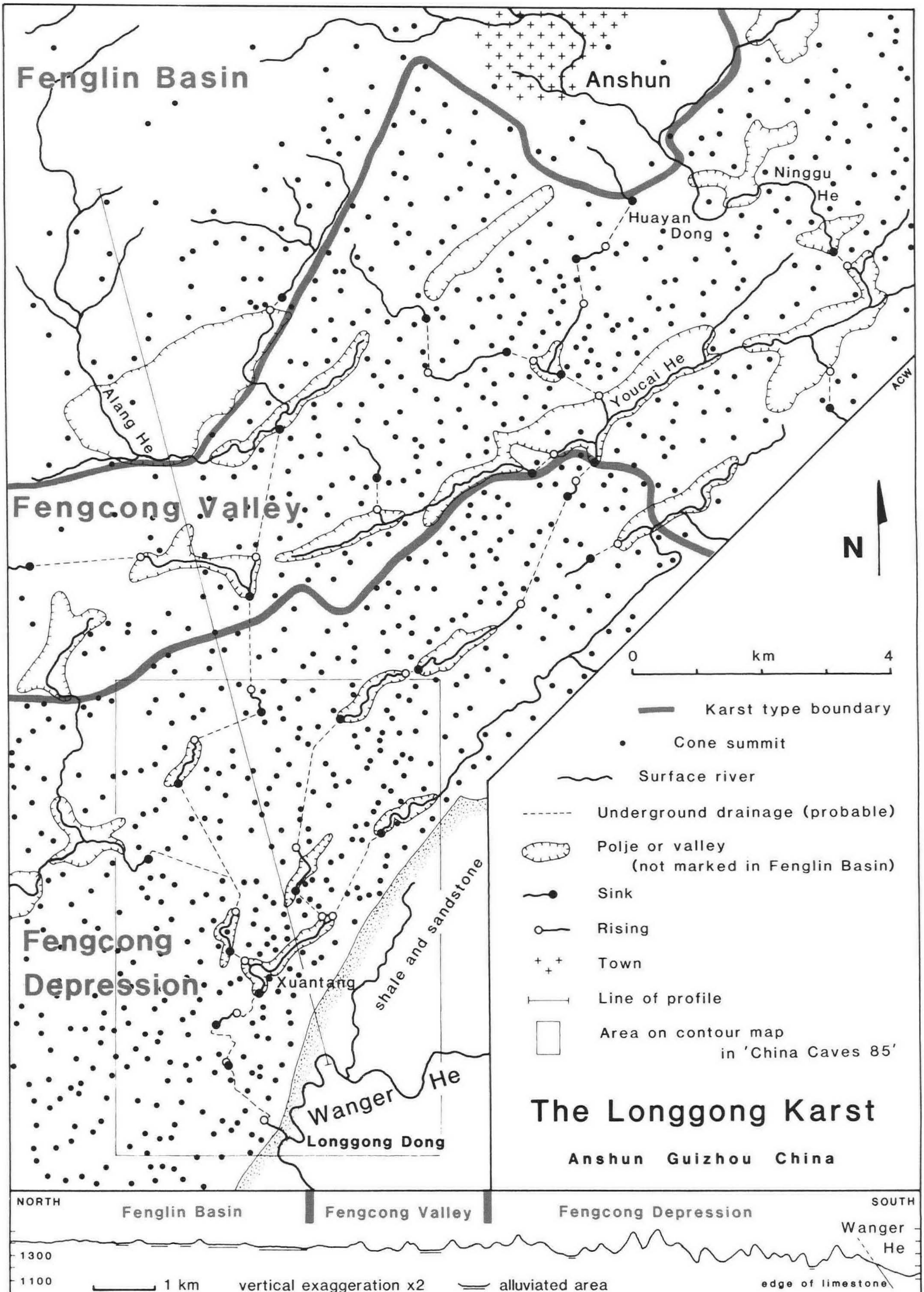
dong	-	cave
fengcong	-	literally peak cluster, pronounced fungtsung
	-	karst with many hills packed together
fenglin	-	literally peak forest, pronounced funglin
	-	karst with isolated hills on alluvial plain
he	-	stream or river
jiang	-	major river
qiao	-	bridge
shan	-	mountain
shui	-	water

Fengcong Depression karst occupies the zone of greatest relief adjacent to the Longgong Dong resurgence on the Wanger He (see contour map prepared from published topographical maps by the China Caves '85 Project : Waltham, 1986). The cones are interspersed with deep depressions with steep sides, and underground drainage predominates. North of this is a band of Fengcong Valley karst. The relief remains considerable, but the fengcong hill clusters are separated by alluviated karst valleys with surface drainage. These show evidence of elongation along the regional strike, and become both wider and longer towards the north; there the valleys reach 1 km wide and are up to 5 km long, with extensive and continuous surface drainage on an almost continuous, and in places thick, cover of alluvium. The valleys are separated by substantial belts of fengcong, but their overall relief is considerably reduced.

In the headwaters of the Longgong catchment, lies a substantial area of Fenglin Basin karst occupying the broad interfluve area between the Wanger He and the Sancha He, to the north. Isolated karst hills, many of which have been modified by quarrying near Anshun, rise from a low-gradient, and somewhat irregular, limestone plain veneered by sediments and extensively terraced for rice cultivation. Red and brown residual soils are thickest on gypsiferous and secondarily dolomitised limestones, and may be up to 20 m deep; some have high iron contents and others contain barite gravels. The increased dolomite content leads to reduced solutional rates and some outcrops are covered by thin sheets of



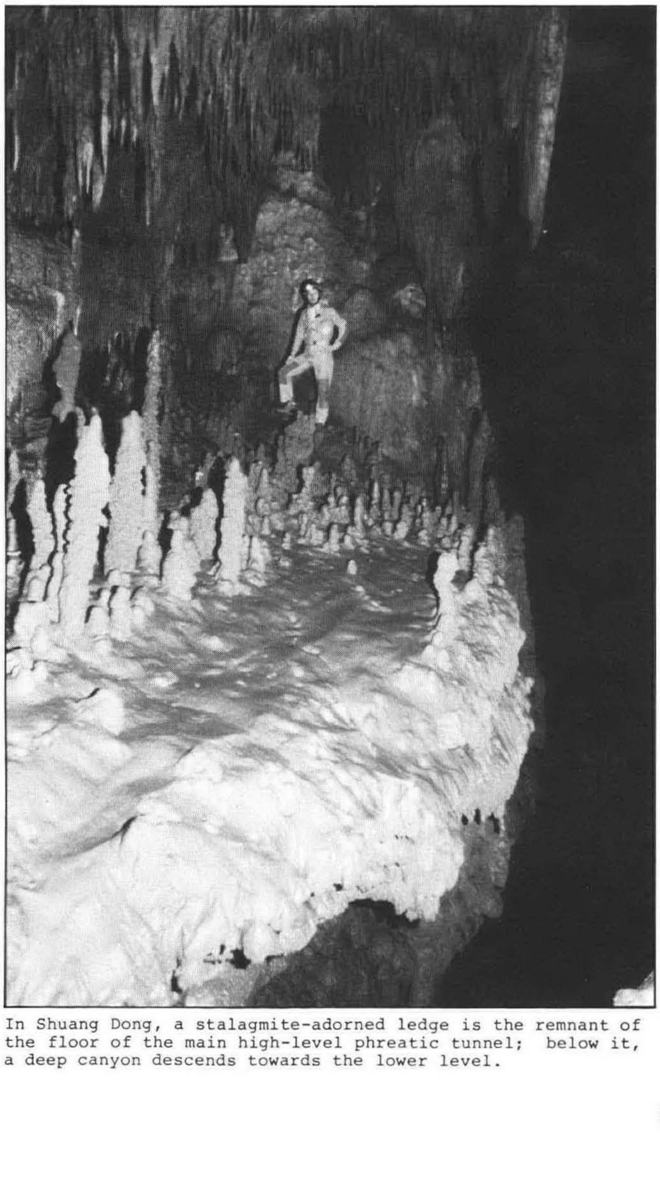
Smooth sided conical hills overlook an alluviated polje floor in the Youcai He catchment in the Fengcong Valley zone of the Longgong karst.


Fenglin Basin
Anshun
Ninggu He
Huayan Dong
Alang He
Youcai He
ACW
Fengcong Valley
N
0 km 4
Karst type boundary
Cone summit
Surface river
Underground drainage (probable)
Polje or valley
(not marked in Fenglin Basin)
Sink
Rising
Town
Line of profile
Area on contour map
in 'China Caves 85'
Fengcong Depression
Xuantang
shale and sandstone
Wanger He
Longgong Dong
The Longgong Karst
Anshun Guizhou China
NORTH
SOUTH
Fenglin Basin
Fengcong Valley
Fengcong Depression
Wanger He
1300
1100
1 km
vertical exaggeration x2
alluviated area
edge of limestone

A thin alluvial cover on a planed bedrock surface forms the northern part of the Anshun basin. Fengcong karst rises beyond a faulted boundary of the basin floor.

Figure 3. (opposite) The karst of Longgong and Anshun, showing the distribution of cones and poljes, the zoning into landscape types and the main lines of surface and underground drainage.

dolomite sand, as on the 1400-1450 m surfaces on the interfluve areas around Anshun. The relief is generally low, but increases southward. The transition between Fenglin Plain and Fengcong Valley is relatively abrupt south of Anshun, but further west there is a more gradual transition and a band of Fenglin Valley type transitional between the two could perhaps be recognised. It should be stressed that the boundaries between the karst types are rarely sharply defined, but involve broad zones of intermediate character and are also dependent on the scale of the survey (Yuan, 1985).



In Shuang Dong, a stalagmite-adorned ledge is the remnant of the floor of the main high-level phreatic tunnel; below it, a deep canyon descends towards the lower level.

This zonation of the karst landscape, from Fenglin Basin on the interfluve to Fengcong Depression adjacent to the incised trunk valley is also observed elsewhere on the Guizhou Plateau. Song (1986) records a similar pattern in the Dushan area of southern Guizhou, and it may also be recognised in the Shuicheng area, described below. The suite of landforms is essentially contemporaneous, in that they were all initiated at approximately the same time. The marked contrasts are a result of the active incision of the major river valleys following uplift in the Quaternary. Adjacent to the rivers, the high relief has permitted development of depressions and cones unconstrained by base level, but the effects of rejuvenation have not yet reached the upstream parts of the landscape, which is still evolving under conditions of low relief. However, if the rates of surface denudation are similar in the two areas, the interfluve landscape is considerably more evolved than that adjacent to the rivers, and is thus representative of the later stages of karst landform development because less time is required for elimination of the limited relief in this area. The spatial zonation is thus doubly instructive, in illustrating the effects of both available relief and also time on evolution of surface landforms in the area.

THE DISTRIBUTION OF CAVES

Within the Fengcong Depression karst, regional water tables are deep and are rarely intersected by depression floors, due to the locally high relief. There is a general absence of surface streams, and both the deepest and longest cave drainage routes are found in this terrain. Close to the Wu Jiang north of Anshun (figure 1), the Longtan shaft is 275 m deep (surveyed by Boothroyd, in Waltham, 1986), and is only one of numerous deep shafts draining the fengcong depression floors in an area with an overall relief of more than 500 m. The caves of the fengcong areas also display many features indicative of falling base levels. Abandoned trunk cave passages commonly occur at different elevations. Two, three or more levels of caves may exhibit features of phreatic origin or of development close to the water table. Some cave systems have a multi-level pattern, while in others the water table and phreatic passages are entrenched by vadose canyons 30 m or more in depth and with gentle gradients. Vadose modification of phreatic features is common, and is further

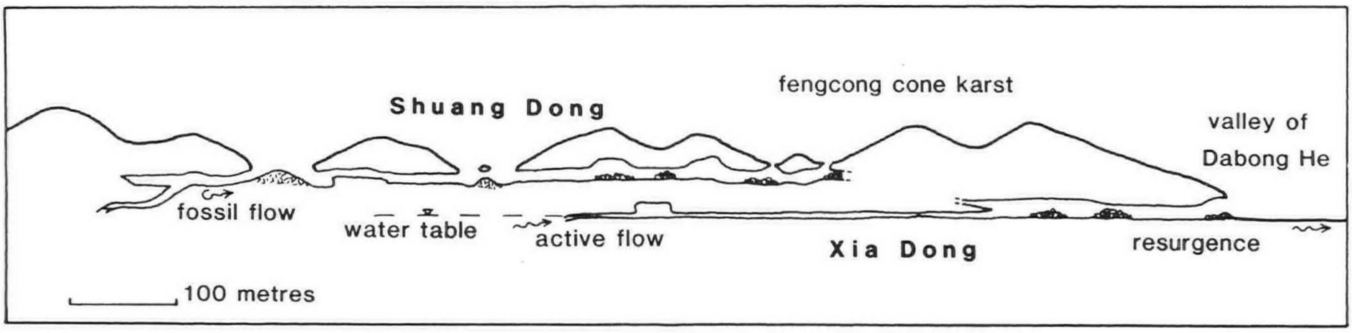


Figure 4. Diagrammatic profile through Shuang Dong and Xia Dong, with the old high-level cave passage now breached by depressions in the karst.

evidence of incision associated with regional uplift. Through-caves have been formed where depressions in the fengcong karst have breached either active or fossil passages, and some short abandoned cave segments have been isolated near the summits of the cones.

Xia Dong and Shuang Dong (figure 4), west of Anshun, exhibit many features typical of these caves. Shuang Dong is an abandoned high-level passage, breached by surface lowering and collapse of the depression floors. Its antiquity is demonstrated by the copious stalagmite deposits which in places almost block the passage. Xia Dong is the active cave, which has suffered recent sedimentation behind the irrigation dam across the resurgence exit. Its main passage is a large tube, with a deep vadose trench, until the old phreatic element is lost in high-level chambers. The upstream active cave follows smaller tubes with more limited entrenchment. This system of caves therefore shows both phreatic abandonment and vadose entrenchment in response to the incision of the Dabong He into which it drains. This river has a series of knick points as a result of multiple rejuvenation, the most conspicuous of which is the Huangguoshu waterfall (Zhang & Mo, 1982: Waltham, 1984)

The Longgong caves

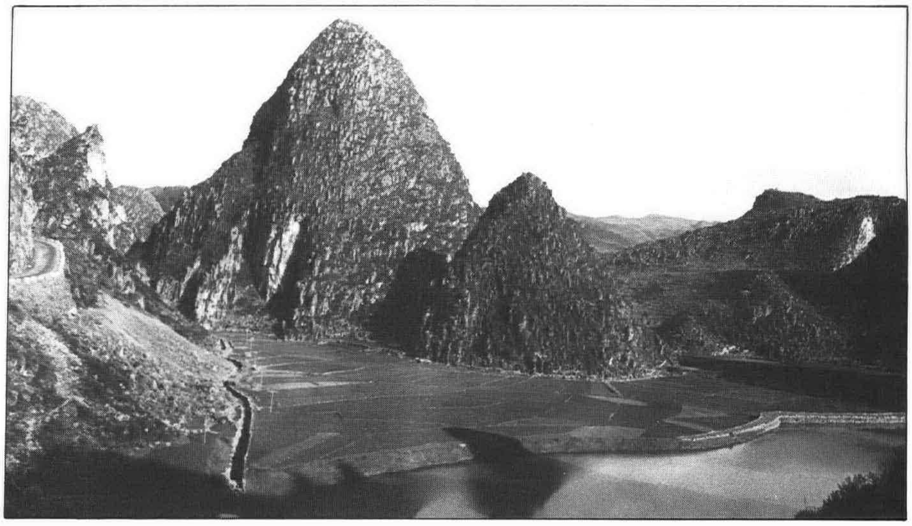
Within the Longgong Dong catchment, there are numerous active and fossil caves, only a few of which were mapped on the China Caves '85 project (Waltham 1986). One stream sinks into Huayan Dong, just south of Anshun; downstream its water rises and sinks ten more times before resurging from Longgong Dong (figure 3). Its 11 underground sections, mostly unmapped, cover a direct total distance of 10 km, while the intervening surface sections cover another 9 km. Overall, the gradients are low. Most underground sections cut across the geological structure, linking fault or fold-guided valleys. Most caves are old deep phreatic systems, with multiple levels indicating a long erosional history and the lack of a shallow impermeable base to the aquifer. Fossil high-level caves have switchback profiles with limited vertical ranges, indicating phreatic development freely utilising inclined faults, joints and bedding planes not far below the contemporaneous water table. Phreatic loops much deeper than about 50 m were probably precluded by the well-fractured state of the karst aquifer.

Clastic sediment has accumulated in the troughs of the phreatic loops, and also in surface basins with low gradients; many caves are flooded by water ponded behind sediments, either underground or in the basins. Some of the depressions between the caves show signs of collapse, particularly in the area between the Xuantang polje and the resurgence. Other depressions have been filled and exhumed; some cave entrances breach thick tufa-cemented screes on depression walls, and some surface rivers have cut down through 8-10 m of sediment in the poljes. Other polje rivers have cut down into bedrock, leaving rock terraces of pinnacled limestone a few metres above present water levels.

The presently active caves are largely phreatic, with only limited vadose features promoted by invasion and rejuvenation. Some old rising phreatic loops have vadose canyons cut through them, and some of these have traces of phreatic development of intermediate age. The Longmen waterfall at the Longgong Dong resurgence (figure 5) provides an example of river capture beneath a phreatic loop. The original drainage outlet was a phreatic lift very close to the

One of the sequence of knick points down the Dabong river valley has the Huangguoshu waterfall in a dramatic setting with a background of fengcong cone karst.

A perennially flooded area on the floor of a small polje in the Fengcong Depression zone of the Longgong karst; sedimentation and collapse has restricted the underground outflow. A small earth dam has been built to prevent complete flooding of the polje.



The Alang He resurges into a small polje in the Fencong Depression zone of the Longgong karst. The cave entrance breaches a thick apron of cemented scree (visible in the roof arch), now partly overlain (on the right) by modern scree. Three levels of truncated fossil caves pierce the conical hill behind.

steeply-inclined limestone-sandstone contact. The Wanger He, flowing on the sandstone and shale, has rapidly cut down to a level 55m below the main Longgong Dong conduit. Consequently the resurging river now drops through a short section of cave which contains the Longmen knick-point waterfall, and the old route is abandoned as the skylight above the Tianchi lake. The long profile of the Longgong Dong system thus steepens markedly towards the resurgence, a feature also observed in other Guizhou caves by Song (1986). This clearly demonstrates the relative rapidity of the fluvial incision of the area.

On the interfluve regions of the plateau the hydrology of the Fenglin Basin karst is quite different. Around Anshun the landscape is best described as rolling, with local relief of less than 200 m. Drainage is by a complex mixture of surface flow and short, low-gradient caves through isolated cones and ridges. Surface rivers follow broad and shallow valleys. The water table is shallow and surface pools and lakes are common. Boreholes demonstrate that the aquifer is mainly a highly transmissive, solutionally developed, fissure-flow type, with occasional isolated segments of large phreatic conduits, as is characteristic of the late stages of karst aquifer evolution.

The cave systems near the major river valleys thus show evidence of a long and complex evolutionary history as they have continuously adjusted to lower base levels. The effects of this incision are not however propagated upstream without considerable lags, related to the breaching of phreatic loops, the clearing of both sediment and collapse debris, and the incision of the surface valley river courses. The underground drainage is therefore in transition; where gradients are steep near the resurgence it may evolve rapidly, but upstream the rate of change is much less, and the interfluve areas are effectively isolated. This permits the continued

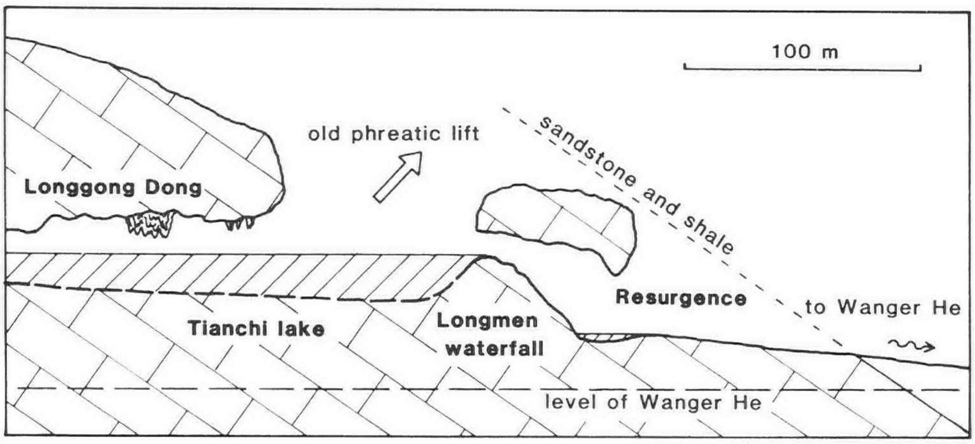
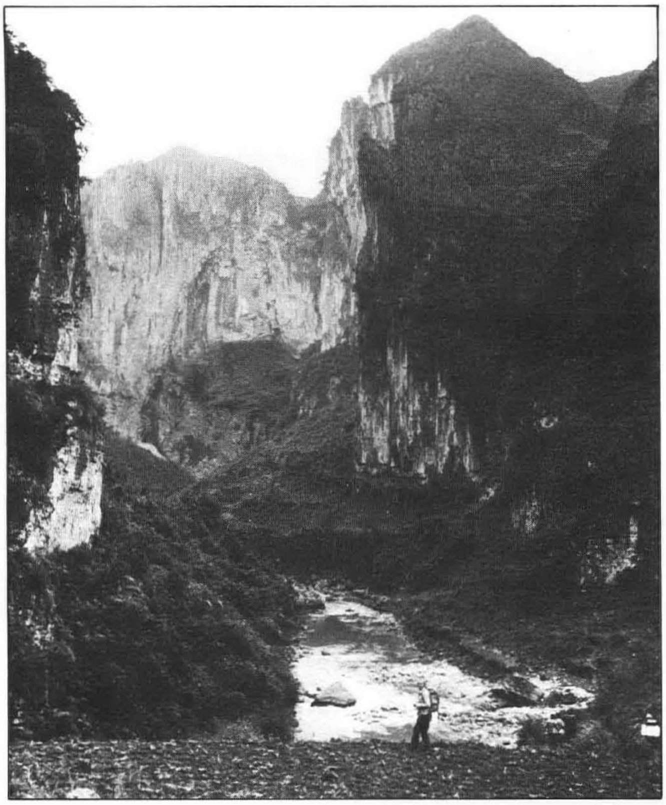


Figure 5. Extended profile through the Longgong Dong resurgence and the underground capture now containing the Longmen waterfall.



The Sancha He heads into a 300 metre deep blind gorge with the shadowed arch of the river cave entrance just visible in the far end wall. The plateau surface above the gorge is a fengcong cone karst. (Photo: Dick Willis)

evolution of the surface landforms of the upstream areas under conditions of stable or slowly falling base-level, permitting surface lowering to give a gradual reduction of the relief. The remarkable contrast in groundwater flow conditions between the interfluve areas and the resurgence zone is thus also indicative of evolutionary sequences in karst landscapes.

RIVER CAPTURE IN THE KARST OF SHUICHENG

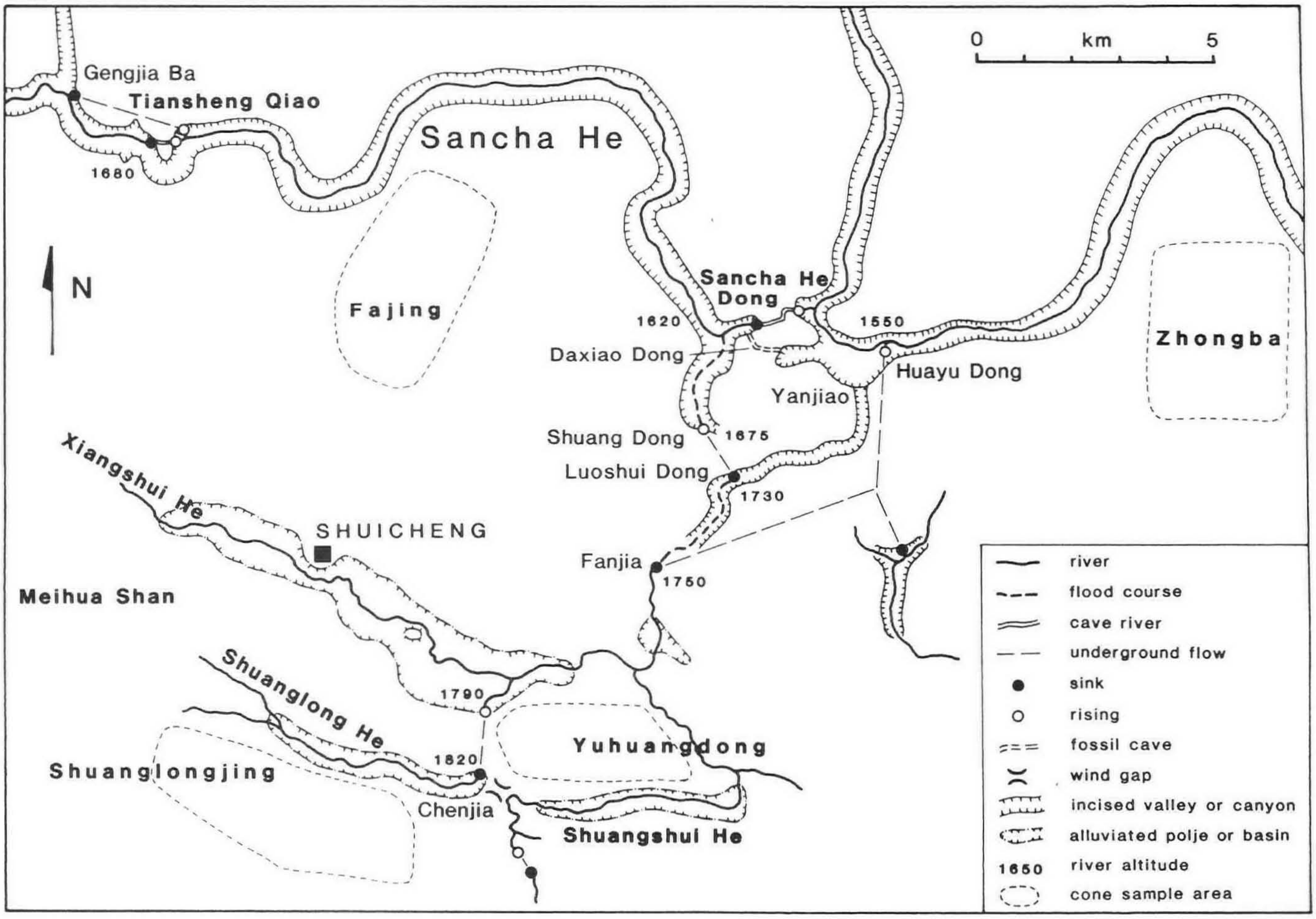
In the Shuicheng area, uplift has been much greater than at Anshun; the karst plateau has a general elevation of around 2000 m, while the Sancha River has incised its valley by some 500 m. In this area the evolving nature of the underground drainage is more clearly illustrated than in the Longgong karst, and underground river capture can be seen to be of considerable importance. The effects on the surface landforms are however broadly comparable to those around Anshun.

Captures and diversions on the Sancha He

The Sancha He is a well-established trunk river with a flow ranging from 5 to over 30 m^3/s. It is therefore large enough to maintain a surface course along almost its entire length, and it is entrenched in a deep valley or canyon with steep and locally vertical sides, indicating considerable disparity between the rates of fluvial incision and slope evolution. There are two places where the river passes underground.

Northwest of Shuicheng the Sancha passes through the cave of Tiansheng Qiao (Natural Bridge). This is a massive tunnel 540 m long which provides an underground cut-off through a major bend in the river's old course (figure 6). A deep, ox-bow, dry valley remains on the south side of the cave, with its floor 30 m above the present river, and was abandoned due to a simple case of underground capture via the shorter route. Some water also sinks into the Sancha riverbed

Figure 6. The Shuicheng area, showing major features of the Sancha He river captures, and location of cone karst areas sampled for morphometric analysis.



upstream of Tiansheng Qiao; from the sink at Gengjia Ba it flows underground 2500 m to resurge from a cave just downstream of Tiansheng Qiao. This appears to be a largely phreatic loop in a primitive state of development.

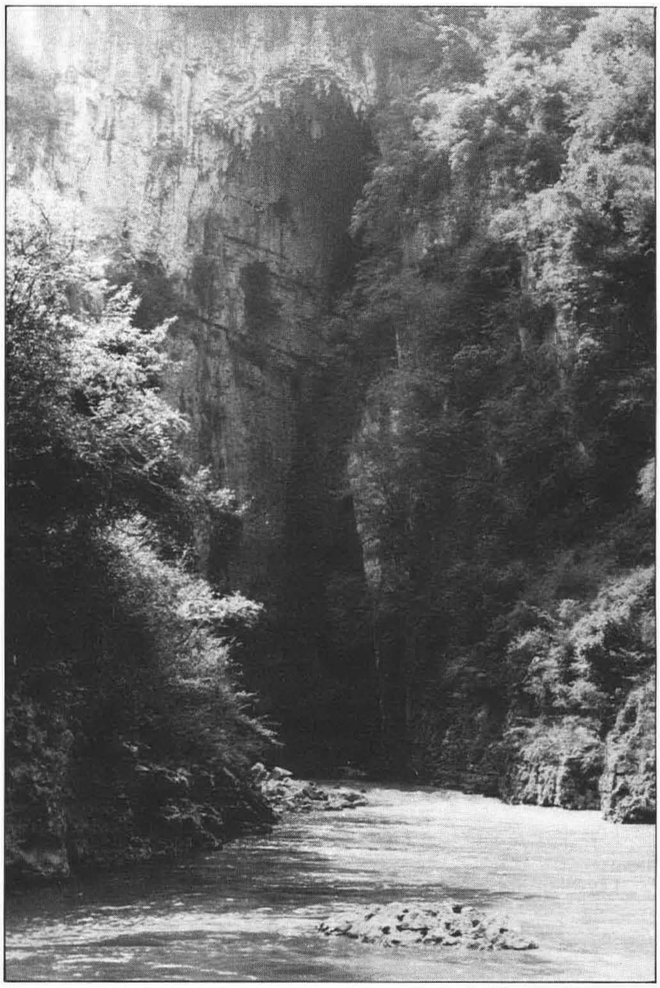
Just 18 km further downstream, the river sinks into the Sancha He Dong (Sancha River Cave, sometimes known as another Tiansheng Qiao), which is 1100 m long to its resurgence (figure 6). This cave is a massive vadose canyon 70 m deep, and any traces of phreatic origins are lost in its high roof. Just to its south, Daxiao Dong (Big Saltpetre Cave) is a massive dry phreatic tunnel, 800 m long, which is an earlier route of the Sancha He. As it lies between 100 m and 200 m above the present river it must be extremely old, and any vadose entrenchment in it is concealed beneath a floor of breakdown and nitrate deposits (cave surveys in Waltham, 1986). The upstream ends of both caves lie in a deep, vertical-walled gorge largely formed by cave collapse, a process which is still conspicuously active at the river cave entrance. Both caves breach a high limestone ridge, capped by steep cones, through which there is no sign of an earlier surface course of the Sancha. The dating of these caves would provide important evidence on the timing and rates of incision of the major trunk rivers.

Captures on the Sancha tributaries

The Xiangshui He is the main river draining through the Shuicheng Basin - a downfaulted block of limestone now supporting a thin floor of alluvium and surrounded by spectacular fengcong karst of tall, steep cones. This river is a tributary to the Sancha, and its valley extends through the karst to where it hangs nearly 200 m above the Sancha near the village of Yanjiao (figure 6). The hanging confluence is a result of Sancha incision since the Xiangshui valley was abandoned due to underground capture. The first capture occurred at the sinkhole at Luoshui Dong, from where the water flows underground for 1000 m to resurge from Shuang Dong onto a surface course to join the Sancha. This route is now only active in the wet season, as the dry season flow (with a mean of 2550 L/s) is taken by a second capture. This sinks at Fanjia, and flows underground for 7 km to resurge from Huayu Dong in the bank of the Sancha, where it is joined by flow from another deeply incised river sinking further east (figure 6).

The Shuanglong He is a major southern tributary of the Xiangshui (figure 6). It sinks at Chenjia to flow 1300 m underground to springs on the margin of the Shuicheng Basin. Just east of the Chenjia sink a wind gap survives as a low saddle; it is floored with fluvial sand and gravel overlain by lacustrine peat, and beyond it the Shuangshui He is an underfit river in a broad fault-guided valley.

The capture of the Shuanglong He may be ascribed to the block faulted subsidence of the Shuicheng basin creating a favourable hydraulic gradient through the limestone ridge at Chenjia.



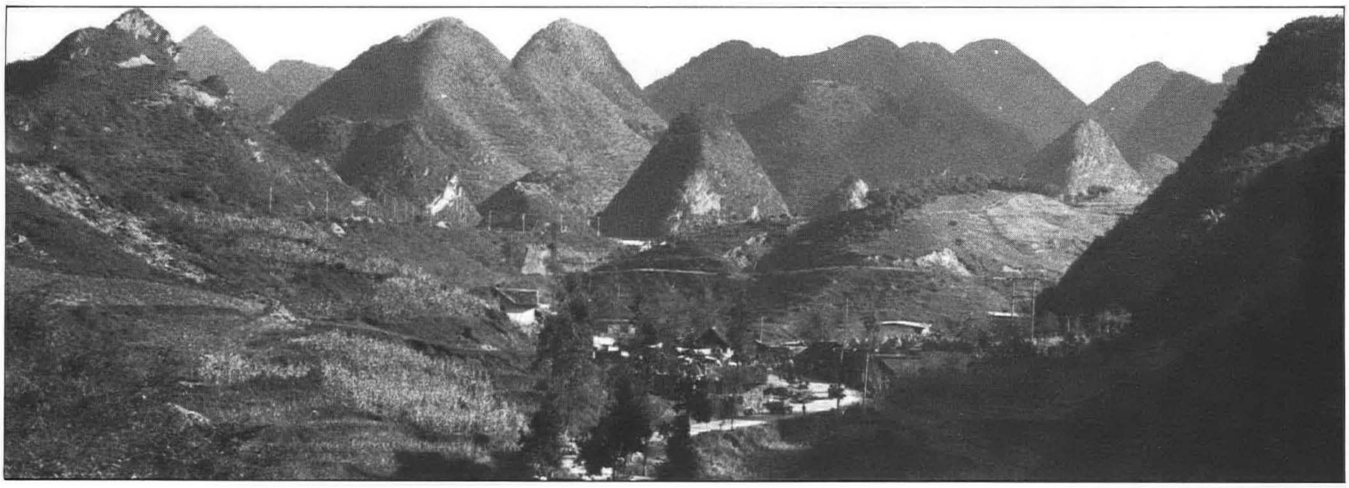
The 60 metre deep vadose canyon entrenched at the resurgence of the Sancha He Dong.

In contrast the double capture of the downstream Xiangshui was a consequence of the rapid incision of the Sancha trunk river, though further block faulting may have been a contributary factor at these sites. As the Sancha incision is itself a consequence of the plateau uplift, tectonic processes may be regarded as the dynamic factor behind all these river captures within the karst.

Rejuvenation of the karst

The zoning of the karst around Shuicheng parallels that in the Longgong area, but the

Fengcong Depression karst east of Shuicheng. As this uplifted area has the depression floors still hundreds of metres above base level, there is no alluviation or development of poljes in the extremely dissected landscape.



The Shuicheng karst, looking down the valley of the Shuanglong He from the upper slopes of the Meihua Shan. The cones beyond the lake and on the right are in the Shuanglongjing sample area, and the Shuicheng basin is in the left distance.

greater uplift has ensured that the rejuvenation is much more extensive, as is also suggested by the more extensive captures described above. Thus Fengcong Depression karst adjacent to the Sancha trunk river passes into a zone of Fengcong Valley karst near Shuicheng which is transitional to Fenglin Valley in the Yuhuangdong Area. Fenglin karst plains are however absent from the interfluve areas, many of which show Fengcong Depression karst with considerable vertical relief. This additional complexity appears to be associated with considerable vertical displacement on Quaternary block faults, which has augmented the differential relief created by fluvial incision. For instance, conspicuous elevated planation surfaces are present to the south of the boundary faults which define the southern margin of the Shuicheng Basin. At higher elevations on the Meihua Shan, the interfluve mountains west of Schuicheng, a Fengcong Depression karst exhibits renewed doline activity and probably contains very deep underground drainage.

MORPHOLOGY OF THE CONE KARST

Study of the Shuicheng cone karst has been pursued by morphological analysis of cones, with the intention of identifying significant differences, geological controls and any evolutionary trends. A total of 745 cones were measured in four sample areas, whose locations are shown in figure 6.

Major topographical and geological features of the four sample areas are shown in table 2. Though the geological structure and the ages of the limestones vary between the areas, there is little overall contrast except that the chert content of the carbonate sequence is notably higher in the Zhongba area; in the other three areas it is either very low or negligible. The Fajing and Zhongba areas are close to the incised valley of the Sancha He; however the two more distant areas are both close to the downfaulted Shuicheng Basin, so a contrast in rejuvenation histories is not instantly recognisable. The sample areas are close enough to each other to have no significant climatic contrasts.

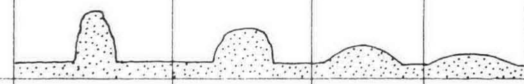
The ratio of a cone's mean diameter to its height permits a classification of the cone shape, as proposed by Balazs (1973). Statistics for the four sample areas are shown in table 3. Most cone ratios lie between 2.0 and 3.5. In three of the areas, the relatively steep cones of the Organos type are dominant, but in the Zhongba region, the hemispherical Sewu type is dominant; this is probably because the more impure, chert-rich, thinly-bedded carbonate sequence in this area is not able to sustain steeper bedrock slopes.

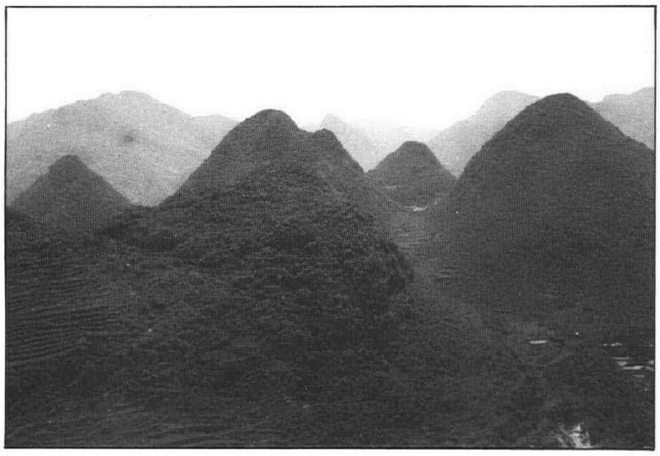
The symmetry of the cones may be expressed in terms of the plan lengths of the two arms of both the major and minor axes which intersect perpendicularly at the cone summit. The six possible classes of symmetry, A to F, based on any equalities of the four arm lengths are shown diagrammatically in table 4. Cone symmetry can also be expressed by the symmetry product, $Pkc = (L1/L2)(S1/S2)$, where L1 and L2 are arm lengths of the major axis and S1 and S2 are arm lengths of the minor axis. Where $Pkc = 1$ the cone is symmetrical, and most of these measured in the Shuicheng region have Pkc values less than 1.25. Statistics of the cones in the four sample areas are compared in table 4. The Zhongba area is conspicuous in having more assymmetrical cones,

Table 2. Geological and physical features of the four sample areas in the Shuicheng cone karst.

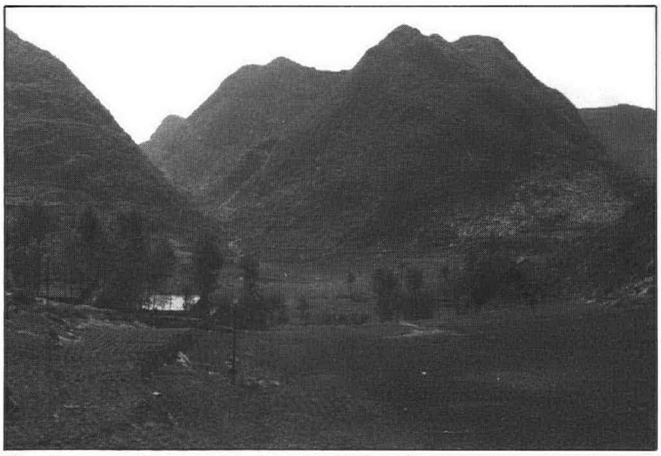
Sample area	Altitude	Height above Sancha He	Distance to Sancha He	Stratigraphy	Lithology	General dip
Shuanglongjing	2100 m - 2200 m	500 m	13 km	Permian Carboniferous	Massive limestone, some with chert nodules, some dolomite.	>60°
Yuhuangdong	1900 m - 2000 m	300 m	9 km	Carboniferous	Massive limestone, some with chert nodules, some dolomitic limestone.	25°-55° mostly 35°
Zhongba	2100 m - 2200 m	600 m	3 km	Permian Carboniferous	Thin-bedded limestone with chert bands and nodules, some dolomite.	25°-70° mostly 40°
Fajing	2000 m - 2100 m	400 m	3 km	Triassic	Massive limestone, some dolomite.	20°-60°

Table 3. Mean heights and classification of cone profiles in the four sample areas in the Shuicheng cone karst.

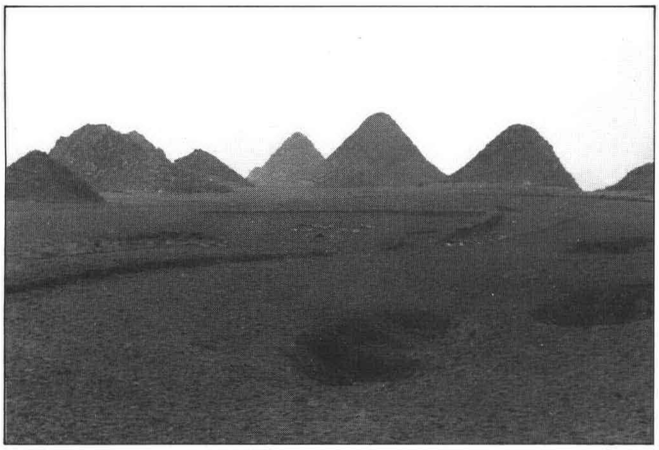
Karst hill type	Yangshuo	Organos	Sewu	Tual	Mean height of cones
Ratio diameter/height	<1.5	1.5-3	3-8	>8	
Diagramatic profile					
Shuanglongjing	1.2%	61.2%	37.6%	0	150 m
Yuhuangdong	0.8%	62.3%	36.9%	0	45 m
Zhongba	1.6%	28.4%	70.0%	0	140 m
Fajing	0	52.6%	47.4%	0	90 m



The Fencong Depression karst of the Shuanglongjing sample area. (Photo: Xiong Kangning).



The Fengcong Depression karst of Zhongba. (Photo: Xiong Kangning).



The Fenglin Basin karst of Yuhuangdong, with small dolines in the foreground developed as a result of recent uplift and rejuvenation. (Photo: Xiong Kangning).

reflected by the higher mean Pkc. Symmetry types E and F are those which are created by a dissected escarpment, and the abundance of the type F cones in the Zhongba area may again reflect a lithological control on cone morphology.

Overall, the cones of the Shuicheng region exhibit a high degree of symmetry, with slope angles dominantly around 45-47°. The extent of summit rounding may then account for the difference between the Organos type and the Sewu type. The degree of symmetry (expressed as Pkc) does not decrease with increased dip of the limestone bedding. But the symmetry product Pkc, does increase as the karst changes from Fenglin to Fengcong. A geological control is also expressed in the orientation of asymmetric cones. In both the Fajing and Shuanglongjing sample areas, major axes of the cones are mostly parallel to the locally dominant joints and faults along which lie

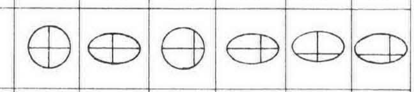
	Symmetrical		Assymmetrical						
Symmetry class	A	B	C	D	E	F	Total number of cones counted	Symmetry Product Pkc	
Diagramatic plan								Mean	Standard Deviation
Sample Areas	%	%	%	%	%	%			
Shuanglongjing	11	55	4	17	7	6	165	1.22	±0.23
Yuhuangdong	29	29	5	22	7	8	122	1.38	±0.32
Zhongba	8	41	2	23	3	23	321	1.75	±0.76
Fajing	15	38	6	23	6	12	137	1.49	±0.51

Table 4. Types of symmetry in the cones of the four sample areas in the Shuicheng cone karst.

the karst depressions, and in all areas, the major cone axes are along the strike of the limestone.

There is no clear relationship between mean cone height and the locations of the three fengcong areas; indeed Fajing, adjacent to the Sancha He, has a lower relief than the Shuanglongjing area, demonstrating the significance of the differential uplift of fault blocks. The Fenglin Valley karst of the Yuhuangdong area is of much lower relief, than the three fengcong areas. Assuming the fenglin evolved from fengcong similar to that of the other three areas, the later stages in landscape evolution involve a gradual reduction in relief by lowering of the cones at a rate greater than that of the intervening plain surfaces.

This morphometric study confirms the remarkable uniformity of the cones, irrespective of their distance from the major base-level river. Only lithology appears to be significant to cone profile, notably giving the more asymmetric and more rounded hills in the Zhongba area. There are two implications of these findings. Firstly, as the karst matures through the Fengcong Depression type, the deepening of the depressions is matched by their enlargement, in the manner envisaged by Williams (1972) in New Guinea. Secondly, provided there is sufficient relief above regional base level, evolution of the landforms of the plateau surface is decoupled from the effects of the base level. Within the single tectonic region of Shuicheng, morphometric analysis has not yet revealed any clear relationship between cone profile and rejuvenation. Further statistical comparisons with karsts in contrasting tectonic environments may more clearly distinguish the steep Guizhou cones, from both the rounded Sewu cones and the precipitous Guangxi towers, on the basis of tectonic history.

DISCUSSION

The evidence described above, together with observations in other karst areas, suggests that the style of karst landforms on the Guizhou Plateau is controlled by the complex relationship between the rate of uplift (determining the available relief) and the rate of surface denudation. Where uplift rates are greater than those of surface denudation, or where previous episodic uplift has generated substantial elevated blocks, cone karst evolution may occur without base level constraints. The sequence is from a shallow doline karst (as occurs in some parts of the Meihua Shan) to the Fengcong Depression type (as in many parts of the Shuicheng region) with

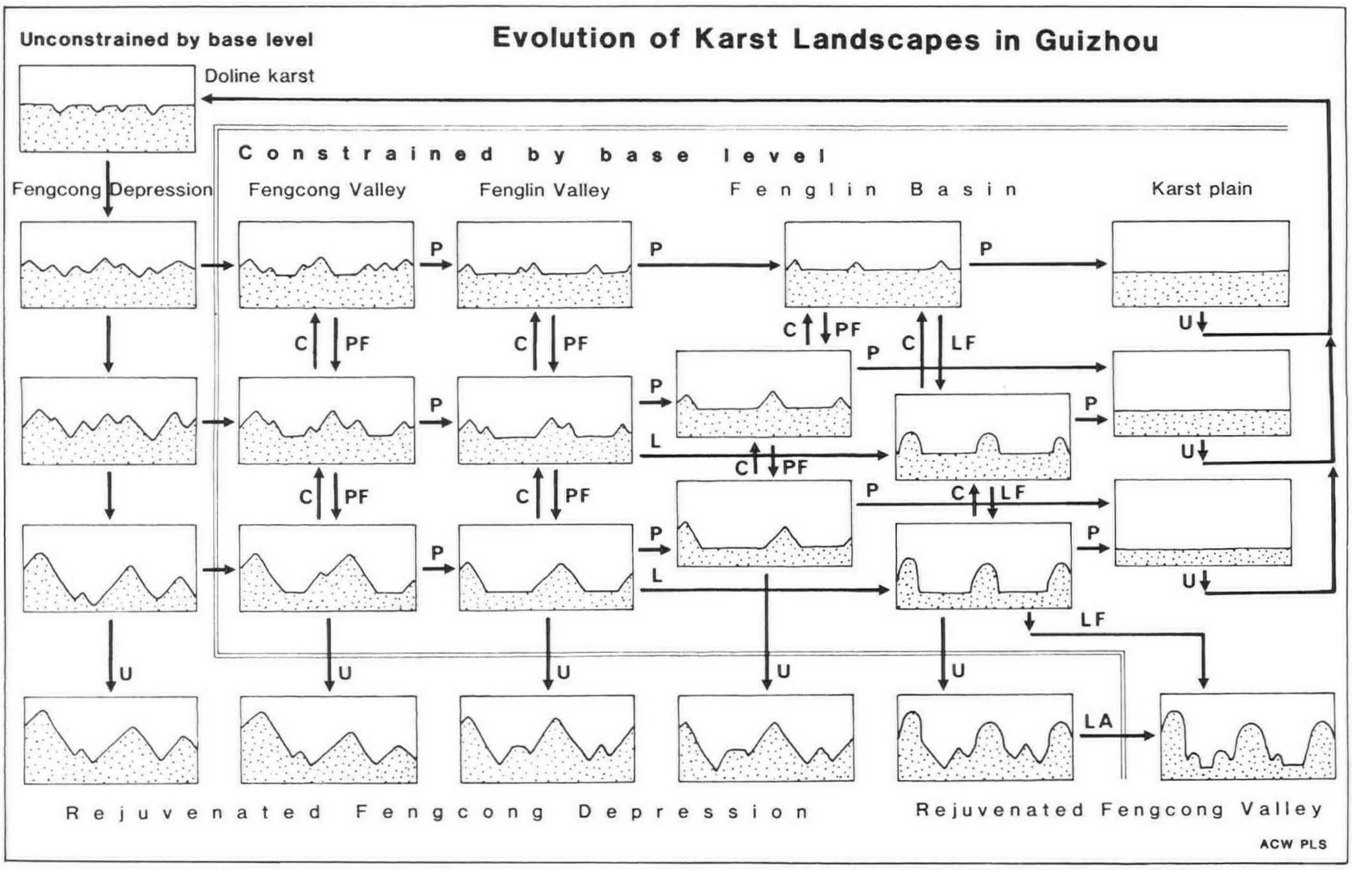


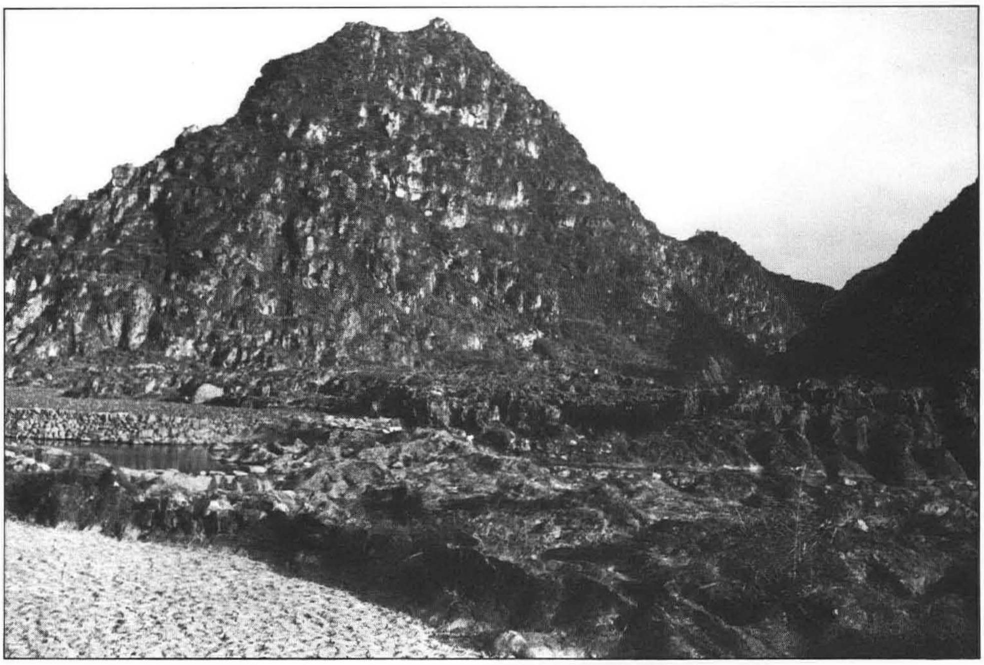
Figure 7. Evolution of karst landscapes in Guizhou. Landform evolution without base level constraint gives rise to Fengcong Depression with increasing relief (left column). Once base level is intersected (where rate of uplift is low compared to surface denudation) evolution occurs through the Fengcong Valley to Fenglin Valley to Fenglin Basin sequence to a karst plain (left to right). Falling base level allows an increase in relief (down columns), while more rapid surface erosion reduces relief (up columns). Cones will persist where lateral planation is less than surface denudation, while towers develop where lateral planation is dominant (note: towers may also develop in Fenglin Valley stage, but are omitted for clarity). Rapid uplift promotes rejuvenation and the development of new fengcong depressions; this effect may be difficult to recognise in fengcong landscapes as features from the previous cycle may have been rapidly eliminated. Rarely, where lateral planation rates are high, for instance where alluvial floors are maintained by continued sediment supply from adjacent non-carbonate outcrops, tower karst may persist through uplift to create fengcong landscapes.

Key to figure 7

- **U** - Uplift (rapid)
- **C** - Cone denudation > planation
- **P** - Planation ≃ cone denudation
- **PF** - Planation ≃ cone denudation; and falling base level
- **L** - Lateral planation > cone denudation
- **LF** - Lateral planation > tower denudation; and falling base level
- **LA** - Lateral planation > tower denudation and alluviation

- Tower
- Cone
- Plain

In this valley in the Fengcong Valley karst of Longgong, the river, in response to base level lowering, has incised about 4m, leaving a bedrock terrace seen on the middle right. The lack of basal steepening of the cones is because surface lowering has matched the rate of lateral planation.



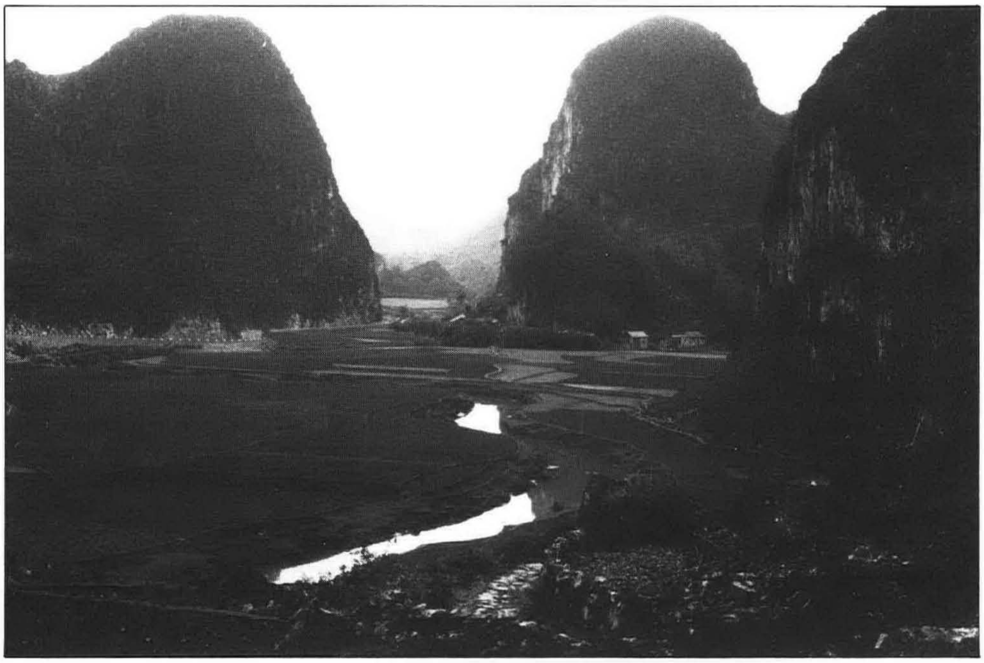
progressive enlargement and deepening of the depressions (the left column in figure 7).

The remarkable uniformity and straightness of the Guizhou slope suggests that after obtaining a characteristic angle, slope retreat is parallel. Elimination of smaller depressions must occur, and overall rates of surface lowering may therefore be partially dependant on depression size. However, if rates of erosion in the depression floors are greater than on the slopes, perhaps due to contrasts in the soil cover and extent of subcutaneous solution (Williams, 1985), steepening may occur to evolve towards towers rather than cones.

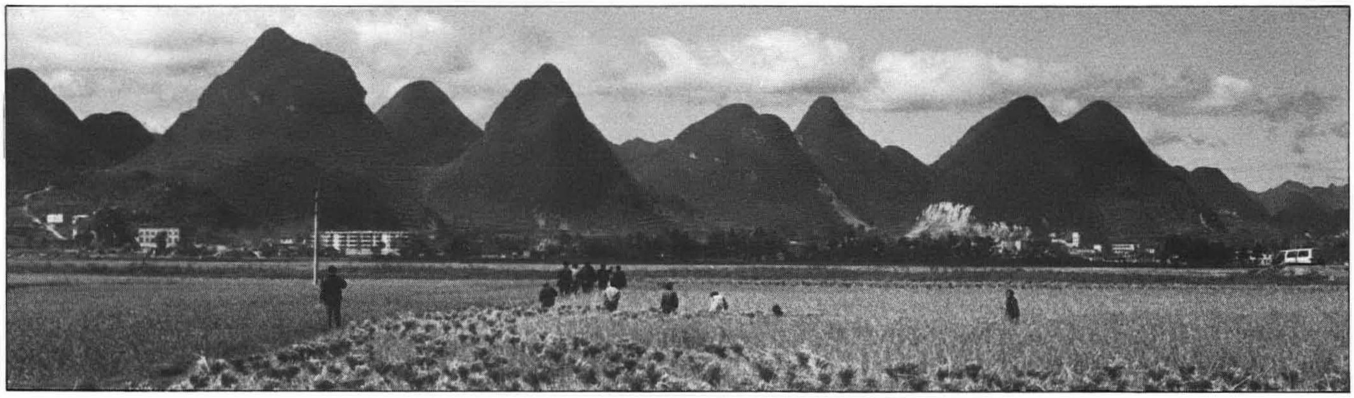
Where relief is limited, or surface denudation rates are higher than the rate of fall of base level (controlled by trunk river incision and tectonic uplift) then development is constrained by the proximity to base level, and surface streams develop to give the Fencong Valley landscape (second column in figure 7). The height of the fencong cones may vary over a substantial range, depending on the uplift history and available relief.

Providing the rates of uplift and base level lowering remain unchanged, the evolutionary path of the landscape is now controlled by the relative rates of lateral planation by the surface rivers, and the rate of surface denudation on the fencong cones. In the unusual situation where surface denudation is less than lateral planation, there is a gradual reduction in relief but the karst remains essentially Fencong Valley type. This might occur if thick permeable soils were present, giving high sub-soil solution rates, but rainfall intensities were low, limiting surface runoff and sediment production (C in figure 7).

More commonly, surface denudation will be roughly equal to, or just less than, the rate of lateral planation by surface rivers, particularly where these drain extensive catchments, as is the case in Guizhou. When the rates are similar, then the conical form of the hills is preserved, but they will gradually be replaced by an expanding alluviated karst plain. The landscape type will thus evolve through Fenglin Valley to Fenglin Basin with conical hills, as now occurs around Anshun (P in figure 7).



Lateral planation has undercut the slopes along the Xuantang polje, in the Longgong karst, to create these steep-sided towers. (Photo: Peter Smart).



Cone karst just west of the Yuhuangdong area rises above the flat alluviated floor of the Shuicheng Basin. The karst is rejuvenated Fengcong Depression where recent erosion has removed all trace of level basin floors which may once have existed between the cones. Compare with photograph below.

However, if fluvial planation is more rapid than surface denudation, due to an input of high sediment loads or very high rates of run-off, then undercutting of the cone margins will give rise to steeper-sided cones and towers (L in figure 7). Once these steep-sided tower forms are developed they will largely be preserved; even if the relative rate of surface denudation increases, the tower form will persist as the landscape evolves into Fenglin Basin.

Further development towards a true tower karst is dependant on the efficiency of the lateral planation eroding the tower bases through a prolonged regime of slowly falling base level (LF in figure 7). The planation is the product of river corrosion, solution and corrosion by water draining off the alluvial flats, and foot-cave development and collapse within the tower margins. Extensive tower karst, as in Guangxi, requires a continued supply of clastic sediment from non-carbonate outcrops to maintain the alluvial profiles, through a period of relatively slow tectonic uplift (LA in figure 7).

There are also important lithological constraints on the evolutionary sequence described above. Only very massive carbonate units can sustain the steep slopes of karst towers; where shaley or thin-bedded carbonates are present, more rounded hills develop to give the Karst Hill Depression type of landscape.

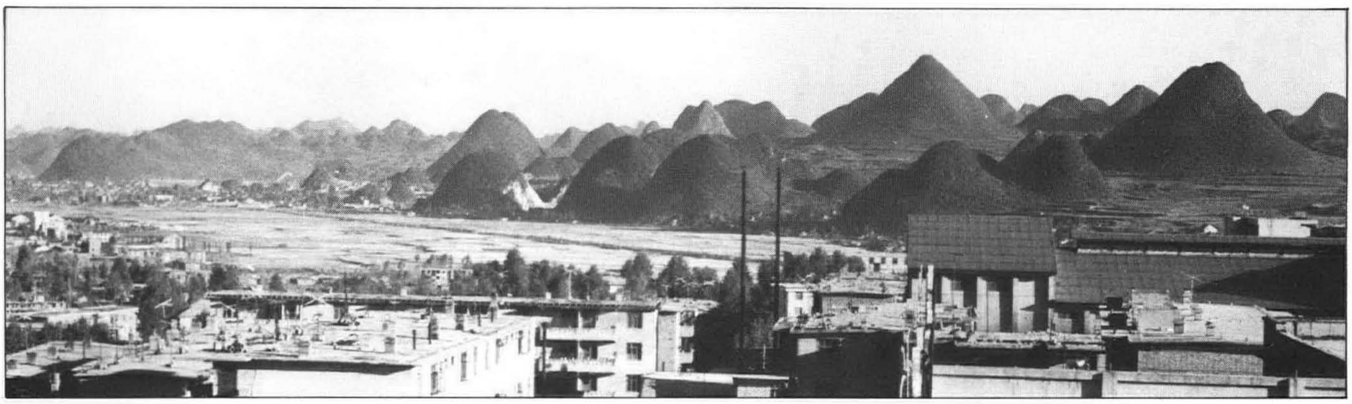
The alternative to completed evolution through to a karst plain is an interruption by rejuvenation, which creates complex multi-phase landscapes. This is caused by changes in the rate of base level lowering as a consequence of episodic tectonic uplift, either on differentially uplifted fault blocks, as at Shuicheng, or by regional rejuvenation of major rivers with knick point migration as around the margins of the Guizhou Plateau. The early development phase may then be abandoned, as a second phase is initiated. Thus doline karst and Fengcong Depression karst can develop within a karst plain or the plain areas of Fenglin Valley and Fenglin Basin (to restart the sequence in figure 7). An earlier interruption of the karst evolution may create new depressions in a Fengcong Valley landscape; this rejuvenated landscape will be complicated by having an initial surface with considerable relief, so that any subsequent summit profile will be irregular. The historical interpretation of these complex multi-phase landscapes is far from simple.

Conclusions

The Guizhou karst offers an understanding of both the highly complex interactions and controls of cone karst, and also its evolutionary sequence. Care is however needed in distinguishing between essentially contemporaneous landscapes which have evolved to different stages, and landscapes in which rejuvenation has superimposed a later phase of development on earlier landforms. This point is demonstrated in figure 7. Assuming evolution commences contemporaneously throughout the landscape, in areas adjacent to incising rivers the dominant karst type is Fengcong Depression with progressively increasing relief (left hand column in figure 7). However, on the interfluves local base level remains high and falls only slowly; relief is thus limited and evolution proceeds through the sequence Fengcong Valley, Fenglin Valley to Fenglin Basin and eventually a karst plain with no hills (top line in figure 7). If the time steps between the individual landscape types illustrated in the figure are equal (not necessarily the case) then the high relief Fengcong Depression karst adjacent to the rivers is of a similar age to the more evolved Fenglin Valley type at the divides. Provided base-level continues to fall at a rate equal to or faster than surface lowering there will be no change in the stage of evolution.

As emphasized by Zhang (1980) headward propogation of changes in the surface drainage system initiates responses first in the underground drainage and then in the karst landscape. Simple models based on dynamic equilibrium will therefore not suffice as much of the landscape is in transition.

Cone karst along the southern edge of the downfaulted Shuicheng Basin. On the right a number of different levels of uplifted basin floors can be seen between the cones of the fenglin. Compare with photograph above.



In the future, dating of speleothems and other cave deposits may permit estimates of the ages and rates of evolution of the Guizhou landforms to be derived. This information, combined with detailed slope processes studies (such as those of Crowther (1986) in Malaysia, and Day (1986) in Belize) which have not yet been employed in China, will refine our understanding of these perplexing landscapes.

ACKNOWLEDGEMENTS

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Caves and Limestones of the Islands of Tongatapu and 'Eua, Kingdom of Tonga

D J LOWE and J GUNN

Abstract: During summer 1986 a team of British speleologists visited two contrasting islands in the Kingdom of Tonga where only minimal cave exploration had taken place previously. On the island of Tongatapu predominantly horizontal cave systems of large size were explored in limestones of Pliocene to Pleistocene age. On the adjacent island of 'Eua essentially vertical cave systems in limestones of Eocene to Oligocene age were found to have cut down into early Eocene volcanic basement and elsewhere horizontal stream caves had cut downwards from Pliocene limestone into Miocene arenaceous rocks. Results of the exploration and survey of these cave systems are presented, with background details of geography, geology, cave biology and hydrology.

INTRODUCTION

The Tonga '86 Expedition set out to find and explore caves on two islands, Tongatapu and 'Eua, where little serious speleological work had taken place. Joanna Ellison, Norman Flux, Dave Gordon, John Gunn and Pete Smith comprised the team and the nominal leader was Dave Lowe. During part of the Expedition the team was joined by John Cunningham, ex government auditor of Tonga and erstwhile explorer (with Karen Anscombe and others) of a number of caves on the two islands. The Expedition was both exploratory and scientific in its conception and proved to be successful beyond expectation on both counts. Many more discoveries are yet to be made and numerous avenues of scientific research have been sign-posted by the preliminary studies in 1986.

Geographical setting

The Kingdom of Tonga, an independent member of the Commonwealth, consists of about 150 islands and many smaller rocks, of which about 36 are inhabited. There are three main island groups, the Vava'u Group in the north, the Ha'apai Group in the centre and the Tongatapu Group in the south, all of which lie within the southern Tropics (Fig.1). As might be expected the climate becomes drier and cooler towards the south and conditions in the Tongatapu Group are clement by European standards, with a mean annual temperature of about 20°C and annual rainfall of about 1500mm. Rainfall is however unpredictable and much of the annual precipitation may occur in a small number of storms. The islands lie in the hurricane belt and though more common among the northern islands, hurricanes do occur in the Tongatapu Group.

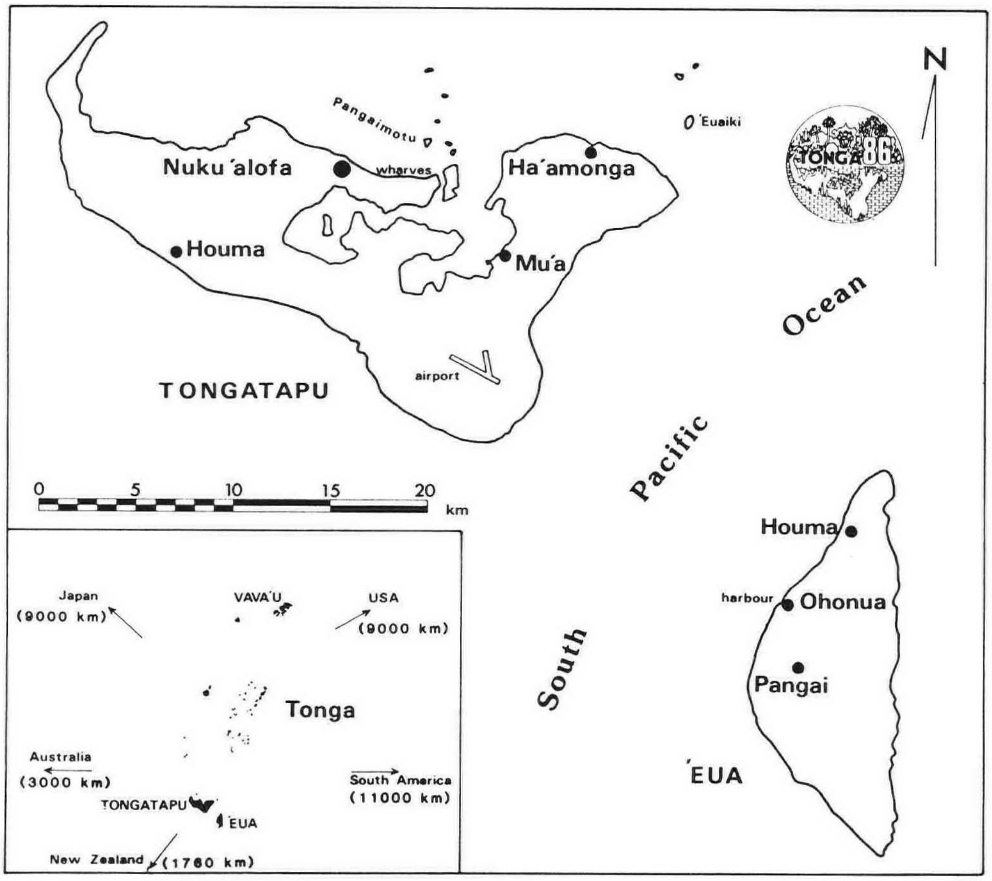


Figure 1

Humidity is high throughout the year, with an annual average of about 77 per cent.

Geological setting

Geologically the Kingdom of Tonga can be divided into three island chains. The oldest islands lie along the eastern margin and include the Nomuka Group and the island of 'Eua. They comprise relatively ancient (by Pacific standards) volcanic basement rocks which are overlain and draped by post-Eocene deposits, mainly limestone, still being formed today. Westwards is a belt of younger islands where massive lagoonal and reefal limestones are being deposited on a relatively deeply submerged volcanic basement. This chain includes the islands of Vava'u and Tongatapu. Tongatapu is apparently at the formational stage attained by 'Eua during the Oligocene - except that Tongatapu currently has no volcanic hinterland. Still farther west is a third island chain which consists of young volcanic islands, still active or potentially active, including Tofua and the classic cone of Kao. In this chain volcanic material is being deposited at present and fringing reef limestones are forming concurrently. A comparison would liken these islands to "proto-'Eua" in early Eocene times.

The young volcanic chain, known as the Tofua Arc is the currently active manifestation of the subduction of the Pacific Plate beneath the Australian Plate and the volcanic products are of typical "island arc" affinities. The Pacific Plate is moving towards the west beneath the Australian Plate which is relatively moving towards the east. The submerged volcanic piles of the Tongatapu - Vava'u chain and the volcanic basement of the 'Eua - Nomuka chain are remnants of earlier episodes of island arc volcanism. That active subduction continues is demonstrated not only by the ongoing volcanic activity but by fairly frequent earthquakes. Two tremors were felt by Expedition members on 'Eua Island, the second being sufficiently intense to waken sleepers at the Houkinima Motel!

Previous cave exploration

Caves have been known on the islands probably since the time of the Polynesian colonisation and those which were obvious and easy of access probably found irregular use as refuge, temporary accommodation or a ceremonial and burial sites. There are many folk tales concerning caves throughout the Kingdom and many of the legends are along familiar western lines - subterranean journeys between well-known cave entrances, miles apart and with no obvious speleogenetic link. Modern exploration is still to corroborate the legends and cave science seems to contradict the more colourful, and less mundane, mythologies of cave formation.

Ana Ahu, on 'Eua, was described by the geologist Hoffmeister (1932), but was not descended until the 1950's. A number of resurgence caves on 'Eua must have been explored by the Tongans and in some the elaborate "plumbing" systems to gather a water supply testify to many hours spent underground. Likewise, on Tongatapu, pools of fresh water inside caves must have provided water supplies, but here there was never any attempt at piping and precarious journeys into the darkness with water carriers must have been the norm.

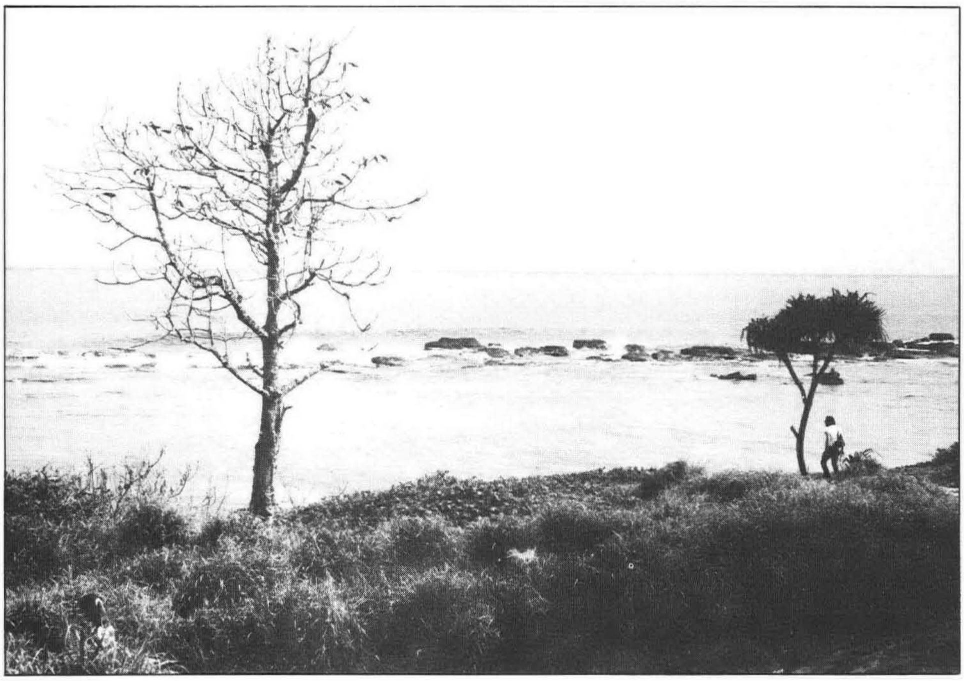
Serious western-type cave exploration began in 1981, when John Cunningham removed to Tonga as Government Auditor. In company with the then Government Geologist, Karen Anscombe, and other ex-patriates he embarked upon a programme of reconnaissance and exploration which included caves on Tongatapu, 'Eua and Vava'u. A synthesis describing the exploration and the caves, with brief speculation upon speleogenesis and its relation to geology has been prepared (Cunningham and Hood, in press). The explorations by 'Tonga '86 represent the first methodical and full explorations of the systems described below.

TONGATAPU

The Tongatapu Group forms the most southerly part of Tonga and Tongatapu itself is the largest island in the Kingdom. About 25000 of Tongatapu's 65000 inhabitants live in the capital city, Nuku'alofa, which stretches along the island's northern coast. A large central lagoon, with reef-strewn entrance, lies east of Nuku'alofa, providing sheltered mooring for smaller boats. It was here that Captain Cook's ship anchored in 1772, though Cook did not discover the island, which was visited by the Dutch explorer Tasman in 1643. Tasman named the island "Amsterdam", but Cook renamed it, after the Tongan manner, as "Tongatabboo".

Geographical setting

Tongatapu has a maximum length (NW-SE) of about 32 km, a maximum width of 18.5 km and a total land area of 257 sq.km. In the north the land lies only a few metres above sea-level, but



Breakers mark the position of the currently forming coral reef around Tongatapu Island.

the terrain rises gradually to 20-30 m in the south where the coast is marked by spectacular cliffs, blowholes and arches such as that at Hufangalupe. The high ground extends around the east coast and maximum elevations in excess of 65m are reached near Nakolo village.

The island is extensively planted with coconut palms, bananas, tapioca, yams and taro, and those areas not cleared for planting are covered by heavy undergrowth. Thus it is difficult to discern the form of the ground surface and rapid reconnaissance is not possible. The overall impression is of a mainly flat terrain with no valley forms, but with sporadic large solution dolines and collapse dolines, all of those examined being associated with cave development.

The climate may be classified as Tropical Seasonal (Koppen Aw) with an average annual rainfall of 1775mm (1945-1965), an average relative humidity of 79% and an average annual temperature of 22.1°C. Mean monthly precipitation, humidity and temperature are given in Table 1 although it should be noted that precipitation is very variable.

Two main soil types are found, "kelefatu", a clay soil derived from weathered volcanic ash, and "tou'one", a sandy soil derived from coral sand and marine debris (Pfeiffer and Stach, 1972). The kelefatu, which covers most of Tongatapu to a depth of 0.5 to 5m is highly friable and freely drained. Tou'one is also well-drained, but is generally thinner and is confined to narrow strips along the coast.

Geology

The surface geology of Tongatapu appears to be simple, insofar as the only rock exposed is Plio-Pleistocene coral reef limestone. According to Cunningham and Anscombe (1985) leached coral grainstones, packstones and boundstones are present. A total thickness of between 134m (near Nuku'alofa) and 247m (near Fua'amotu in the southeast) has been proved in boreholes. In terms of karstification the most significant points are that the limestone extends to well over 100m below sea-level and generally the rock is highly porous, except where the voids between individual coral masses have been infilled by fine-grained detrital material.

Hydrology and hydrogeology

Tongatapu has no perennial surface drainage, no lakes and no reservoirs. Pfeiffer and Stach (1972) suggest that there is some intermittent surface flow on the northern part of the island after heavy rainfall. The presence of talus cones and soil material around the entrances of several caves also indicates that there is intermittent flow which causes soil erosion, or that such flow has occurred in the recent past.

Mean monthly rainfall (1945-1965), humidity and temperature (1949-1960) at Nuku'alofa, Tongatapu.

Month	Rainfall(mm)	Relative Humidity(%)	Temperature(°C)
J	210.8	80	24.1
F	254.0	81	24.7
M	244.6	81	24.4
A	155.2	79	23.6
M	97.0	81	21.7
J	93.5	79	20.8
Jy	107.4	79	19.8
A	112.0	78	19.8
S	113.8	75	20.3
O	117.9	76	21.1
N	119.9	76	22.2
D	142.7	78	23.3

Table 1

Cave	Grid reference	Elevation	Length	Depth
Ana Hulu (1)	970 536	2m	c.420m	+9m
Ana Nakolo (1)	954 472	35m	c.180m	-10m
Fatumu Cave (2)	962 526	25m	c.132m	-17m
Fua'amotu (1)+(2)	937 464	3m	400m+	+6m
Haveluliku Incline (1)	971 537	17m	c.52m	-16m
Matt Dean's Cave (1)	828 546	12m	50m	-6m
Oholei Cave (2)	967 503	25m	300m	-20m
Pila's Cave (2)	835 545	15m	c.64m	-9m

notes:

(1) Cunningham and Hood (in press). Caves were not surveyed to a high standard and there are discrepencies between figures quoted in the text and on surveys. No surface elevations are given and these are interpolated from the 1:25000 map of Tonga on the basis of the quoted grid reference.

(2) Tonga '86 Expedition surveys to BCRA Grade 5c. Surface elevations interpolated from the 1:25000 map of Tonga.

Table 2 Caves of Tongatapu

The first published account of the island's hydrogeology is that of Pfeiffer and Stach (1972), based on a visit in 1971. They prepared an inventory of springs and wells, surveyed the ground elevation of 46 wells for which water level data were available and from this produced a contour map of the groundwater table. This was found to be always less than 1m and generally less than 0.5m above mean sea-level. Fluctuations were thought to be no more than a few centimetres and the effects of tidal variations were thought to extend no more than a few hundred metres inland. These authors also noted that: "the limestones are of karst-type with open cracks" and "the presence of solution channels and big caves is apparent in many places" - though they did not elaborate. Groundwater recharge was estimated at 10% of rainfall, i.e. 175mm/year.

Water level measurements from 39 wells were the subject of more detailed analysis by Hunt (1979) who was apparently unaware of the earlier work and did not visit the island (Hunt, written communication, 1986). His piezometric contour map is virtually identical to that of Pfeiffer and Stach, but his estimate of recharge, based on finite difference calculations, is substantially higher at 425mm/year. Hunt also suggests that the thickness of the fresh water lens floating on top of denser sea water beneath the island will vary from zero around the coast to a maximum of about 20m near central portions of the island.

Caves and cave development

There are 8 known caves on Tongatapu, 3 having been explored and surveyed for the first time by the Expedition (Table 2), whilst a fourth, Fua'amotu, was visited and partly resurveyed. Six of the caves, including the 5 longest are located in the south-east corner of the island, where the elevation is greatest (65m near Nakolo) and the limestones attain their maximum thickness (about 250m). They lie on both sides of a groundwater divide postulated by Pfeiffer and Stach (1972) and are aligned along groundwater flowpaths which these authors suggest (Fig.2). Two of the caves, Ana Hulu and Fua'amotu, have entrances close to mean sea-level and both contain substantial pools of fresh water. Tourist literature (e.g. Packett, undated) frequently refers to an underground river "of unknown length" in Ana Hulu, but Cunningham and Hood (in press) state that it does not exist, though the cave does contain water up to 20m deep. The cave was not visited by the Expedition, but Cunningham and Hood's description suggests that its basic form and origin are similar to those of FUA'AMOTU, which was explored. This cave has two

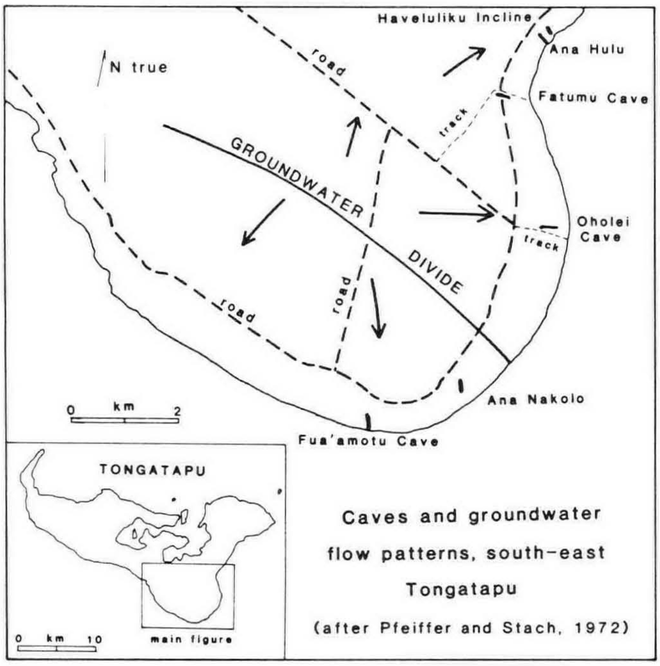


Figure 2

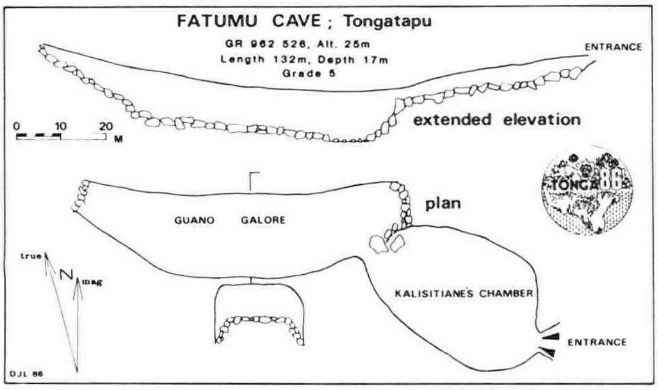


Figure 3

entrances which lead into a low wide (4 to 23m), sandy-floored chamber. At its northern end a small passage leads on for 26m to another chamber which is 10m long, up to 20m wide, but generally less than 1m high. Another short crawl leads to a third chamber of similar size and with abundant breakdown. From here the passage is generally 2 to 3m square for 35m to a pool. A narrower passage continues north for about 65m before ending in breakdown (Cunningham and Hood, in press). The main passage enters a low chamber 23m long, beyond which it narrows to a canal with extensive fresh speleothems. A narrow rift leads north to an upper level with extensive breakdown. The main passage continues to a large chamber with a series of fine columns, which have been broken during tectonic activity and recemented. No animal life was observed in Fua'amotu, though charcoal-like deposits were found, which could be of organic origin.

Of the other four caves in the southeastern corner of the island, Fatumu and Oholei are entered from collapse dolines and the other two, Ana Nakolo and Haveluliku Incline, appear, from Cunningham and Hood's description, to be entered via similar collapses. The entrance to FATUMU CAVE lies at the foot of an earth talus slope and gives access to a pair of chambers (Fig.3) with liberal deposits of guano. The extent of the breakdown in the second chamber made it difficult to determine whether the lowest point was on bedrock, but the presence of small pools of water indicate that this is the case. The passage terminates in a massive choke. Both chambers are homes for large populations of swifts and possibly also of bats, though none of the latter were sighted. The decaying guano piles appear to be releasing heat, as the temperature in the cave was noticeably warmer than that outside. An unpleasant atmosphere made breathing through a face mask highly unpleasant, so the masks were dispensed with. Either the team was extremely lucky or the cave is histoplasmosis negative.

OHOLEI CAVE (Fig.4.) has its entrance at the base of an impressive doline. There is a choice of climbs down to an earth talus cone with a slope of 30-35°. Water in a pool at the base had a total hardness of 405mg/l and calcium and magnesium ion concentrations of 122 and 24mg/l respectively. These values are lower than those from a pool in Fua'amotu Cave (470, 142, 28mg/l) which is closer to sea-level and may contain some saline water. The Oholei pool lies in a relatively low section of passage and at its end the roof rises, probably as a result of breakdown which almost fills the

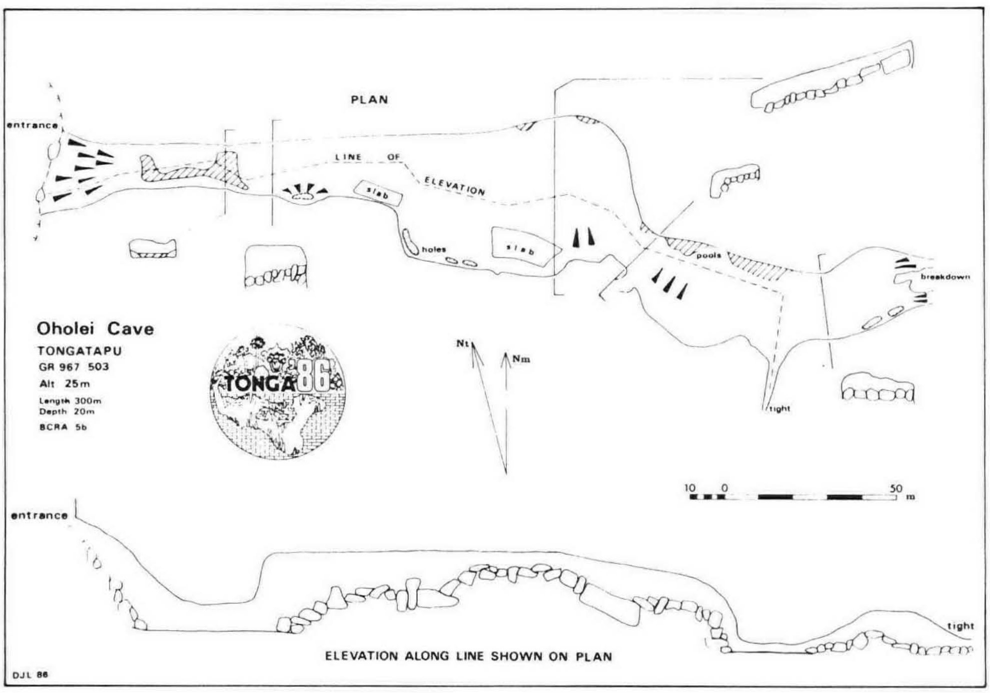
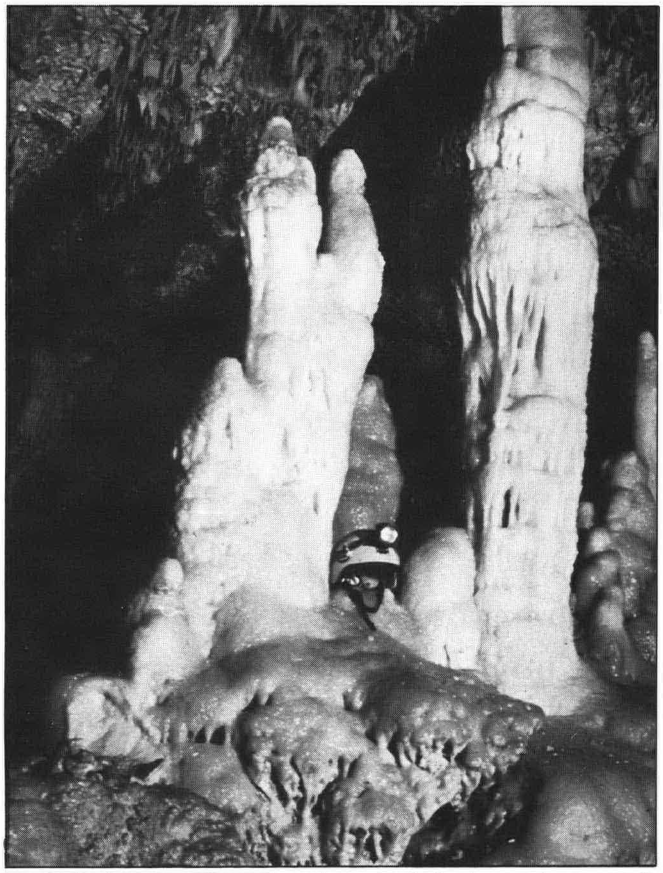


Figure 4



Relatively young formations in one of the inner chambers of Fua'amotu Cave, Tongatapu Island.

passage in places. The ensuing passage would have very impressive dimensions if the breakdown material was removed, being up to 50m wide and 20m high. The cave ends in a confusing choke which could probably be penetrated given sufficient time. There is certainly considerable potential as the end point is several hundred metres from the coast, where a series of short but large passages probably mark the position of an old rising.

Like Fatumu, Oholei is the home of a large cave swift population. Large quantities of guano are spread throughout the cave and the guano heaps support a thriving hypogean fauna which includes cockroaches and cave crabs. An extensive collection was made (see biological report, below).

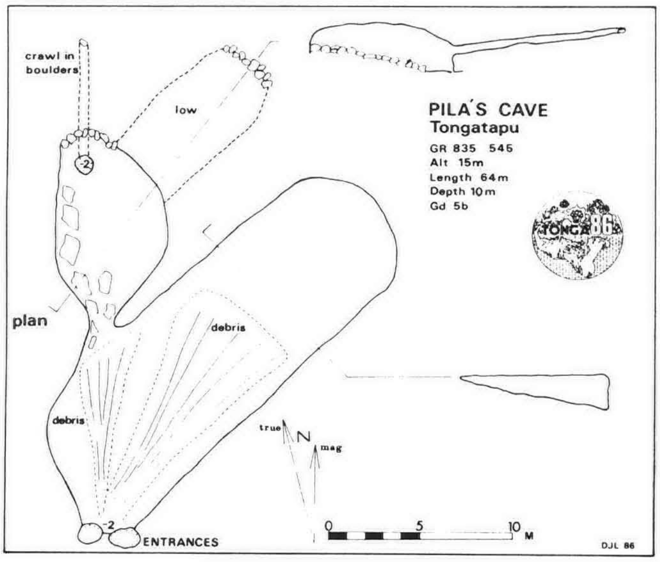


Figure 5

Although there is no clear evidence for the origin of any of the Tongatapu caves it is suggested that Fatumu, Oholei and, probably, Ana Nakolo were formed by phreatic solution when the land was lower, i.e. the relative sea-level was higher. Elevation of the land has left the caves relict and they have since degraded by breakdown at least partly induced by tectonic activity. The smaller dimensions and lower elevation of Fau'amotu and Ana Hulu possibly indicate a more recent origin though they too appear to be largely relict and modified by breakdown. If this thesis is correct then the present day locus for phreatic cave development should be at or just below sea-level and it is likely that solution is possible at these great depths due to the effects of mixing along the freshwater/salt water interface. A number of more general implications regarding the formation of phreatic caves on small islands follow on from the above considerations, and these will be referred to in the section concerning speleogenesis of the Top Area on 'Eua Island.

Two caves which lie outside the south-east corner of Tongatapu are Pila's Cave (Fig.5) and Matt Dean's Cave, both of which are small isolated chambers whose origins are unclear. Possibly they are of similar age to Fatumu and Oholei caves.

'EUA

Lying to the south-east of Tongatapu, 'Eua is the second largest island in the Tongatapu Group. It has about 4000 inhabitants, most of whom live on the western side of the island, particularly in a series of settlements which form a ribbon-development along the main north-south (unmade) road. At Ohonua there is a small harbour, blasted from the coral reef, where cargo and passengers are embarked and disembarked, weather permitting. A grass airstrip has been constructed near Niua relatively recently and small "Islander" aircraft provide a daily shuttle service to Tongatapu. Neither air nor sea ferries operate on Sunday.

Tasman was the first European to sight 'Eua, in 1643, but he did not land. He did however name the island "Middleburgh"! In 1773 Captain Cook anchored at 'Eua and after recognising it as Tasman's Middleburgh, he wisely restored its Tongan name, a phonetic rendition which has become 'Eua over the years.

Geographical setting

'Eua island has an area of 87 sq.km., with a maximum length of about 19 km (north-south) and maximum width of 7 km (east west) (Fig.6). By local standards it has a high relief, reaching 312m at Soldier's Grave in the centre of the island. Well over half the land is over 100m about sea-level, with most of the lower ground being flattish terraces and alluviated lagoons on the western side. To the east the land rises to a central spine running north-south and dropping away in a series of crags and terraces to the coast. Locally there are spectacular 100m cliffs, dropping directly into the Pacific Ocean.

Surface drainage is limited throughout most of the year. Small perennial streams are believed to drain areas of impermeable rock in the centre and north-east of the island, their flow being to the east. These areas were not visited during the Expedition and it is unsure whether the streams, shown on 1:25000 maps, exist or whether they have significant flow all year round. On the western side several streams are shown and are indicated as ultimately reaching the sea at Ohonua (Fig.6), but again a perennial flow seems unlikely. Certainly those streams examined during the Expedition were either lost underground or absorbed into somewhat depressing swampy areas east of Petani. Water from springs east of Kolomaile, particularly Shower Cave, Fish Tail Cave and Ana Peka Beka was shown to sink and rise again in very complex fashion before becoming lost in the swamps. Other strong springs are said to exist in the western part of the island, one in particular at "Kahana Cave", near Houma in the north. A search for this at the start of the Expedition proved abortive, but since flow figures are quoted in literature it must exist, and is probably worth another search. On the east side of the island only one rising is known, having been located by Norman Flux during his post-Expedition reconnaissance. The water emerges from breakdown at sea-level, so no accurate estimate of flow could be gained - the flow is, however, "very large". The logical assumption on the grounds of geology and topography is that this rising serves the shaft systems in the Eocene limestone of the Top Area (see below).

'Eua was originally totally forested, with abundant hardwood, including sandalwood, fruit trees, banyans and coconuts. Toll has been taken by clearance for agriculture and commercial exploitation, but there is now greater control as well as an ongoing programme of scientific replanting. Where the ground has been cleared and the soil is suitable various crops have been planted. Taro is ubiquitous, even being found planted in the alluvial floors of dolines, and coconuts are also everywhere. Additionally there are all kinds of fruit trees, including bananas, and vegetables such as manioki, yams and sweet potatoes. A recently developed cash-crop is vanilla. There is one herd of dairy cattle at the Agricultural College and a few other beef cattle scattered around the island. Pigs roam everywhere in the village areas, as do chickens and a smaller number of goats.

The climate of 'Eua is broadly similar to that of Tongatapu, but perhaps slightly cooler and slightly wetter overall, with an equally high humidity. Rainfall can be torrential with the island lying on the edge of the hurricane belt and much of the surface terrain reflects flash flood erosion. In contrast to Tongatapu there are many deep valleys, mainly dry or seasonally wet, which

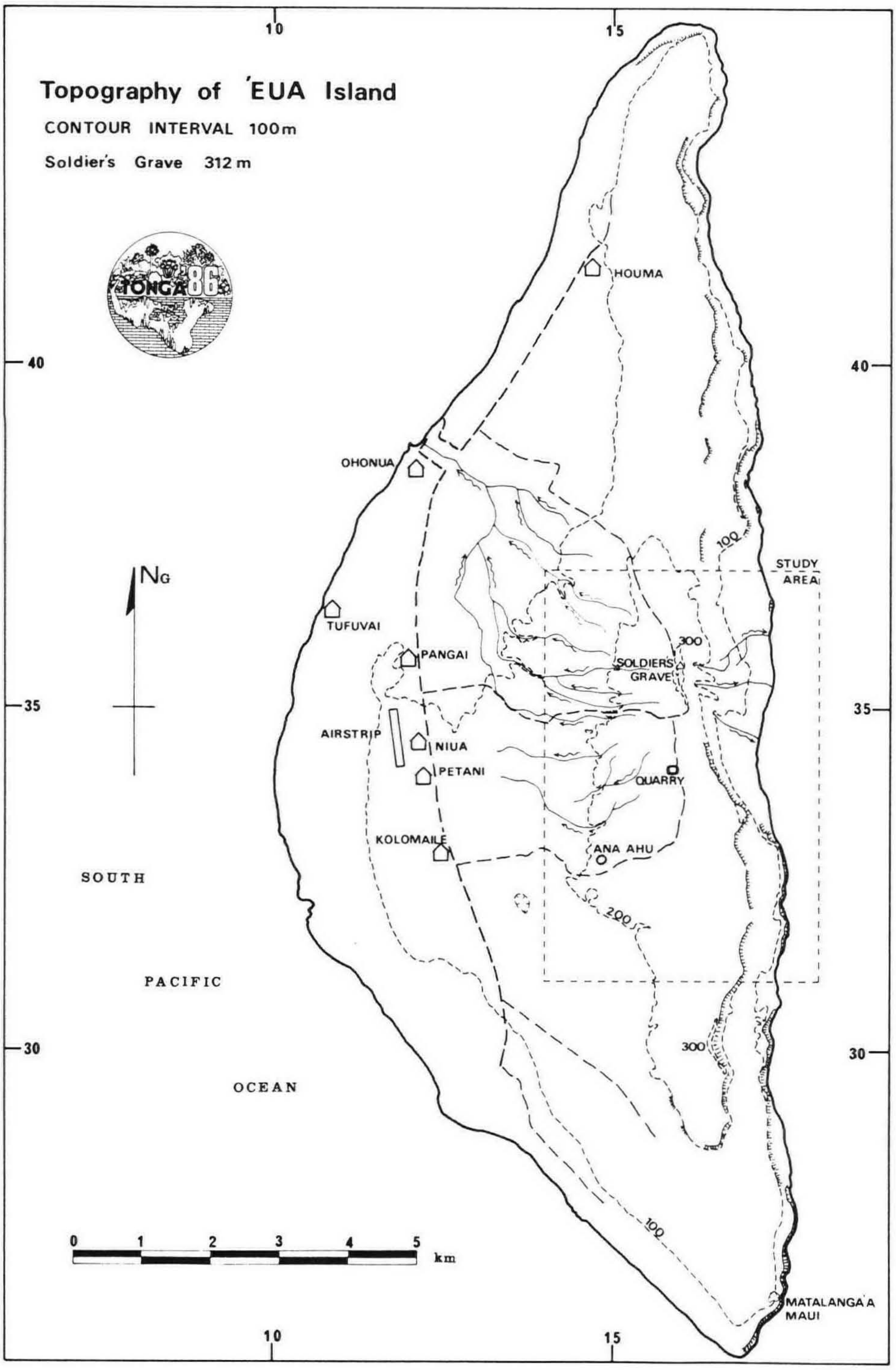


Figure 6

are generally steep-sided or even precipitous. Valley sides are deeply gullied and soil stripping is locally extreme. Particularly on the high limestone ground, but also on the lower limestone terraces, solutional and collapse dolines are a common feature, often located where surface valleys have intersected fault planes.

Communications on the island vary from good to impossible. The western low ground has a fairly reasonable set of dirt roads based on a main north-south highway. Branches lead west to the coast and east into the forested hills. There is also a reasonable high level road running along the island's spine, which becomes vague to the north and south of the Top Expedition Area. The route most often used by the Expedition was eastwards from Pangai climbing steadily onto the ridge road, which gave access to the more obvious caves. Other tracks and trails are vague and unmapped, often overgrown and constantly changing. Future explorers would be well advised to carry out a pace and compass survey of forest tracks before commencing doline examination.

Geology

The geology of 'Eua as understood prior to the Tonga '86 Expedition is described by Cunningham and Anscombe (1985) (Fig.7). Limited Expedition resources did not allow time or manpower for specific detailed geological work, but during exploration the lithology and effects of structure were constantly observed. Samples of representative rock types were collected and will eventually provide more-detailed information on the origins of the cave-forming rocks on 'Eua and may help to prove or disprove certain existing theories.

Reef limestone is forming along the island coast at present, and has probably done so throughout the Quaternary and much of the Tertiary periods. The oldest exposed rocks are of early Eocene age and comprise a complex of extrusive and

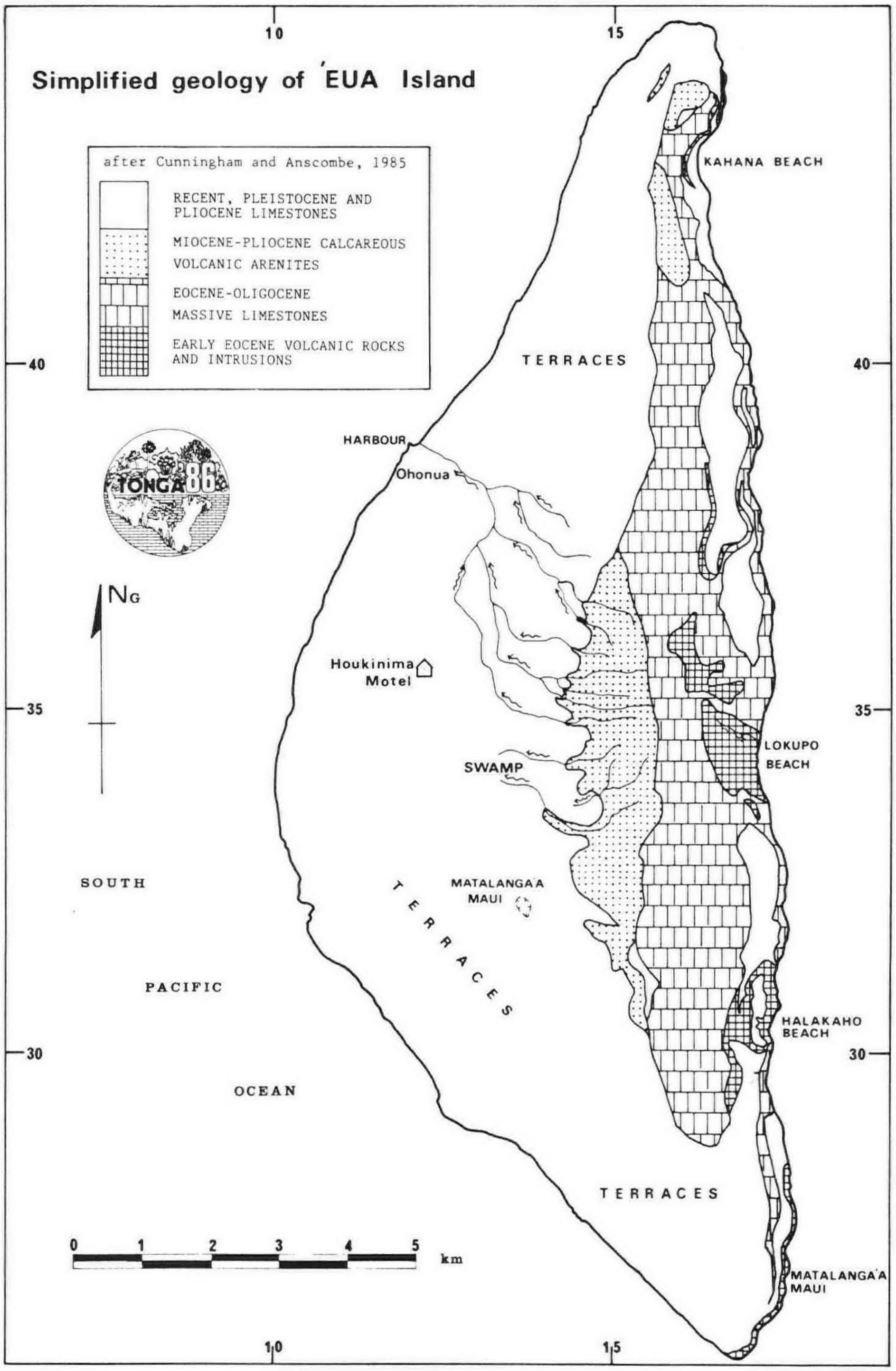


Figure 7

intrusive igneous material of "island arc" type. There was almost certainly significant tectonic and erosional modification of the proto-'Euan landmass, coupled with oscillations of sea-level, before an essentially limestone sequence began to be deposited on the irregular basement surface in mid-Eocene times. A number of sedimentary breaks are recognised within the younger rock sequence, indicating emergent episodes of non-deposition and/or erosion. Starting in mid-Miocene times a sequence of sandy deposits, derived from pre-existing rocks in the area, was deposited, possibly on a highly karstified surface. With these exceptions the geological column from the Eocene to the present day is composed of limestone of one sort or another, as shown in Table 3.

Throughout the geological history covered by the above sequence it is likely that fringing reef limestones have formed contemporaneously with massive shelf limestones, in water of different depths and salinity. No attempt has been made to differentiate lithologies within limestones of a given age and it is un-realistic to separate the limestones of Recent, Pleistocene and Pliocene age since most earlier attempts at subdivision were based upon the recognition of supposed depositional terrace features. It is suggested here that at least some of the terraces represent erosional features cut into pre-existing rocks and in some cases 'palaeontologically disguised' by a veneer of younger rock, joint fill and so on, contemporaneous with, or immediately post-dating, the erosional episode. Evidence for this hypothesis is far from conclusive, but previous anomalies of dating can be clarified if the relationships of cave passages to terraces become more apparent and more sensible if erosion, rather than deposition, is assumed.

Structurally the island is relatively simple. According to Cunningham and Anscombe (1985) a gentle anticline runs the length of the island, but it is unclear whether this represents a true fold or if the dips are a primary depositional or consolidation feature. A number of major fractures are recognised, generally trending NW-SE but swinging closer to north-south in the northern part of the island. Where observed during the Expedition there was little evidence of substantial vertical movement on these fractures, and it is considered probable that they are strike-slip (wrench) faults, exhibiting lateral, generally dextral, movement. Strata between the major lines of strike-slip movement have undergone torsion in such a way as to generate two additional fracture sets, mutually at right angles; one set of relatively open tension gashes, the other of secondary wrenches.

View from central 'Eua towards the south. Careously weathered, possibly dolomitised, Eocene limestone in foreground and forming distant "terraces".

QUATERNARY	
Pleistocene to Recent	reef and detrital limestones
TERTIARY	
Pliocene (?lower to upper)	reef and massive, foraminiferal limestone
BREAK	
lower Pliocene to middle Miocene	calcareous volcanic arenite (lithic sandstone) with subordinate mudstone locally
BREAK	
Oligocene to upper Eocene	massive foraminiferal and algal limestone (shelf facies)
upper Eocene to middle Eocene	basal conglomerate/ conglomeratic limestone
lower Eocene	igneous basement complex

Table 3

Most unconsolidated material on the island can be considered as alluvium, fairly extensive deposits occupying generally depressed areas on the western side of the central high ground. Elsewhere alluvial wash is present in most depressions and valleys. Beach sand of reworked coral and volcanic material is present along parts of the coast, though elsewhere high cliffs drop straight into the ocean.

General background to the caves

Certain of the caves on 'Eua have been known to the local inhabitants, some probably for generations. Generally they have only been given a name if they are spectacular, such as Ana Ahu (Smoke Cave) or if they have some feature that makes them more noticeable than other local holes, for example Ana Peka Beka (Swift Cave). It appears that there are several "Swift" caves, since swifts inhabit several caves. Prior to European interest in them, the only attraction the caves seem to have held was as a water supply. Water could either be piped out of them, or the islanders could go in and get it. Details of the water's potability are dubious, but most 'Euans seem to be fairly healthy. There are stories of Tongans entering caves to capture crabs for food, but it seems unlikely that this would be the case with the caves explored during the Expedition. Though cave crabs were present, they had less meat on them than the spiders that they resembled.

Many folk legends persist about caves and karst features. A hugh doline called Matalanga'a Maui, south-east of Kolomaile, is said to have been formed by the hero and demi-god Maui, who simply scooped up a very large chunk of the island and hurled it away to the south-east. The hole where it landed, a very impressive blow-hole, is also called Matalanga'a Maui.

Hoffmeister (1932) noted that there were caves during his geological work, but it was not until the 1950s that Ana Ahu was descended by two Europeans, using a 300 foot rope hauled by three Tongans. Then in the early 1980s much of the island was reconnoitred by Karen Anscombe, John Cunningham and friends who carried out preliminary

Spectacular cliff of Eocene limestone overlying volcanic basement at sea-level, on the SE coast of 'Eua. A small (c.4m x 3m) cave passage at the level of the "200 Foot Terrace" has been truncated at the upper left of the cliff.

exploration and survey of some systems (Cunningham and Hood, in press). The members of the Tonga '86 Expedition were the first fully equipped and experienced cavers/cave scientists to study the 'Euan caves.

KOLOMAILE AREA

Geology

Kolomaile village is situated on the so-called "400-foot terrace", a broad, sub-horizontal shelf which varies in height from 100 to 120m. Hoffmeister (1932) concluded that the "400-foot terrace" was probably of Pliocene age, but Cunningham and Anscombe (1985) suggest that the limestones which form the terrace are of Quaternary age. On purely geometrical grounds there is a strong possibility that the "400-foot terrace" is an erosive, rather than depositional, feature, cut into rocks of Pliocene age, or older, and with a superficial cover of late Pliocene or Quaternary limestone. At the inland margin of the terrace the land rises steeply, forming vertical scarps in places. Above 120-130m limestone gives way to a calcareous volcanic arenite of probable late Middle Miocene to early Pliocene age and about 35m thick, with its upper surface 155 to 165m above sea-level. The arenites are overlain disconformably by coral and foraminiferal limestones of Pliocene age (Cunningham and Anscombe, 1985). Structural data are lacking in the Kolomaile area, but Expedition observations underground indicate that the succession is essentially sub-horizontal, locally with a gentle dip towards the west or south-west. A number of faults or fracture/joint zones of limited displacement trend generally south-west to north-east and have played a significant part in guiding cave development.

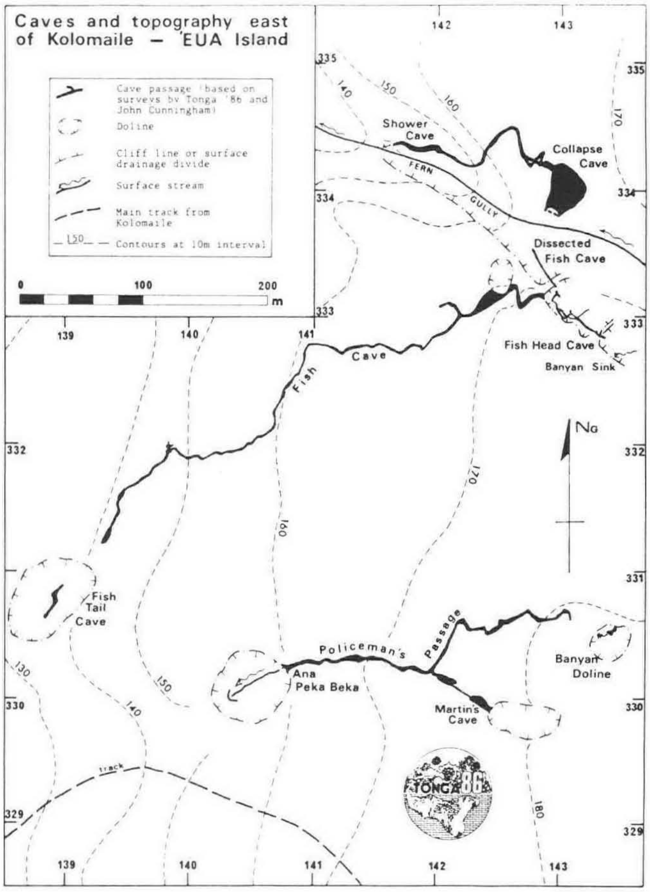


Figure 8

Physiography and hydrogeology

The surface of the Pliocene limestone is generally sub-horizontal with about 1m of soil cover supporting patches of taro and other root crops. A few large banyan trees remain and on steeper ground there are dense thickets of vines, creepers and a few salato, a large stinging plant. On the lower ground of the "400-foot terrace" there are large areas of various plantation crops. A number of isolated, steep-sided dolines, probably mainly of collapse origin, penetrate the surface of the Pliocene limestone and in the north of the area a deep, steep-sided valley (Fern Gully) with a perennial stream runs from east to west (Fig.8). Two smaller streams to the north and south of Fern Gully sink into the limestone and emerge at separate risings close to the junction of the "400-foot terrace" and the Pliocene limestone/arenite scarp. Water from the northernmost rising, Shower Cave, joins that from Fern Gully and, after part has been abstracted for domestic supply, the remainder flows across the terrace for about 1.5 km to be absorbed in a large swamp. Water from the second rising, Fish Tail Cave, is also abstracted for public supply, as is that from a third rising, Ana Peka Beka (Swift Cave, also known as Policeman's Passage). Considerable effort has gone into building the abstraction system, which extends to the upstream end of both caves, in an attempt to avoid contamination by the droppings of numerous swifts and (?) bats which inhabit the caves. According to Filipe Koloi (oral communication, 1986) of the Tongan Water Board, water tracing experiments using Rhodamine dye were carried out prior to the abstraction works. One further successful trace was undertaken during the Expedition, proving a flow from Banyan Sink through Fish Head, Fish and Fish Tail caves (Fig.10).

That flow which is not abstracted from inside Ana Peka Beka emerges from the large cave entrance at about 142m above sea-level. After crossing about 80m of the floor of a closed depression, probably a collapse feature, the stream sinks again. Its underground route is inaccessible but the water emerges from the other side of the ridge in the next collapse doline. On the downstream side of this doline is a large cave passage, which was explored through the next ridge, but not surveyed. The water emerging from this cave is joined by that from the Fish Tail Cave rising and the combined flow continues in a westerly direction across the "400-foot terrace". The narrow stream channel is incised up to 10m into the terrace surface and there are several more sinks and risings, some of which are associated with short lengths of cave passage which terminate in sumps. A dry channel continues beyond the final point at which water was observed during the Expedition, but the feature was not followed to its eventual conclusion due to more pressing explorations. As there are no risings known between Kolomaile and the coast it is assumed that the ultimate rising is intertidal or submarine. An intertidal rising was located west of Pangai, but this is thought to be too far north to be the Kolomaile water.

The Caves

Three cave systems were explored, one associated with each of the risings described above.

SHOWER CAVE - COLLAPSE CAVE (Figs 8 & 9)

This system is noted in the index of Cunningham and Hood (in press) but there was no description nor survey in the version supplied to the Expedition. The upstream end of the system is entered through Collapse Cave, a large chamber with its lower entrance 10m above the floor of Fern Gully. Almost at the centre of the chamber there is a large talus cone which lies beneath a skylight. The chamber is formed entirely in limestone of presumed Pliocene age, as is a small passage which leads off from floor level at its north-west corner. Tramps Passage (named after "Tramps", the Tongan Rambling And Multifarious Pursuits Society, led by Bronwen Corrall, the Acting British High Commissioner, who carried out the exploration and survey) is a relict phreatic passage which meanders above, but does not currently give access to, the present day streamway. The streamway is reached by a climb down a boulder slope in the main chamber. Upstream is inaccessible, but downstream is a pleasant vadose streamway with a number of sporting cascades and deep canals. The streamway is some 185m long, and its aqueous nature is enhanced by a dam at the resurgence, to aid exploitation for public supply. The whole of the streamway, which has a vertical range of almost 30m, is developed in the calcareous volcanic arenite.

THE FISH CAVE SYSTEM (Fig.10)

As Fish Cave was surveyed and described by Cunningham and Hood (in press) it was accorded just one exploratory visit on the Expedition. This was intended to push the final duck described by Cunningham and Hood, and it appears this was passed before the team was halted by another intimidating duck. The passage is small, with only 2cm of airspace continuing. An overland survey was carried out from Fish Cave entrance to the rising (confirmed by fluorescein tracing) which was found to be 46m lower. A previously unrecorded cave (Fish Tail Cave Fig.8) was explored upstream from the rising for 30m to a duck, the water level being artificially raised behind a dam installed to maintain flow into a mains pipe. The Cunningham and Hood survey (in press) places the end of Fish Cave about 60m from Fish Tail Cave at a depth of 45m, and it seems reasonable to assume that the duck was reached from both sides,and represents the final obstacle to a through trip. If a connection could be forced,perhaps in drier conditions with the water level behind the dam lowered, the cave would exceed 600m in length, easily the longest in Tonga.

In contrast to Fish Cave, which is a generally comfortable, walking-size passage, Fish Head Cave is low, tight, aqueous and hard on the knees. Water tracing using fluorescein dye proved that the source of the cave stream (which also flows through Fish Cave) is a nearby sink (Banyan Sink) at the base of a cliff (Fig.10).

The doline in which the lower entrances to Fish Head Cave are located is adjacent to a dry valley which is tributary to Fern Gully. About

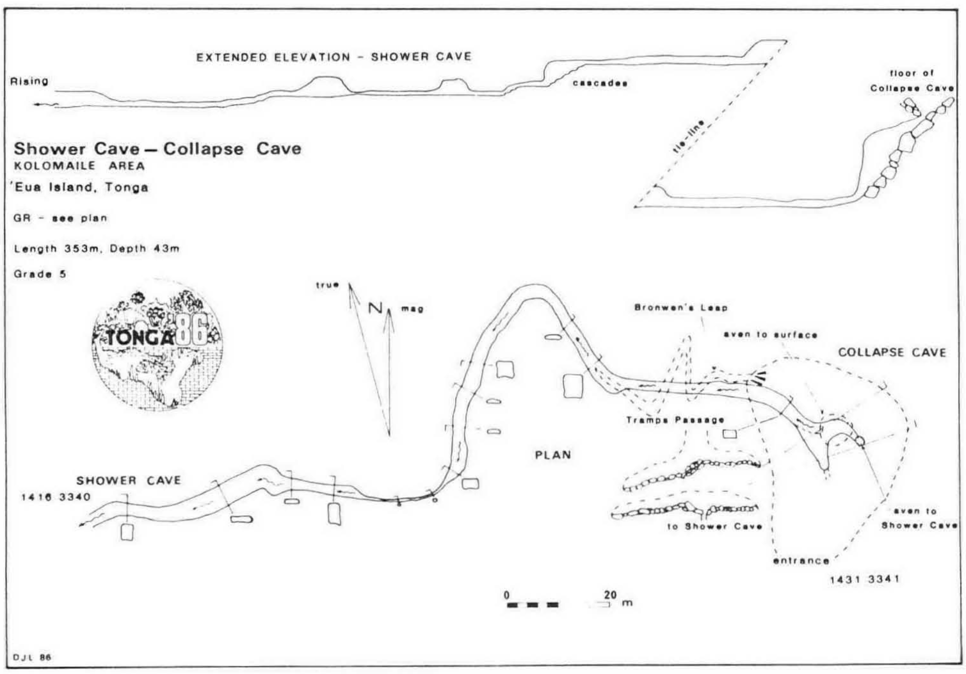
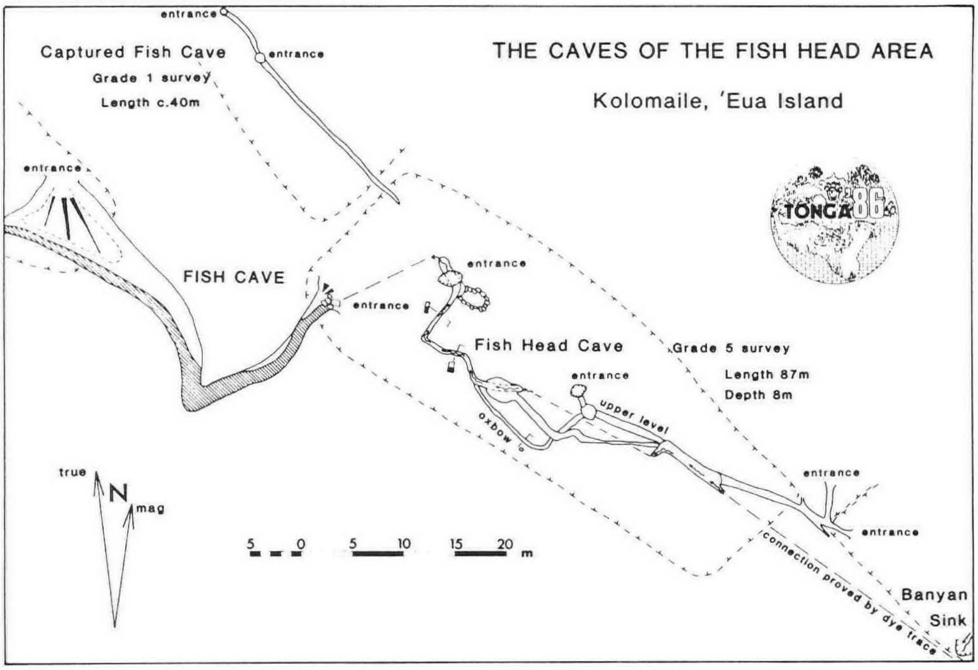


Figure 9

Figure 10



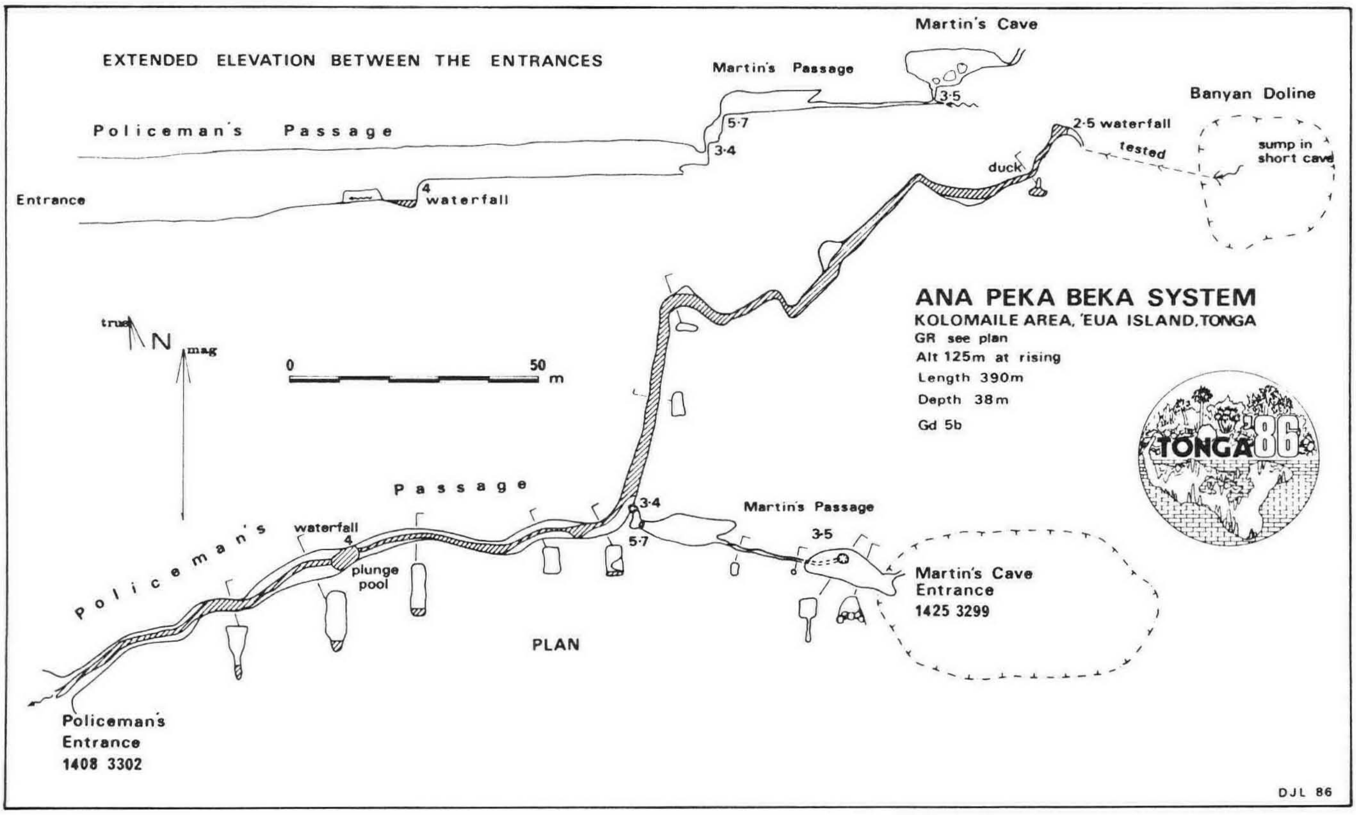
35m of passage was explored near the head of this valley back towards the abandoned upper levels of Fish Head Cave. It appears that Fish Head Cave might originally have been tributary to Fern Gully but has been captured by the Fish Cave drainage. Hence the unsurveyed relict passage was named Captured Fish Cave.

ANA PEKA BEKA (SWIFT CAVE) (Fig 11)

Cunningham and Hood (in press) provide a description of a cave with a large, impressive entrance which they named "Policeman's Passage" as a result of a brush with the local constabulary, who strongly disapproved of Sunday caving. Local enquiries revealed that the cave is known as Ana Peka Beka. Cunningham and Hood also entered and partially explored Martin's Cave, but were stopped by a pitch. This was descended during the Expedition and found to link with Ana Peka Beka, bringing the total length of the system to 358m and its depth to 38m.

The downstream entrance to Ana Peka Beka is an impressive vault, 15m high, developed in arenite but with the overlying limestone forming its roof. Large vadose canyon leads to a 4m waterfall, rendered extremely slippery by the droppings of the many swifts (peka beka) which inhabit the cave roof. Above the waterfall the streamway continues and progressively decreases in size, until a top waterfall is reached; above this the passage can be seen to continue but is too constricted for easy progress. Wooden shuttering extends up the waterfall, supporting a white plastic pipe, about 25 cm in diameter, which extends right through the cave and beyond, carrying water to the 'Euan "mains". Its installation must have taken considerable time and

Figure 11



effort, the idea presumably being to draw off water uncontaminated by the swift droppings which coat the walls and floor throughout the cave. However, this presupposes that the water entering the pipe at the top of the waterfall is of potable quality. Cunningham and Hood (in press) suggest that the source of the water is a stream which sinks about 220m to the north (Banyan Sink), but Expedition water tracing showed that this water enters Fish Head Cave (see above). The source of the Ana Peka Beka stream was proven to be a sink in Banyan Doline, just 25m east of the end of the known cave. Banyan Doline is 15m deep, steep sided and probably a collapse feature. On the upstream side a few metres of large cave passage end in a sump and the downstream side is impenetrable as a result of collapse. The ultimate source of the water seems to be diffuse recharge from the area to the east.

The entrance to Martin's Cave is in a doline some 60m south-west of Banyan Doline; this provides a rather tortuous and sporting route, down three short pitches, following a tributary stream into Policeman's Passage.

Speleogenesis

The majority of cave passage in the Kolomaile area is formed in the strata which lie beneath the Pliocene limestone, referred to by Cunningham and Anscombe (1985) as "volcanoclastics". Cunningham and Hood (in press) infer that the caves originated as phreatic tubes, at the base of the Pliocene limestone, which were then incised vertically into the "volanoclastics", presumably by mechanical action. Analyses of samples collected during the Expedition indicate that the lower rock would be more appropriately termed a calcareous volcanic arenite and as the calcium carbonate content of all specimens tested exceeds 50% (and is as high as 82%) there are strong chemical grounds for considering it an impure limestone. Hence mechanical action may be less important than originally thought and there is no longer a necessity to postulate cave inception being limited to the base of the limestone. In general the latter situation is apparent however, though the lower streamway in Fish Cave is entirely within the arenite, with no sign of having cut down from the limestone base. Nevertheless the majority of the passages in the area are of simple cross-section and there are no extensive abandoned passages, so the hypothesis of initial phreatic development followed by vadose downcutting appears to be well founded. The absence of multiple levels also suggests that the downcutting was/is a response to a single phase of uplift. Expedition overland survey established that the risings for the three Kolomaile systems are at a similar altitude (124 ± 3m). This elevation coincides with the edge of the arenite outcrop and the top of the "400-foot terrace". The precise inter-relation of the terrace to the geology is debatable but, whatever the origin and nature of the terrace, the cave systems described could possibly be graded to its upper surface.

The major complication to the simple picture described above is Collapse Cave, a substantial cavity which has formed largely in Pliocene limestone, has little lateral extent and is perched 10m above present drainage in the adjacent Fern Gully and 15m above the streamway of Shower Cave. One possibility is that Collapse Cave is a remnant of a formally more extensive system developed in the Pliocene limestone, with the underlying arenite forming drainage base level. Missing upstream passages could be buried beneath extensive breakdown which floors the entire chamber. Several solution notches are visible in the sides of Fern Gully at about the same altitude as Collapse Cave. Lower down the valley, close to the Shower Cave entrance, but higher, are several short fragments of 'ancient' cave passage, well-blocked by old calcite and detrital deposits. These fragments are at or just above the limestone/arenite contact and might represent the remains of the primary phreatic drainage route of the area, of which Collapse Cave was a somewhat higher tributary. On these grounds it is possible that Fern Gully itself might be, at least in part, of cavern-collapse origin. It is now grossly overdeepend, with its bed well below the old cave level and it seems fairly certain that sudden accelerated downcutting, due perhaps to uplift, left the older passages high and dry, with the newly rejuvenated stream eroding easily into the underlying arenite.

The above is extremely speculative, but it does point out the need for further investigations in this area. Future exploratory work should preferably be tied to a programme of speleothem dating. Study of the terrace area west of Ana Peka Beka would be of great interest, firstly in helping to confirm the ages of the limestones preserved in the terrace, which could be Pleistocene, Pliocene or Eocene, and secondly in establishing the age of the caves present. The latter, though not studied by the Expedition, are apparently very recent in origin, but if the limestone is older than previously supposed,and if the area was exposed to erosion in late Tertiary times, the possibility of older fragments of passage cannot be ruled out. A vast doline, Matalanga'a Maui, which lies on the terrace to the south-east of Kolomaile village, indicates massive collapse into a significant cavity, or equally significant long-active solutional activity.

The first waterfall in Policeman's Passage, Ana Peka Beka, is over faulted Miocene volcanic sandstone. The pipes above carry water supplies to the surface from the upstream limit of the cave.

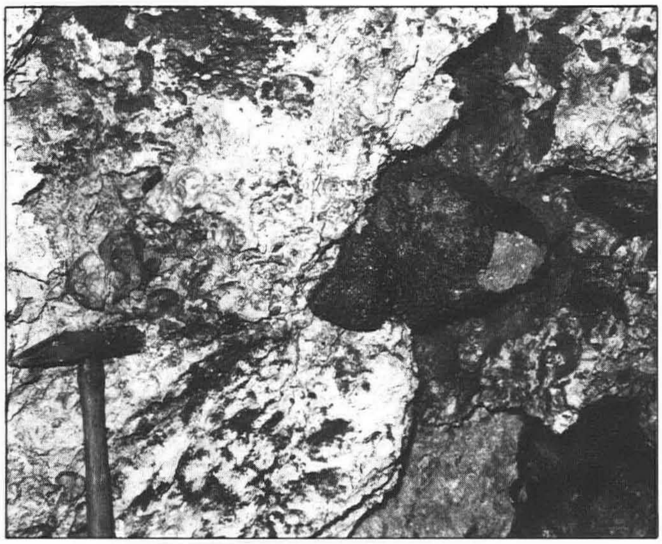
TOP AREA

So far as is known there is no local geographical name for the area of relatively high ground where most of the Tonga '86 exploration and reconnaissance took place. By default therefore the area became known as the Top Area and is topographically and geologically distinct from the lower ground which has been described as the Kolomaile area. The area straddles the roughly north-south ridge road and reaches Parkers Hill in the north (Fig.12) and Ana Ahu in the south. Westward and eastward exploration stopped at the first significant cliff or steep drop off of ground level. An area adjacent and south of the Expedition Top Area was examined by Norman Flux after the main explorations and the combined area is shown on the accompanying maps.

Geology

Rocks which form part of the early Eocene volcanic basement come to the surface in the north and east of the area. There are magnificent exposures of generally reddish agglomerate on Parker's Hill and other volcanics including tuffs and lavas are exposed at lower levels to the east, but were not inspected during the Expedition.

The volcanics seem to form a very uneven palaeo-surface which was probably the product of rapid but intense erosion, possibly coupled with uplift, prior to the deposition of the overlying beds. In all caves that were explored to sufficient depth a basal conglomerate was recognised as forming the lowest part of the main Eocene limestone sequence (Fig.13). The thickness of the conglomerate was highly variable, as would be expected on such an uneven depositional surface, and its composition, at least in terms of clast size, was equally varied. The conglomerate matrix was of limestone material indistinguishable from some of the lithologies in the overlying beds, but there were inclusions of broken, pre-existing limestone, probably of reefal type, and of macro-fossil material. Since macro fossils were rare in the overlying rocks this would imply a significant change of depositional environment between the period just before conglomerate deposition and the deposition of the main limestones. Almost all the clasts in the conglomerate are of volcanic material and they range in size from sand grains to boulders a metre or more long. In general the smaller clasts, up to small cobble size, are very well rounded, whilst the larger ones exhibit marked rounding of edges and corners. The clasts are generally ill-sorted and chaotic, except that in general terms the larger sized material is concentrated at certain locations. If a local source is envisaged for the clastic debris in the conglomerate - the Parker's Hill volcanic rocks that formed "proto-'Eua" being the obvious analogue - then it is difficult to conceive any other depositional environment than the inundation by the limestone sea of a pre-existing beach deposit or rolled boulder bed. In order that the limestone sea could lap onto the volcanic landmass there must have been a relative sea-level rise, the corollary being that before transgression the landmass was bigger and higher and probably weathering/eroding rapidly. Much of this debris, which judging by today's exposed rocks was never particularly indurate, would have found its way to relatively lower ground, possibly ultimately to sea-level, where relatively high energy conditions would quickly knock off the corners and produce the rounding visible in the conglomerate clasts today. Without a precise picture of the topography of the "proto-'Euan" volcanic landscape it is not possible to predict the possible extent of these beach areas, nor whether all the clasts were formed at the same time, but the detailed information with regard to the limestone/volcanic interface that is being observed in the caves will ultimately make the picture a good deal clearer, partiularly if deeper caves to the south and east are located.



Boulders of early Eocene volcanic rock and fossiliferous limestone enclosed in a younger limestone matrix form the basal conglomerate of the Eocene limestone sequence exposed at the foot of the third pitch in Third Cave.

Lying as it does on the irregular surface of the volcanic basement and apparently having a more

Surveying in the streamway of Third Cave; the roof is of Eocene limestone basal conglomerate and the walls and floor of Eocene volcanic rock.

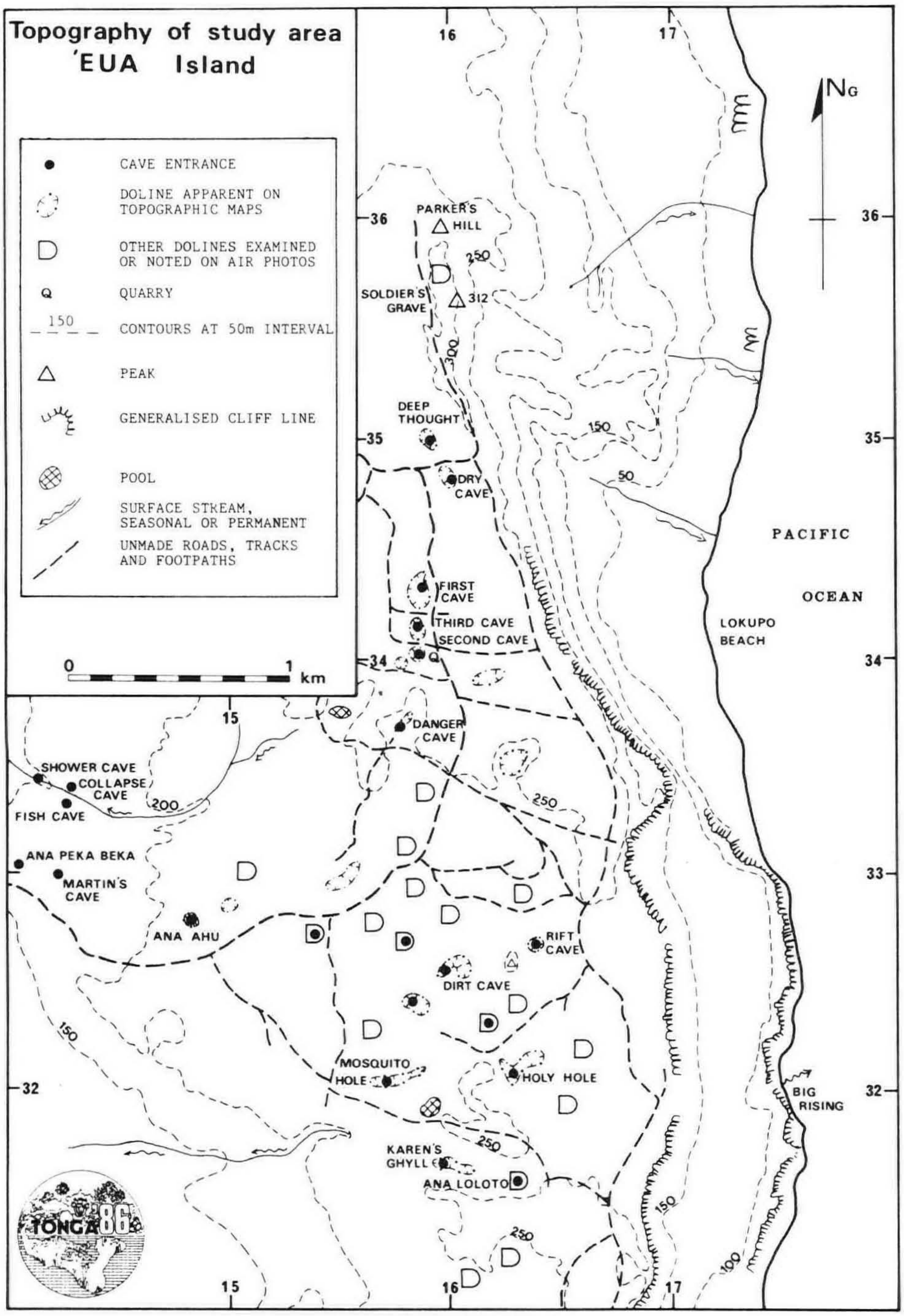


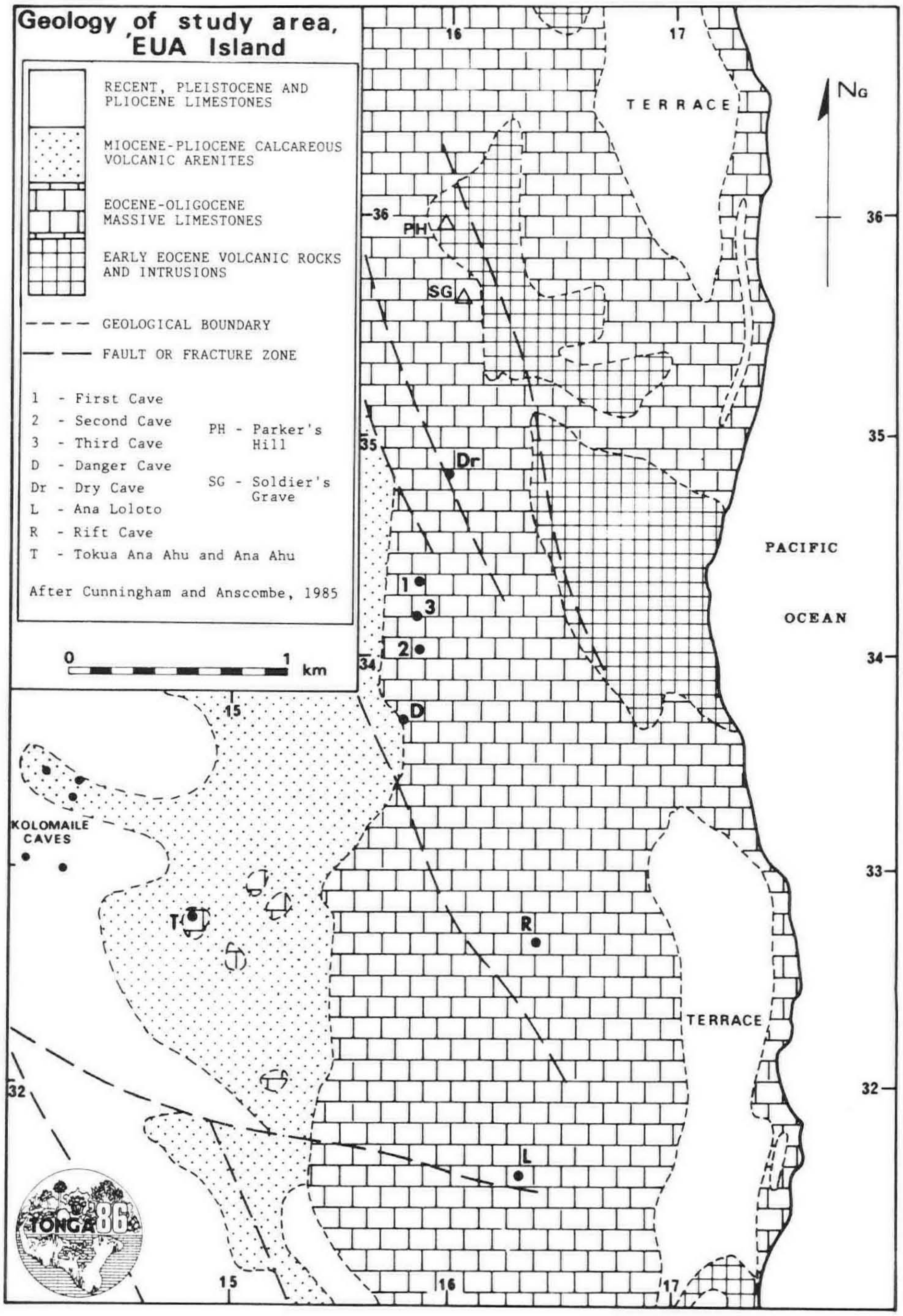
Figure 12

or less planar upper surface, it is not possible to recognise a consistent thickness for the overlying Eocene limestone sequence. It is certain that the limestones thin away against the volcanic pile around Parkers Hill and this thinning may be in part a depositional feature and partly an erosive effect. The maximum thickness proved by cave exploration is 120m (in Rift Cave and Ana Loloto), but again this is probably not a reflection of the true thickness of beds penetrated by the caves. Repetition of parts of the sequence is to be anticipated where the caves cross faults. On strictly topographical grounds a thickness greatly in excess of 120m might be present, but again the rocks at sea-level on the east coast are probably stepped down eastwards by faults and no meaningful figure can be quoted.

There are, within the Eocene sequence, a number of distinct lithologies including a friable, "chalky" limestone with algal nodules and marly bands, a very hard and massive sparry limestone and an equally hard rock composed almost entirely of broken fossil debris. These three lithologies were noted during the first day's exploration in Dry Cave, where there seemed to be a repetition of the sequence down the cave exposure. First impressions were that this reflected a cyclic series of depositional environments, but in retrospect it is considered more likely that the repetition is structural. In other words a limited limestone sequence is penetrated by the cave passage which then crosses a fault into a higher part of the same succession - and so on. This is not proven conclusively by fossil or marker band evidence, but the behaviour of the basal conglomerate, where exposed in Rift Cave, indicates that step-down fault repetition is a realistic possibility. It is also now apparent that the differing lithologies exposed at the surface reflect different parts of the succession faulted to a particular level rather than lateral facies variation. In all probability, only one major depositional cycle is represented in the Eocene sequence, lithological variation indicating the change of depositional facies with time.

As mentioned, the upper surface of the Eocene beds is nominally planar, but it has been significantly modified by faulting and

Figure 13



karstification. There is no direct evidence for significant former episodes of karstification, but there are a number of circumstantial indications. No Oligocene rocks are preserved on 'Eua (unless part of the Eocene sequence is in reality of Oligocene age). Whether rocks of this age were deposited and subsequently removed, or whether they were not laid down, is uncertain, but in either case a significant erosive episode is implied. Certainly enough time was available between the completion of deposition of the preserved Eocene sequence and the commencement of arenite deposition in Miocene times for the older material to have undergone diagenesis and for significant karstification to have taken place. It is postulated here that such erosion occurred during late Oligocene times and included not only the development of surface karst features such as dolines, but also of sinks and underground drainage systems. In addition it is postulated that there was major solutional cavern development along a contemporaneous freshwater lens/saltwater interface.

Concurrently the volcanic hinterland was being similarly subjected to intense erosive activity and abundant rock debris was produced and moved around by flash floods and wind action. Classic wind-faceted pebbles (dreikanter) have been recognised among derived clastic deposits.

The second indication of Oligocene karstification is the presence of outliers of red sediments, derived from volcanic basement material, within depressions in the Eocene limestone surface. It is possible that these depressions are palaeo-dolines and that the preserved infill is part of, or contemporaneous with, the Miocene volcanic arenite sequence which forms a larger outcrop to the west of the Top Area. More research must be done on the outlier material in order to confirm its age and mode of deposition.

Across the present day limestone plateau, which has been visibly lowered by solution, there are remnant spines, pillars, and ridges of hard, splintery, crystalline limestone. As a result of the solutional activity the lateral equivalents of the upstanding remnants are unavailable for examination, but must have been more prone to karstic solution. In every example examined the adjacent underlying rock was softer than the remnants and not obviously crystalline. No specimens of the upstanding rock type were retained and no petrographical or palaeontological study has been possible. It is suggested here that the remnant rocks represent neptunean infill of palaeokarstic features or a combination of this with subsequent dolomitization of infill and wall rocks. The remnants invariably exhibit careous, vughy, weathering, and future sampling and analysis should confirm whether or not this feature is indicative of secondary dolomitization.

Other potential indications of palaeokarst processes, which may refer to Oligocene or more recent erosion, will be mentioned in the speleogenesis section.

Overlying the Eocene (? to Oligocene) massive limestone sequence in the Top Area are Miocene deposits, previously referred to as volcaniclastic sandstones, but here termed calcareous volcanic arenite. Where best exposed, in the Kolomaile caves, these rocks are speleogenic and contain up to 82 per cent carbonate. In the Top Area exposure is poor, the best section being in the Ana Ahu doline and valley above. The rock is soft, apparently flat bedded and essentially arenaceous. The sand grains are almost exclusively lithic and quartz grains are conspicuously absent. There is a predominantly carbonate matrix and a proportion of clay/silt grade rock debris among the more general medium to coarse detritus. Elsewhere it is reported (eg Cunningham and Anscome, 1985) that the Miocene succession includes mudstone and siltstone, but no such exposures were noted during the Expedition. Spreads of red "clay-soil" are present locally and it is difficult to conclude whether this material is reworked rock or simply unconsolidated Miocene sediment. The rock has no direct bearing upon the caves of the Top Area, except in providing a relatively impervious catchment for the Ana Ahu system, and secondarily as a source of clastic infill material.

No rocks younger than the Miocene arenites are preserved in the Top Area and it would seem unlikely that any were deposited. If this is the case then the corollary is that the area has been positive throughout Pliocene to Recent times and hence susceptible to karstification. There are supposed Pliocene terraces to the east of the Parkers Hill and Rift Cave/Ana Loloto areas (Fig.13) at lower level. It is suggested here that these terraces are essentially erosive rather than depositonal. Even if erosive in origin these terraces would be expected to have a veneer of Pliocene reefal material or beach rock, which on the one hand confuses the age of the massive sub-surface limestone, but on the other gives reliable date for the cutting of the terraces. Whatever their mode of origin there would seem to be a link between sea-level during their formation and an early phase of speleogenesis within the Eocene sequence (see later).

A number of major fractures are mapped across the area (Fig.13) and are implicated in the formation of Dry Cave, Ana Loloto and Karen's Ghyll. As mentioned in the general geology section these are probably strike-slip (wrench) structures with little vertical displacement. Many of the caves in the blocks between the major faults exhibit passages guided by two fracture systems mutually at rightangles. Neither of these fault directions is parallel to the major mapped structures. One set invariably has a noticeable hade, the other set is often vertical. A possibility suggested here is that the two sets have formed as secondary fractures in response to coupled distortion of the rock mass between adjacent pairs of major strike-slip faults. If this is the case one set would be expected to be normal tension faults/gashes, the other set second generation wrenches. More work remains to be done on the analysis of survey data and direct measurement underground, to test whether the fracture sets present fall within theoretical expectations for such a strike-slip generated couple.

The caves

Many caves are now known in the Top Area and undoubtedly many remain to be found. Not all of the known caves are fully, nor even partially explored. Several have been explored by John Cunningham et al and were not revisited by Tonga '86 members; brief descriptions of these will be given, based upon the more detailed accounts in Cunningham and Hood (in press). For those systems re-explored by the Expedition the description will be based upon expedition observations and survey data wherever possible. As far as practicable the caves will be described beginning with the farthest north and moving generally southward, and reference should be made to Figure 12 for details of the locations.

PARKER'S HILL CAVE (GR 159 358) was explored by the Cunningham team in 1984. During Tonga '86 its entrance could not be relocated by Cunningham, nor later by Norman Flux during his reconnaissance. The latter did, however, locate a doline at approximately the correct location with dipping bedrock exposed, and it is uncertain

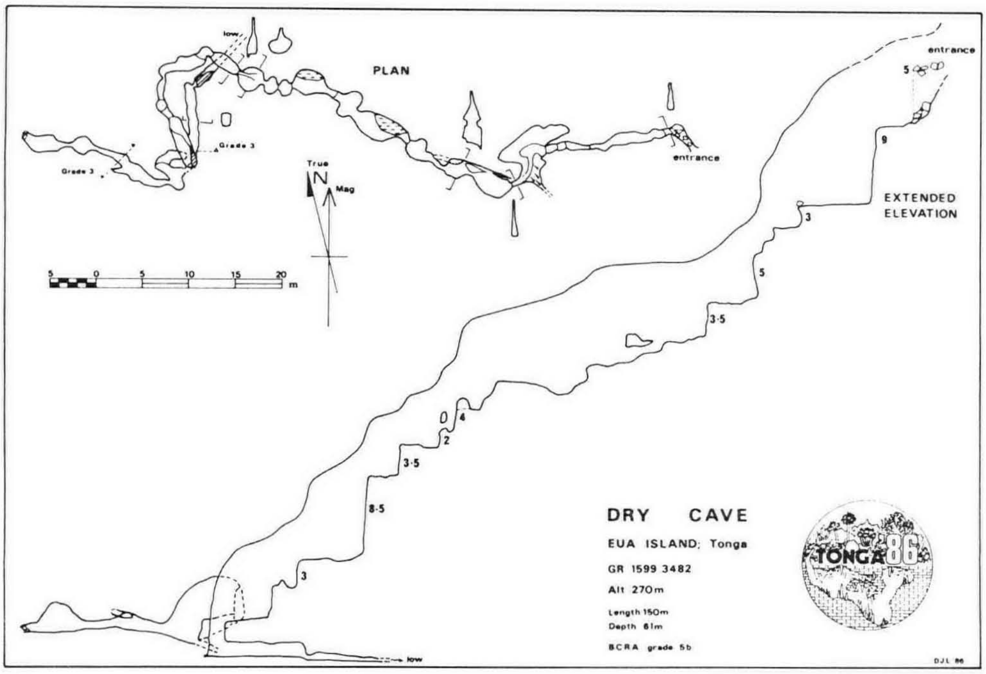


Figure 14

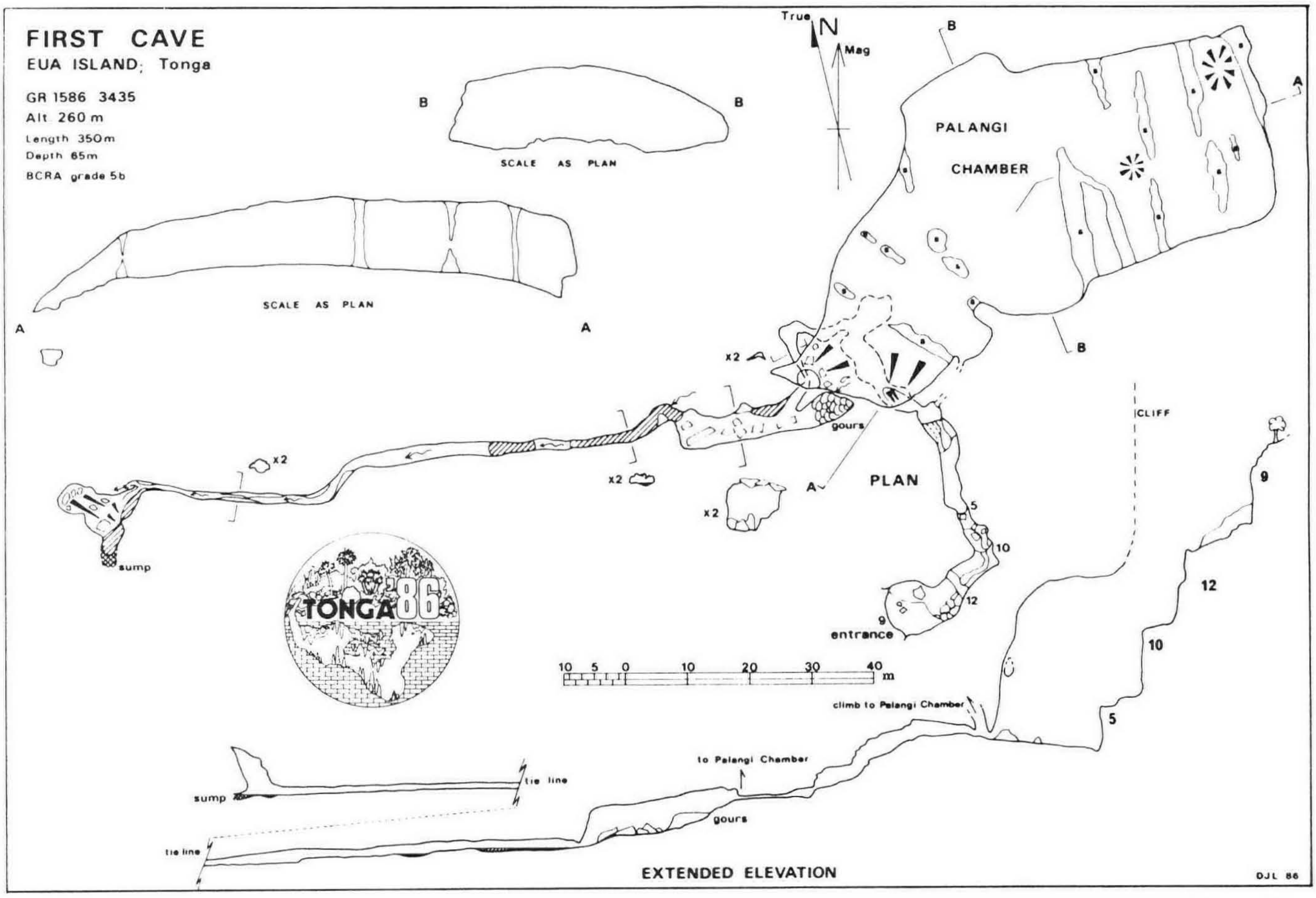


Figure 15

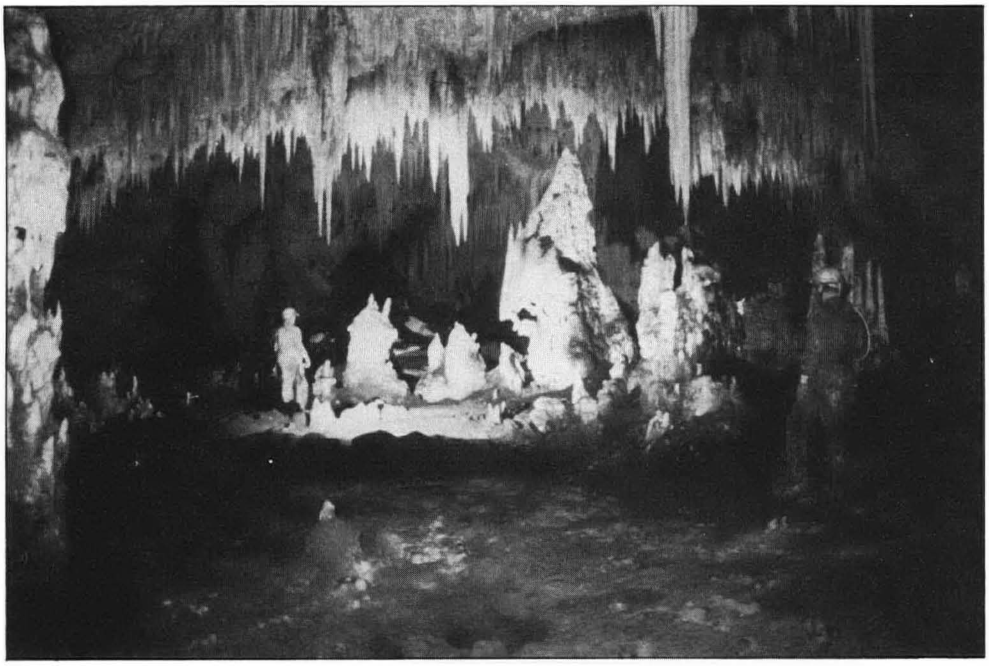
whether this might have been the recently blocked entrance to the cave. According to the first explorers' description the cave is fault guided and drops fairly steeply for 25m entirely in limestone, despite close surface proximity to the volcanic basement. A squeeze through a boulder choke gives access to a chamber with a red clay floor and some dead and active formations. Another chamber is beyond, with roof and floor of red clay suggestive of infill and re-excavation. A small trickle of water has cut a channel in the clay floor. Scrambling over boulders leads to an effective blockage of calcite flow. The water passes beneath the flow and bats are audible beyond, suggesting an appreciable enlargement. Current depth is 33m and length 105m.

South of Parker's Hill Cave are a number of minor dolines which appear to be seasonal sinks, but no open passage was noted during the Expedition. In the same area, probably at about GR 159 357, just west of Soldier's Grave, the team was shown a large cave by one of the Tongan drivers. This cave is known, in literal translation, as "the stone that speaks", or perhaps more prosaically ECHO CAVE. Though a fairly obvious feature, the hole was unknown to Cunningham. There are two entrances, one of which is a sheer drop from the surface. The second, formed on a complex fault system, leads horizontally into the side of the main shaft. An exposed climb leads to the boulder-covered floor of a partially unroofed chamber beneath the surface chasm. Rapid reconnaissance found no way on, but hindsight suggests that open cave might be found with a more rigorous search.

DEEP THOUGHT (temporary name) was missed by the Expedition reconnaissance team. Norman Flux returned and found a large, enticing entrance a few metres farther on. He explored down drops of 13m, 8m and 4m to a point where the cave, which is probably fault-guided, levelled out and the roof lowered. This point is probably close to the limestone base, but there is abundant guano, suggesting that passages or chambers exist beyond the squalid low section.

The entrance to DRY CAVE (Fig.14) which lies on the same fault line as Deep Thought, was pointed out by Cunningham, who had carried out a partial exploration in 1984. The entrance is large and inviting, but with an abundance of loose rock and jammed boulders. A series of short pitches and scrambles drops down the fault plane to enter a chamber with an abandoned mud-filled inlet on its south-east wall. Beyond the chamber further fault-guided passage leads to a second series of short pitches in a fairly large canyon. A self-drilling anchor was used on the 8.5m drop, where no natural belay point is available; the rock here is highly suspect and care is essential. The last drop enters a rift chamber, and the cave turns back on itself as a much lower passage, leading to an arbitrary end where the roof lowers. Back in the rift chamber, a hole on the right enters a high and muddy abandoned phreatic passage, blocked by mud and boulders. The phreatic development is believed to lie in the basal limestone, at a depth of about 60m, but the volcanic basement was not positively identified.

The entrance to FIRST CAVE was first observed from the opposite side of its doline, a gaping rift splitting a limestone cliff. Its name was intended for temporary identification, but no local name has been found. A sinuous route down the steep and vegetated southern slope of the doline leads to the brink of the entrance shaft (Fig.15), in the shadow of the cliff, where a steady stream of cave swifts (peka beka) fly in and out. From here the cave leads along a major fault and into a high aven chamber. Massive flowstone with sub-horizontal layering forms the higher part of the walls and a hole high above, where swifts come and go, is the way into Palangi Chamber, as described below. Beyond the aven a complex route forward through breakdown leads into a small phreatic passage and a large chamber with an impressive bank of gours running in from the east and basins of clear water on the floor. To the west leads into a low para-phreatic streamway for about 100m, following a fault line. The main



Palangi Chamber, First Cave - the first astonishing group of calcite formations in this vast and ancient cavern.

passage then swings to the south along another fault, to end in a sump after about 15m. This last fault throws down to the east and a steep mud and boulder slope leads up the fault plane to the west, but no open way on was located. The fault appears to bring the limestone against basement at stream level, but passage may be present at higher level on the upthrow side.

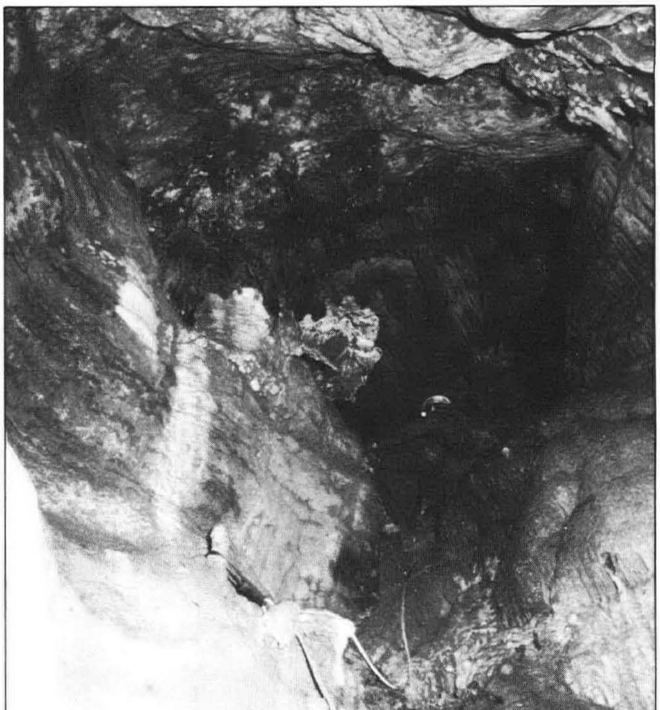
Back at the aven chamber below the entrance pitches a tricky upward climb over slimy calcite gives access to a dusty, crater-like chamber. Downhill in the funnel of the crater leads to a hole in the floor and a 5m drop which connects back to the small phreatic passage close to the gour chamber. Uphill in the crater, over boulders coated with guano, leads through an archway into the first part of Palangi Chamber; this is up to 100m long, 40m wide and 20m high, with a profusion of calcite decorations. The floor comprises massive calcite bosses, flatter cushion-like calcite spreads, abundant guano and, rarely, bedrock. There are swift nests on the walls, particularly the north-west wall, which seems to be a fault plane. High in the roof there are dark clusters of roosting creatures - whether these are bats or more swifts was not confirmed. The guano piles are seething with life and extensive collections were made by the Expedition team.

No way on was found from Palangi Chamber, and how it fits into a picture of cave development on 'Eua is, as yet, uncertain, but will be considered in more detail in the speleogenesis section below.

The First Cave doline is an overdeepening along a marked north-south linear feature, which the 1:25000 map shows as a valley. Whether the valley line is fault-guided is uncertain, but it seems likely that a primitive drainage system did once occupy it, flowing southwards. A number of solution dolines have formed in the valley floor at points where west-east fault systems are intersected. First Cave is presumed to be the latest of these, and several more are known to the south.

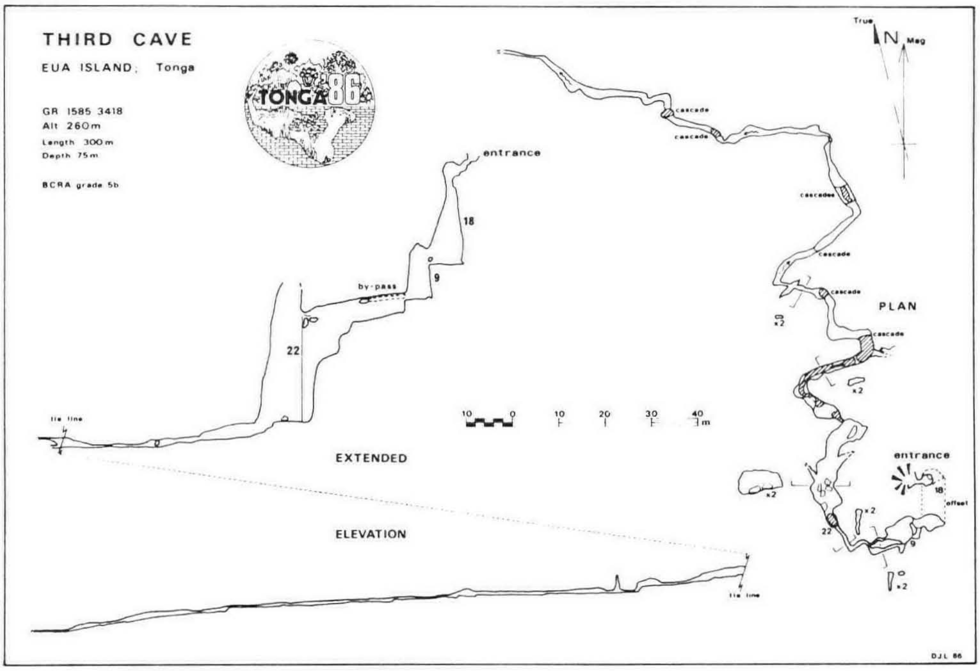
THIRD CAVE (Fig 16), the next in the line down the valley, was the third entrance to be located by the Expedition in the Top Area, and its uninspired name reflects a similar origin to that of First Cave. In contrast, its entrance is a small triangular hole in the base of a conical doline, almost totally buried in tumbled vegetation. Beyond the entrance zone of boulders, a sequence of fault-guided shafts offers a rapid descent; the third drops a splendid 22m, down a fault, into a pool with walls of conglomeratic limestone. Northwards the cave drops down over boulders and the fault plane, passing through more conglomerate and funneling down into a streamway with the floor and parts of its walls cut in dark volcanic rock. This continues for over 200m, and cascades mark small steps down across faults which throw down towards the downstream direction.

The next doline to the south contains the entrance to SECOND CAVE, a fairly impressive cleft in the south wall of the depression (Fig 17). A scramble over boulders along a fault rift leads to a pitch and then an awkward little climb into an equally awkward dog-leg phreatic passage. Another shaft follows in a very tight rift, widening downwards into a chamber which meets a vadose passage, dry at the time of exploration. Upstream



The first ascent to Palangi Chamber, First Cave, involved difficult free climbing over bedded calcite and flowstone with a slippery coating of guano.

Figure 16



is initially low with a scalloped roof, but the height increases until another fault is met on a sharp bend. Farther on the rift breaks into a round chamber probably below or close to the next doline south-west of Second Cave.

Back at the intersection with the entrance passage, downstream continues with alternate phreatic and vadose sections until it reaches the top of a larger shaft. This again is formed on a fault and drops 14m, with a short drop below onto a mud floor with a pool. The walls of the pool are in conglomerate, and a tiny passage chokes rapidly in the same material. The chamber, the pool and the choked passage, collectively known as The Slime, represent the most revolting find of the Expedition, in complete contrast to the fine shaft that drops into it.

The next doline to the south is blind, but probably once gave access to the Second Cave inlet passage. Still farther south is a valley system, which might once have been the continuation of the First/Third/Second lineament. Following it down, a depression is eventually gained with several more stream courses entering. It obviously receives an awesome quantity of water during flash floods and the cave leading from the centre of the drainage web was named DANGER CAVE by John Cunningham, who recognised the potential flood hazard (Fig 18). During Expedition explorations, the greatest danger was a spider of quite unbelievable size, which lurked in a side tube - but then it didn't look like rain. Inside the excavated entrance a tubular phreatic passage meanders northwards. After about 50m the floor drops away to a staircase of shafts (most can be free-climbed) on a major fault system. The final drop is into a chamber with walls of basal conglomerate and a pool of clear water in the floor, but there is no obvious way on and the volcanic basement has probably been reached, at a depth of only 35m.

The area to the south of Danger Cave has many dolines (Fig.12), some with cave entrances which were located by Norman Flux after the main Expedition and await exploration. Only RIFT CAVE, was examined (Fig.19), and is probably impossible to find without incredible luck (as on the first visit) or without the aid of a previous visitor.

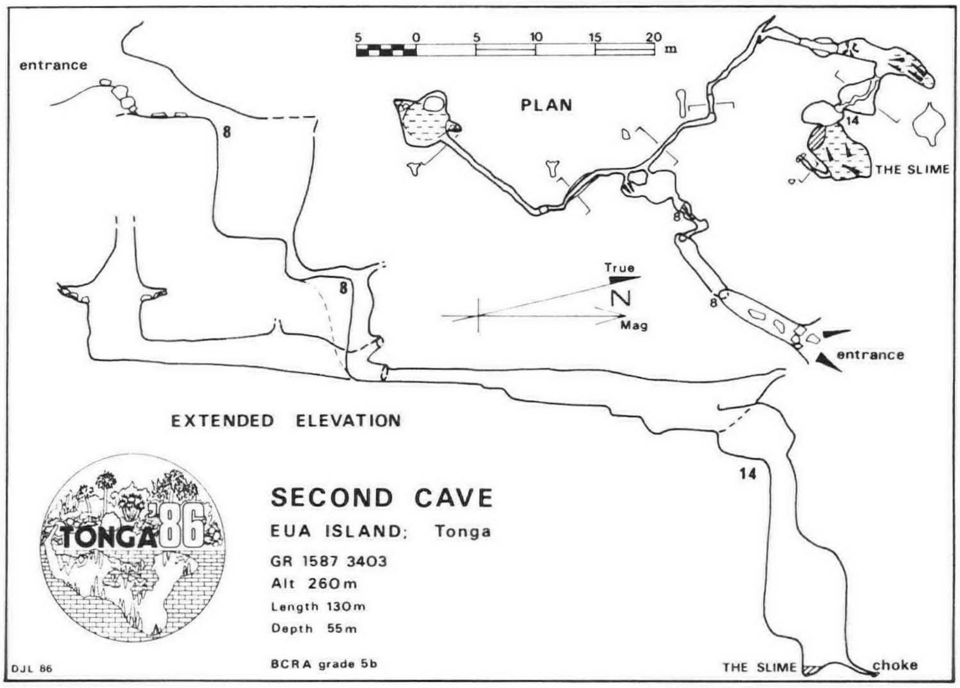


Figure 17

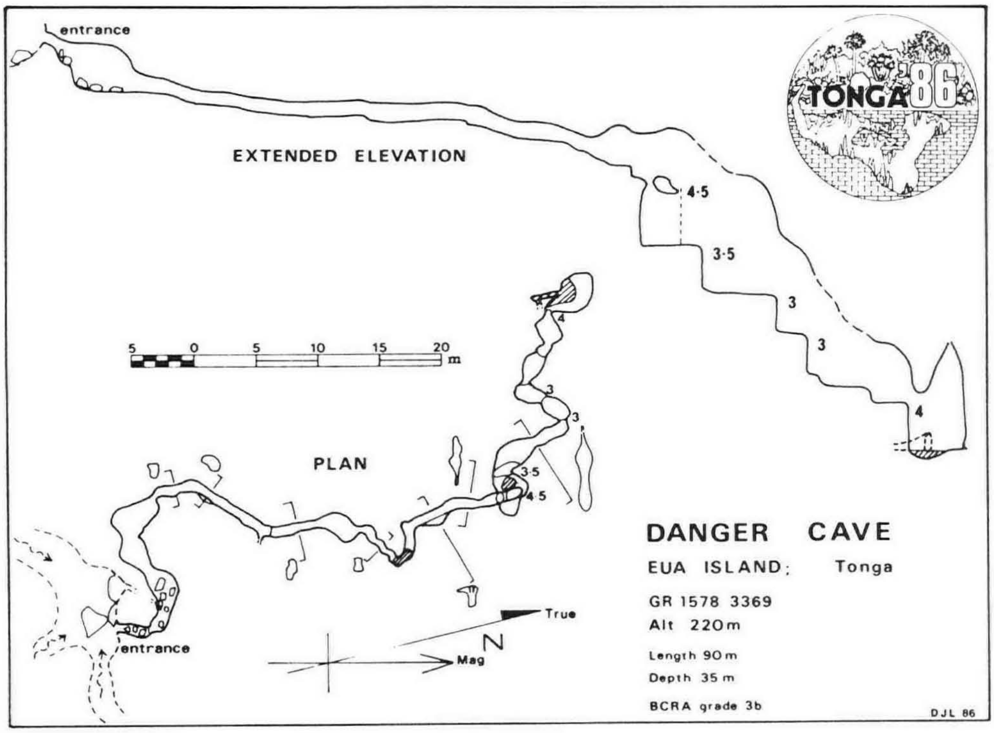
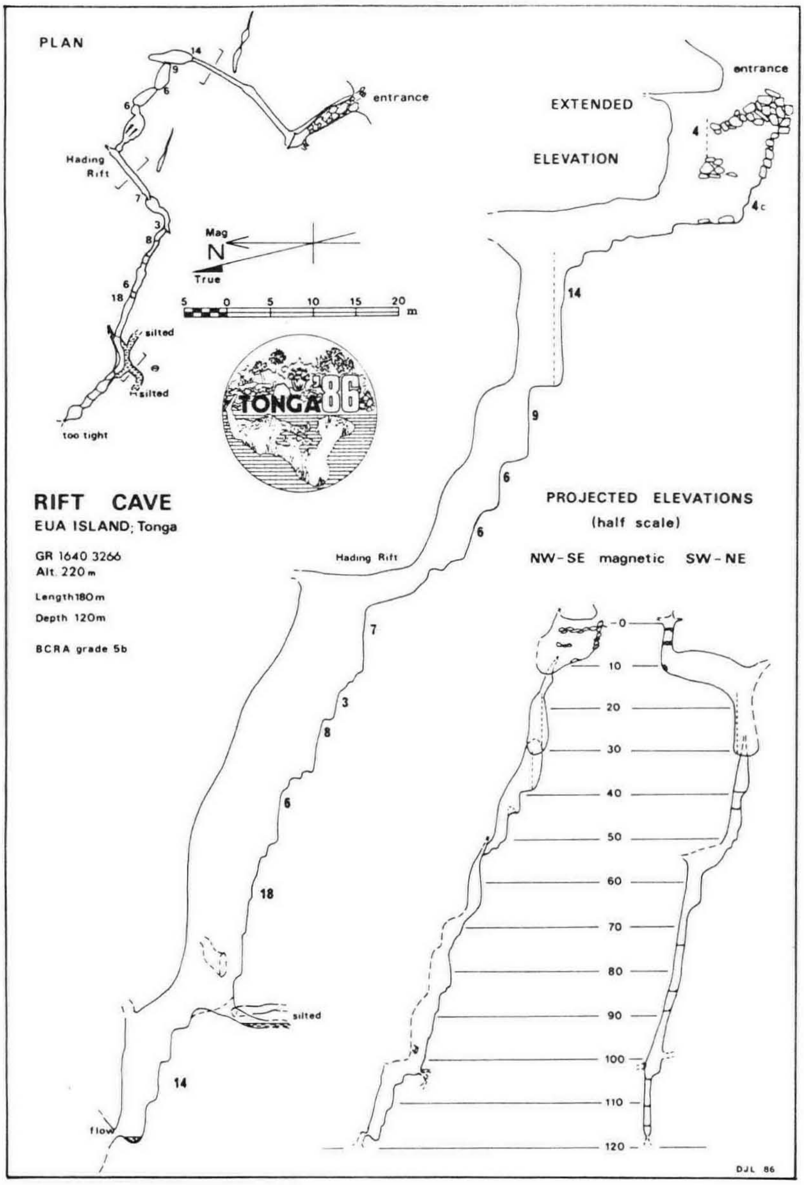


Figure 18

The entrance fissure which gave its name to Rift Cave, formed on a vertical fault.



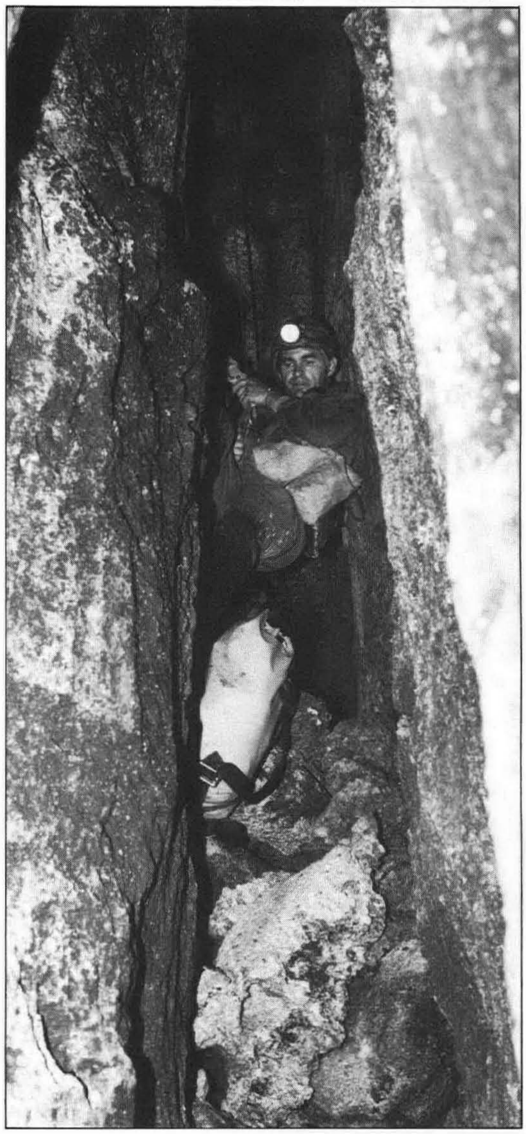
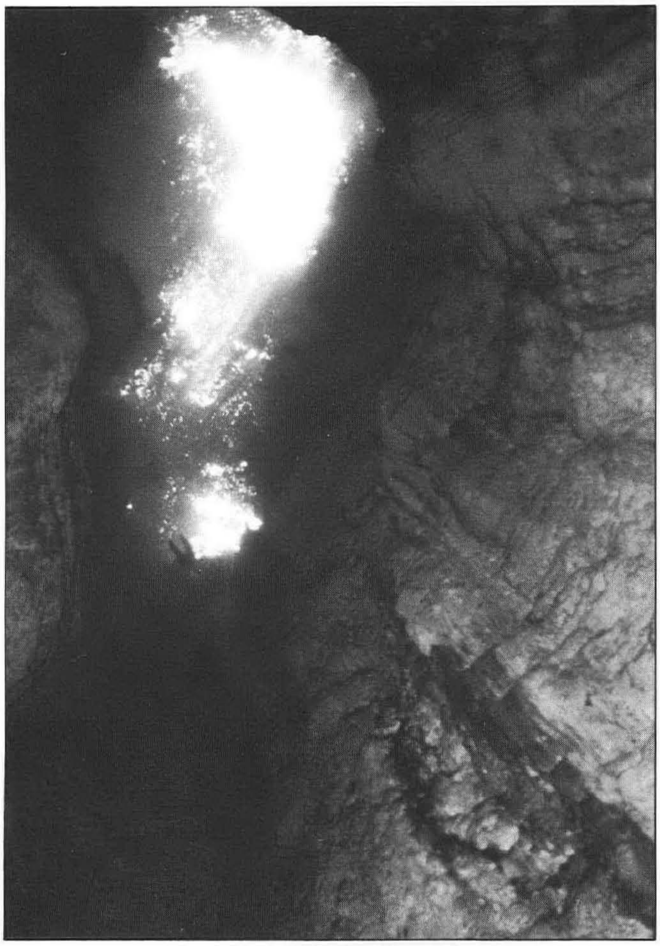


Figure 19

A cliff face in the side of a large doline is split by a fault rift with a route in over enormous jammed boulders. A hole in the floor can be free-climbed into a second fault rift at right-angles to the first. The fault plane hades steeply and is very narrow at low level, but an awkward higher traverse leads on to the head of an impressive elliptical shaft. At the base a window in the west wall marks the first of a series of pitches down another fault. Below, the rift narrows until it reaches another at right angles, which is almost certainly a lower continuation of that met at the foot of the entrance rift, and has a distinct hade. After only about 5m horizontal passage another rift on the entrance direction contains a continuous series of five pitches. At the foot of these drops silt-choked phreatic passages have been intersected in the south wall of the rift, and conglomerate is exposed in the same wall. To the north at a slightly higher level is another passage in unusually friable sandy limestone; how this relates to the main rift and the phreatic tubes to the south is unknown.

The main fault must drop the limestone sequence to the north, since the conglomerate is not visible in the northern wall, and nor is volcanic basement exposed in the remainder of the accessible cave. A hole in the floor is climbed to the head of a 14m shaft and there is no way on at floor level, where bulbous calcite flow all but blocks the continuing rift. It is possible to see past the constriction into a rift of much larger size with another vertical drop estimated at 5m. The total explored depth of Rift Cave is 120m, with more depth below and no sign of reaching the volcanic basement.

To the south and west of Rift Cave there are many dolines, at least 12 of which have open cave entrances. A number of these were partially explored by the Cunningham team and their entrances relocated during the Norman Flux reconnaissance.



Looking up the 70m entrance shaft of Ana Ahu (Smoke Cave), a massive rift formed on a complex fault zone.

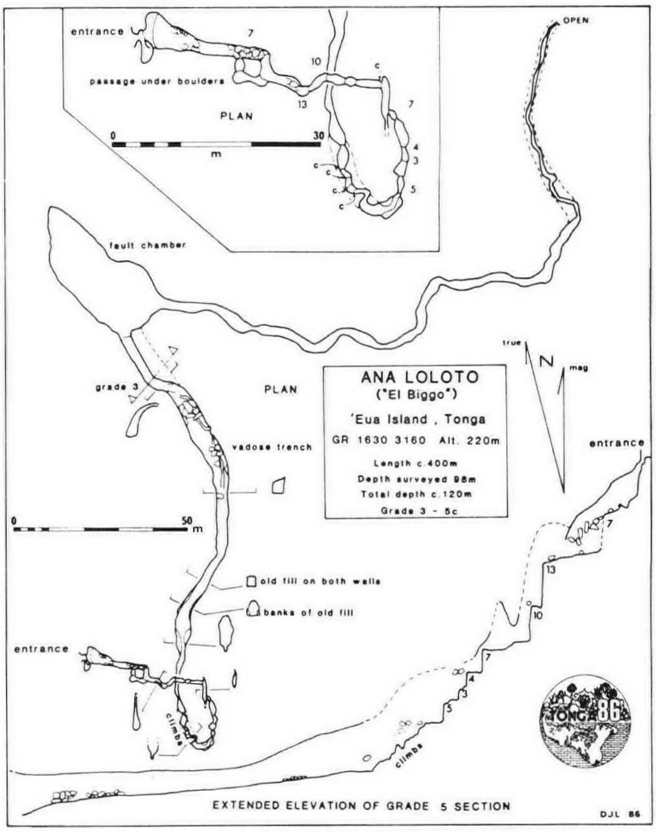


Figure 20

DIRT CAVE (GR 162 326) is a mud-floored pot about 8m deep, with a large colony of melanistic moths. A hole high on one side of the pit gives access directly to the top of an undescended shaft, where stones fall for 2 seconds.

HOLY HOLE (GR 163 321) was partially explored by the Cunningham team. The entrance is large and lies on a fault. A 10m open scramble leads to the lip of a 15m shaft, liberally supplied with precarious boulders. The rift varies from 6 to 2m in width and then narrows to a fissure at the head of a second shaft. This is only part descended, loose rock having deterred the Cunningham party, but its total depth is estimated at 30m.

MOSQUITO HOLE, a choked sink, is incorrectly located by Cunningham and Hood, and is now believed to occupy the eastern end of an elongate depression at GR 158 321. At the western end of the depression, there is an open hole with 50m of passage to a vertical drop estimated at 12m. This cave is un-named.

KAREN'S GHYLL (GR 160 316) is another Cunningham discovery, at the confluence of three periodic stream courses. A 7m vertical scramble through a boulder choke enters a small chamber, and pitches of 8, 9 and 10m, with an excess of loose rock, reach a ledge, with a continuation of unknown depth below. Karen's Ghyll is known to take a major stream in rainy conditions and exit through the boulder choke would then be very difficult.

A short distance to the east, on the same fault line as Karen's Ghyll is another entrance, given the temporary name "El Biggo", and now renamed ANA LOLOTO (Fig.20). There is a large entrance and rift chamber with a steeply sloping boulder-covered floor, down to a series of shafts. These are followed by a succession of free-climbs obliquely down a fault rift (with unexplored higher level) to pass beneath the entrance passage. The passage then begins to enlarge and there are banks of fill and remnant fill adhering to both walls. Enlargement continues and a narrow vadose trench is cut into the floor, locally covered by boulders. After 150m the passage breaks out into a huge fault chamber, which is not fully explored. To the east a major phreatic route meanders away and has been followed for about 200m. Towards the limit of exploration the passage becomes narrow at floor level, but the way on is open at higher level.

BEGIN'S (sic) described by Cunningham and Hood and possibly slightly mislocated is now believed to lie at GR 158 327. There is no open passage but an impressive 6m deep pot, 10m by 5m, lies on a fault trending east-west.

Other entrances discovered during the Norman Flux reconnaissance remain to be explored and other dolines to the south of the Karen's Ghyll - Ana Loloto fault line remain to be checked. Ana Loloto ends at a depth estimated at 120m below surface, at an elevation close to or slightly below the end point of Rift Cave. As in Rift Cave, the basement has not been reached and since the limestone sequence continues to sea-level on the east coast of 'Eua, where a major rising lies at sea-level (GR 175 320) there seems no reason to doubt that open passage will continue downwards for another 100m or so. The straight line horizontal distance from the end of Ana Loloto to the sea-level rising is about 1km.

To the west of this area, on cultivated land overlooking the Kolomaile area, are several dolines which are cut through Miocene calcareous volcanic arenites to expose the massive Eocene limestone. Only one doline currently has any open cave with two entrances in the same depression.

ANA AHU (Smoke Cave) has the most impressive entrance yet known on the island (Fig.21). A small stream trickles down a stepped arenite waterfall, and then falls 70m down a superbly fluted shaft. The shaft lies on a major fracture zone which has been partly responsible for the solutional fluting. The shaft foot is littered with breakdown and dead trees. A few metres up the north wall are a number of windows which connect to the active passage inside. A major canyon leads off from the north-east corner,

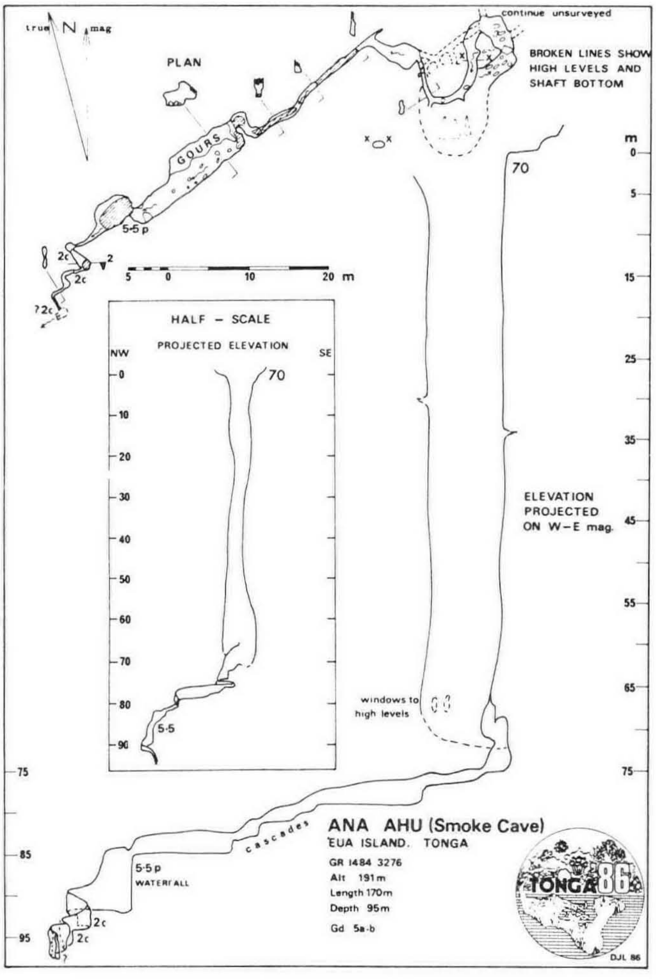


Figure 21

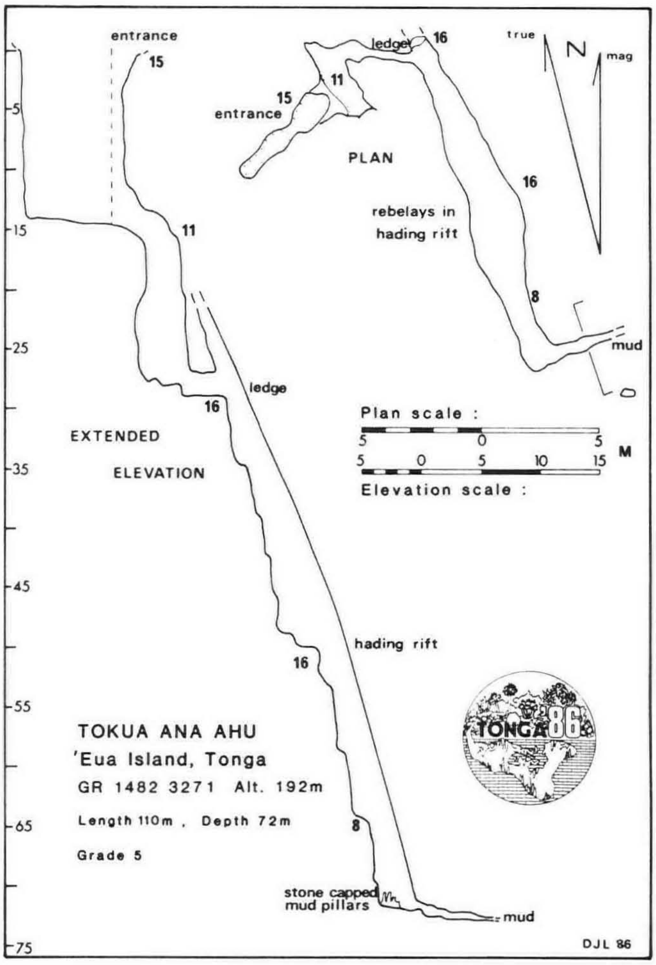


Figure 22

dropping steeply until a climb down over a large boulder is necessary. High-level passages at the top of the climb were not explored by the Expedition, but are reported by Cunningham to continue for a considerable distance. Below the climb, a cleanwashed streamway leads on, to enter a rift chamber with impressive gours, flowstone cascades and a scalloped roof. The chamber also supports at least one large crustacean (?crayfish) which was clever enough to outwit the Expedition biologist. Beyond, the passage becomes smaller and a series of tight bends and small pitches follows. Tackle ran out on the Expedition descent and the way on was open but tight.

Higher on the side of the doline, where it seems limestone has been upfaulted relative to its level at the Ana Ahu entrance, is a second shaft, which elsewhere would appear impressive. This is the entrance to TOKUA ANA AHU (Ana Ahu's Sister) (Fig.22). From the surface, where the major hazard is a local farmer with a machete, two vertical shafts descend to the top of a steeply hading rift. This falls another 40m, and at the foot, a tight passage leads off along the fault plane, rapidly becoming impassable. The trend of the fault responsible for the hading rift in Tokua Ana Ahu is the same as one which is thought to guide 90° offsets to the main fault trend below the second pitch in Ana Ahu.

The most significant result of the Ana Ahu doline explorations was the discovery that the bottom of Ana Ahu is below the resurgence caves of the Kolomaile area to the west. Thus the Eocene limestone aquifer is separate from that in the Mio-Pliocene rocks to the west.

Speleogenesis

As pointed out in the geology section above, it is considered probable that conditions currently pertaining in other island chains to the west of 'Eua reflect those which existed in the proto-'Eua area during earlier epochs. Thus, by examining the geological activity at present in the islands of the Tofua Arc and Tongatapu - Vava'u chain, it is reasonable to apply the tenet that "the present is the key to the past" and gain insights into processes in the 'Eua area from the time its volcanic basement formed in the early Eocene. These processes include karstification and speleogenesis.

The oldest rocks known in the 'Eua area were formed by volcanic activity during the early part of the Eocene (Table 4) and details of earlier geological events are lacking. A hypothetical model linking geological history and speleogenesis, with particular reference to the 'Eua Top Area is outlined below.

Era	Period	Epoch	Duration (millions of years)	Age of start (millions of years)
CENOZOIC	QUATERNARY	Holocene	0.01	0.01
		Pleistocene	c.1.6	c.1.6
	TERTIARY	Pliocene	5	7
		Miocene	19	26
		Oligocene	12	38
		Eocene	16	54
		Palaeocene	(not considered)	

Table 4

1. Early Eocene. Eruption of island arc type volcanic rocks, initially sub-marine, but ultimately producing sub-aerial "andesitic" cones, which were the first islands. The volcanic material included pyroclastic as well as extrusive material and significant piles of volcanic rock were formed below wave base in addition to the more obvious visible cones.

2. Early to late Eocene. The volcanic islands and submarine shoals provided a substrate upon which animals and plants with calcareous skeletons were able to grow. Fringing reefs and flat reefs were formed around the islands, together with lagoonal type limestone deposits and limestone-bound conglomerates. It is probable that similar, if not identical, conditions currently exist in Tofua and the other islands in the active western chain.

3. End Eocene. Limestone deposition was probably discontinuous throughout the Eocene due to sea-level fluctuations (just as in the British Carboniferous limestone). The unconsolidated lime sediments and reefal frameworks were episodically undergoing diagenesis,and possibly also karst development, and the main limestone sequence preserved on 'Eua today was probably indurate by the end of Eocene times.

4. Late Eocene - early Oligocene. Intense tectonic activity at about this time produced a more significant uplift of the volcanic and limestone pile. It is probable that the uplift resulted in fault formation, though the nature and magnitude of the faulting is unknown. Faunal material diagnostic of the Oligocene overlying the Eocene sequence, might simply indicate that there was a brief return to marine conditions, with re-submergence, of an already lithified Eocene land surface.

5. Oligocene. The contemporary upper surface of the thick Eocene (? to Oligocene) limestone sequence was above sea-level throughout the Oligocene and subject to karstification. While the land surface was undergoing karst landform formation, close to sea-level cavern development was commencing along the interface between the island's freshwater lens (which had formed due to joint/fault/palaeokarstic/reefal porosity in the rock) and saline water. Major solutional chambers and passages formed where lithological, structural and water conditions were suitable. It is suggested that Palangi Chamber, in First Cave, had its origin at this time. Terrace fragments preserved at about 230m above sea-level tie in with the level of Palangi Chamber and may mark the position of an Oligocene wave-cut platform/terrace.

6. Uplift continued, probably in pulsatory fashion, throughout the Oligocene and similar solutional caverns formed at progressively lower levels in the limestone sequence, though still close to sea-level, and the earlier passages rose progressively higher. On being raised the passages moved from the phreatic to the vadose environment and became at first active or periodically active drains and later were totally abandoned and subjected to massive speleothem deposition. The precise date of the speleothems is unknown and could be much later than Oligocene. Thus, Palangi Chamber (and contemporary passages/chambers) was at this stage comparable with such caves as Oholei and Fatumu on Tongatapu. On the land surface fairly intense karstification took place and classic features were formed. Whilst the limestones were still "tight" and while surface water flows were high, valleys were cut in the land surface, sometimes of considerable depth. Where these valleys cut across faults or major joints solutional activity became focussed and dolines began to form, eventually giving rise to sinks and then to higher level cave systems.

7. Miocene. The island was partially re-submerged in Miocene times, during a period of general instability which might also have included renewed volcanic activity. Whether the submergence was permanent or periodic is unknown, but on the basis of the amounts of Miocene sediment preserved, it seems likely that deposition occupied only a small proportion of Miocene time. On the other hand, the sediments are generally soft and friable, so much more could have been stripped away. Sedimentation was of essentially sandy material, the sand grains being predominantly small fragments of igneous rock. Preserved samples show a very high percentage of calcium carbonate, within the grains and, more particularly, in the matrix. The depositional environment is difficult to imagine. They have been described as deep marine, with some indications of a turbiditic origin, but the evidence is far from conclusive. The angularity of the clasts could indicate rapid and proximal deposition of material being eroded from the adjacent volcanic pile and the local turbiditic characteristics could simply reflect earthquake generated mass flow of soft sediment. During its period of submergence the pre-existing karst landscape was overwhelmed by these sandy sediments and undoubtedly abundant detrital material found its way into the existing caves. Whether such an environment could lead to total infilling of passages deep underground seems unlikely, but soft sediments, slurries and suspensions will move considerable distances under the influence of seismic shock, and often include large clasts. Some of the sediments still visible in caves where re-excavation has taken place are chaotic and ill-sorted. A mode of emplacement as suggested above cannot be discounted, though other, better documented, mechanisms and a younger age seem more likely.

8. End Miocene into Pliocene. The situation described above possibly persisted into the Pliocene, but uplift was almost certainly progressing again. Faulting during the various Miocene fluctuations not only produced additional sets of fractures within the Eocene-Oligocene sequence, where it truncated existing cave passages and left them apparently isolated (as at Palangi Chamber), but the activity involved also led to slump faulting in the recently consolidated Miocene sediment. With uplift karstification and cave formation recommenced in those areas where water was able to sink, and again along the freshwater/saltwater interface.

9. Pliocene. Continuing from the above situation, Miocene cover was stripped from the higher ground with some of the debris, no doubt finding its way underground. Meanwhile around the coasts reef limestones were forming, on top of the Miocene arenites in some areas, elsewhere directly on the palaeokarstic surface of the Eocene limestones. Possibly at the same time erosive terraces were being cut on the exposed eastern side of the island. These features, after later uplift, formed what is now known as the "400 Foot Terrace". Old phreatic remnants discovered in Rift Cave and Ana Loloto are related to this Terrace level, either having commenced formation along the contemporary freshwater/saltwater interface, or having graded to a resurgence at the contemporary sea-level.

10. Pliocene. Spasmodic uplift continued through the Pliocene. Limestones formed early in the epoch were uplifted, together with underlying rocks. At some stage during this uplift cave inception took place at the base of the oldest Pliocene limestones and these early passages were the precursors of the caves of Kolomaile (described elsewhere). In the Top Area cave formation continued in the Eocene limestone, initiating as seepages down the more open fault planes, which were probably tension gashes forming part of a secondary wrench system. These more vertical sections were separated by short phreatic developments where the descending water was diverted sideways due to unfavourable lithologies or fault tightening. In some cases the new passages intersected fragments of palaeo-caverns, some of which were sediment filled, and commenced their re-excavation by channeling vadose streams into them. Concurrently the limestone surface was lowered by solution, leaving upstanding remnant material which might be palaeokarstic fill and/or dolomitised rock.

11. Pliocene to Holocene (Recent). Similar conditions continued, the most significant factor being a continued overall uplift (or lowering of sea-level) such that progressively higher terraces appeared above water and progressive base level phreatic cave developments were drained. Climatic changes also occurred and seismic activity continued. The short phreatic sections of the upland depression-drain sink caves were incised as uplift continued and where basement was reached incision continued downwards into the relatively soft basement rocks. Where flowing water encountered early fill, or fill laid down during later flood events much of the debris was washed out - though in the case of some of the conduits involved it is hard to envisage such a removal, unless in part it was accomplished under the semi-explosive influence of a backed-up head of water.

12. Today. All the caves explored in the Top Area are essentially vadose slots, locally with short sections of preserved phreatic passage at roof level, and all are fault-guided. There is little evidence of independent phreatic conduit development within the recent formational phases, though there is much low level phreatic development which is probably old and associated with by-gone sea-levels. Where these caves end at basement they generally do so at a sump, and these sumps are well above any possible resurgence level. It is fairly certain that the sumps are structurally imposed, where the cave passages following a fracture set in the limestone, on top of the basement, encounter another fracture which has an upthrow across its path. In this situation the logical continuation, if any, would be at higher level on the upthrow side, a situation which would be quite possible in phreatic conditions. With drainage on uplift the upfault route would eventually be abandoned as slow seepage took over along the fault, sufficiently far laterally to re-enter the limestone at the nearest point with favourable hydraulic conditions. Tight fault-guided water routes were encountered in most caves in the Top Area. Two particularly good examples were in First Cave, one where water enters the recently-drained para-phreatic streamway from the Palangi Chamber north wall fault, the other at the end of the streamway, where two apparently independent sumps lie on two perpendicular fault lines. With resurgences appreciably lower than even the deepest sumps it is to be assumed that there is a second generation of passages still to be explored, and indeed the caves south of Danger Cave, where the basement seems to be at lower level, might already be in a suitable lithological and structural position to be the key to the main drainage system.

13. Other facets. Around the coasts, particularly the cliff lines of the east coast, fragments of ancient cave passage are exposed. No accurate levelling has yet been carried out, but on theoretical grounds these fragments are probably representative of the interface phreatic developments which formed at or close to sea-level and were uplifted and truncated. So far as is known these caves are either blocked by fill, or faulted off, but there is reasonable chance that abandoned high levels in the currently active systems, left high and dry after uplift, could reach surface in the cliffs.

Phreatic passage modified by breakdown below Palangi Chamber in First Cave; small remnant deposit of clastic infill on ledge to the right.

There are of course other, and more traditional, scenarios of speleogenesis that could be applied to 'Eua. For instance all of the stages mentioned above could have taken place in one continuous phase following post-Miocene uplift. Elsewhere work has been carried out to try to tie speleothem dates to the ages of formation of marine terraces (for example Williams, 1982). Such an approach on 'Eua would suffer the same drawback experienced elsewhere - the speleothem will only give a minimum age for the passage - but in addition there is no suitable technique to apply to events which might be 30 million years old.

In Tonga there remains the advantage that comparisons can be made between stages of cave development in the distant past, some preserved only in fragmentary form, and events which have taken place relatively recently in islands immediately west or are taking place today in the westernmost island chain. No such comparisons can be made in older and apparently more stable karst areas, but who is to say that speleogenesis did not take place during the oscillations and reef-buildings of the Dinantian, which after all occupied a similar amount of geological time? A speleological laboratory such as this must be virtually unique, and it is to be hoped that suitable follow-up work will be carried out.

WATER CHEMISTRY

Part of the Expedition programme had been to make a series of spot analyses of bulk water quality by field measurement of specific conductance, pH and temperature. Unfortunately both instruments failed irrepairably after only one day in the field, effectively curtailing the planned programme. However, water samples were collected from sites representative of the main process environments, for later analysis. Duplicate titrations for calcium hardness and total hardness were performed on each sample using standard techniques. The results, expressed as calcium and magnesium ion concentrations, are given in Table 5.

The small number of samples precludes any firm conclusions but several interesting points emerge:

1. The calcareous nature of the arenite is apparent from the high calcium concentration. Subsequent tests of three samples of arenite showed values of 55%, 65% and 82% carbonate.

2. The greater concentration of calcium in streams draining the Eocene limestone than those draining the arenite may be a result of different equilibrium conditions in the two areas. In the area above First and Third caves the soil is generally less than 1m thick and solution may be expected to take place under open system conditions. In contrast the Kolomaile area has thicker soils and is less well drained, making closed system conditions more likely (Gunn, 1986). That this would more than compensate for any increase in soil CO_2 resulting from greater plant growth in the lower area can be seen from figures provided by Picknett and others (1976). A soil CO_2 of 2.5% under closed system conditions would result in a theoretical calcium concentration of 50mg/l whereas 1.5% CO_2 under open system conditions produces a theoretical 85mg/l Ca at 20°C.

Calcium and magnesium concentrations (mg/l) in water samples from caves on Tongatapu and 'Eua islands.

Site and lithology	Ca^{2+}	Mg^{2+}
(1) Calcareous volcanic arenite ('Eua)		
Stream sinking into Ana Ahu	34	3.6
Fish Tail Cave (at rising)	39	3.9
Ana Peka Beka (main inlet)	42	4.1
Ana Peka Beka (Martin's Cave inlet)	50	3.6
(2) Eocene limestone ('Eua)		
Third Cave stream	82	3.6
First Cave stream	85	2.8
(3) Plio-Pleistocene reef limestone (Tongatapu)		
Oholei Cave pool	122	24.3
Fua'amoto Cave pool	142	27.9

Table 5

3. The calcium concentrations in the Tongatapu cave pools are higher than those normally encountered in karst systems and would require a theoretical soil CO_2 concentration of over 6% under open system conditions and over 10% under the closed system conditions that seem more likely on Tongatapu. This, together with the very low Ca:Mg ratio suggests that some mixing with saline water has taken place. Measurement of chloride content would be needed to confirm this.

CAVE BIOLOGY (by Dave Gordon)

Little is known about the hypogean faunas and floras of the vast area covered by the South Pacific and until the Tonga '86 Expedition nothing was known about the cave biology of the Tongan Islands. Study of specimens collected during the Expedition will increase knowledge of South Pacific cave faunas dramatically and highlight some of the intricate problems of evolution and response to Quaternary climatic change that the invertebrates have faced on isolated tropical islands.

During the Expedition explorations invertebrates were collected from various cave environments on Tongatapu and 'Eua in order to facilitate inter-island and inter-environmental comparisons within the Tongatapu Group. Standard collection and preservation techniques were used, as recommended by the British Museum (Natural History) (Cogan and Smith, 1974; Lincoln and Sheals, 1979). Collecting was accomplished mainly by the use of baited pitfall traps and light traps, or by hand collecting and netting. Anaesthetization, fixing and preserving were accomplished using 2% propylene phenoxytol, 10% formalin and 80% alcohol solutions. Reasonably good results were obtained.

This is a preliminary report since the systematics and identification of the faunal collection are currently being carried out by the Entomology Divison of the Department of Industrial Research (DSIR) in Auckland, New Zealand, under the direction of Dr Peter Maddison. Although a detailed description of the cave faunas of 'Eua and Tongatapu must await these results, it is possible to make a number of initial observations.

In caves where a large quantity of soil had slumped or washed into the entrance, a trogloxene community of soil invertebrates was invariably present. Annelida (worms), myriapoda (centipedes and millipedes), mollusca (snails) and arachnida (spiders and mites) were predominant. This assemblage was confined to the entrance facies and entirely absent in the deep cave environment.

The entrance walls of active river caves and damp caves were inhabited by a troglophilic community. At least six arachnid species (spiders) and two dipteran species (flies) were noted and some localities supported large populations (more than 200 individuals) of lepidoptera (butterflies and moths). Some elements of this fauna were found additionally in the deep cave environment.

A rich troglobite fauna was present in all caves where guano was present and a totally dark, deep cave, habitat prevailed, together with constant high humidity and relatively constant temperature (Barr, 1968). In cave entrances and sections of passage where the humidity was found to be less than 100% (using a whirling hygrometer) faunas were generally sparse, even if abundant food material was present. Several swift corpses were observed in these environments, at various stages of decay, but apparently untouched by invertebrates.

In the deep cave environment rich faunas were present on the cave walls, around the edges of guano mounds and on mounds of swift guano, but not in areas covered by bat guano. Barr (1968) has noted that: "Few troglobites appear to be adapted to feed exclusively on bat guano". This difference in the utilisation of swift and bat guano is possibly related to the differing modes of excretion of nitrogenous waste exhibited by birds and mammals. Reptiles, birds and insects excrete nitrogenous waste as uric acid, which is effectively insoluble in water. On the other hand, amphibians and mammals excrete urea, which is water soluble and therefore susceptible to leaching. Some support for this idea comes from Barr (1968), who observed a complex fauna living on cricket guano in the U.S.A., and Chapman (1981), who identified a troglobitic community existing around scattered cave swift droppings in Sarawak. Unlike on Tonga, however, in Sarawak large accummulations of swift guano were relatively devoid of life. A detailed comparison of the guanobite ecology of the Sarawak and Tongan faunas should, therefore, provide interesting insights into the evolution of guanobia in the Tropics.

A number of detritivores and carnivores seemed to be confined to cave floors and the edges of the guano mounds. In both habitats corpses were consumed quickly, in contrast to the cave wall habitat where arachnid corpses were often noted to be colonised by fungi, but otherwise untouched.

In active river caves an aquatic community of crustacea (shrimps) and insects was collected, but no fish were observed. The crustaceans seem to be confined to the hypogean environment and were not present in representative samples collected from surface streams and lakes. One possibility is that this aqueous fauna represents an evolved relict community, originally marine, isolated in the hypogean domain following uplift.

In conclusion, the Tongan caves contain rich and varied invertebrate faunas (as well as swifts and bats) adapted to several different environments and habitats. Prior to the Tonga '86 Expedition these faunas were completely unknown to science and study of them will potentially yield invaluable results in several different fields of biological research.

THE TONGAN PEOPLE AND CULTURE

The Tongans are Polynesians, speaking their own Polynesian dialect, and were established in the archipelago at least 3000 years ago. It is believed that the first Polynesians travelled from south-east Asia, by way of intermediate island groups, to Tonga, in double canoes, carved with stone tools and lashed together with coconut-husk string. Tonga had a highly developed social system long before the arrival of the first European explorers,and despite inevitable interaction with "western" influences since the 17th century, the Tongan language and customs seem to have survived remarkably well.

Wesleyanism is today the most widespread religion in Tonga and there is strict observance of the Sabbath which precludes all work, sport and cave exploration on Sunday. Tonga is a constitutional monarchy and the King is the head of the government, with a wide influence.

The population of Tonga is of the order of 100,000, with about 60 per cent on Tongatapu. Historically the economy was based upon agriculture and fisheries, but today more and more people are involved in service industry, the civil service and manufacturing, as well as a variable involvement in tourism.

Pigs are the most important livestock in Tonga, and there are probably as many pigs as humans on the islands. Estimates have been made of up to 3000 slaughterings each Sunday to provide the basis of a weekly feast, whilst for a National festival as many as 8000 will be slaughtered. The feasts are gargantuan in their conception, with up to 30 different dishes, including pork, fish, crustaceans, beef, fruit and vegetables, much of which is cooked, wrapped in banana leaves, in an earth oven or "umu". The national drink, kava, is made from the kava tree, and is drunk ceremonially and socially.

CONCLUSIONS AND FUTURE WORK

It is possible that karstification, including speleogenesis, was in progress on the island of 'Eua as long ago as mid-Oligocene times and that the caves already formed and forming at that time were morphologically comparable with those explorable and developing on the island of Tongatapu today. This hypothesis has important consequences in terms of cavernous porosity within the limestones of the area, and hence possible significance in any future search for water or petroleum resources. On a more parochial level caves on the two islands give valuable insights into cave formation in fairly young limestones, particularly into the importance of such factors as basement and structural guidance. Hypogean faunas recovered from caves on Tongatapu and 'Eua represent previously unknown adaptations and could indicate an evolutionary line from marine to troglobitic adaptations. Any future studies in the area should include exploration of as many caves as is possible, coupled with accurate survey and levelling. If possible future study of the 'Euan terraces should be carried out, to elucidate their mode of formation and their age. The opportunities for biological research are immense - Palangi Chamber alone could provide more than one doctoral thesis.

ACKNOWLEDGEMENTS

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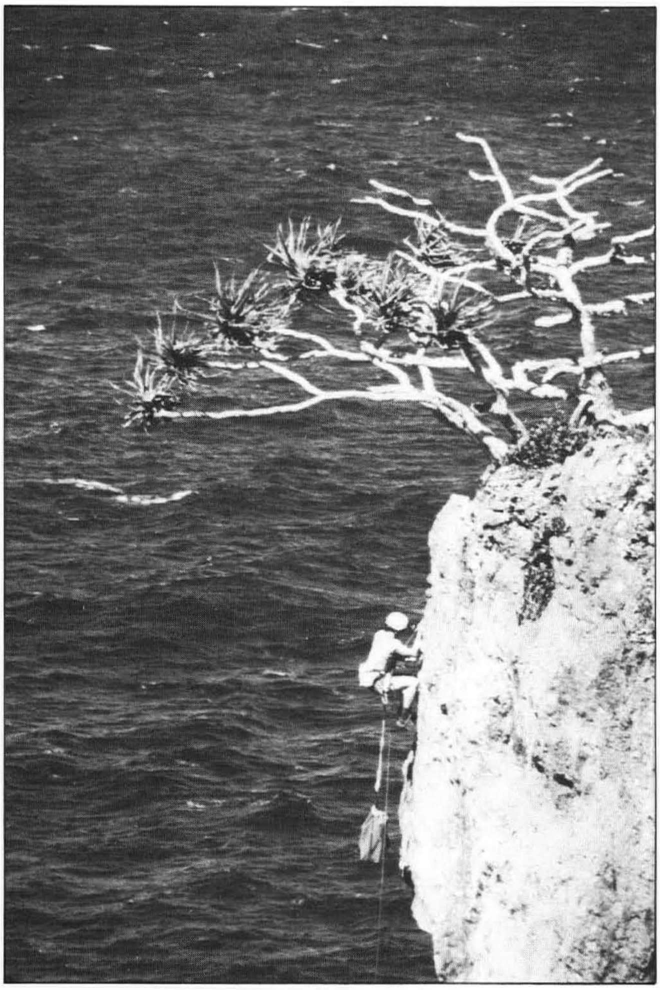

Prusiking 60m above the Pacific after exploring a truncated cave passage on the cliffs of SE 'Eua.

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The Evolution of the Castleton Cave Systems, Derbyshire

Trevor D FORD

Abstract: Lying beneath the topographic watershed the Castleton cave systems demonstrate a complex history of events, from mid-Carboniferous karstic erosion, Permo-Triassic vein mineralization and faulting to exhumation in late Tertiary times. Initial stages of the present karstic system utilized mineral vein cavities under bathyphreatic conditions as denudation bared the limestone surface. A phreatic tube network developed and with falling water-tables in Pleistocene times due to the incision of Hope Valley, vadose canyon cutting ensued in the main stream passages. Abandoned dry passages show speleothem growth in Ipswichian, mid-Devensian and post-glacial times. Solifluction gravels choke some early passages whilst others are filled with derived loessic clays. Although having a complex history the Winnats Pass can be shown to be a relatively young feature, as are the dry valleys of Cavedale and Perry Dale.

INTRODUCTION

Lying at the northern end of the Carboniferous Limestone massif of Derbyshire, the Castleton area presents a complex system of caves as yet incompletely explored despite the efforts of many cavers over the years, whose drainage system is only just being unravelled by a series of dye tests, flood pulse studies, and hydrochemical analyses. As exploration continues and hydrological studies progress (e.g. Gunn, 1985) our knowledge of the present day situation improves, but it is the geomorphological story on which I want to concentrate herein, how the cave systems evolved to their present form and what the controlling factors were. As a corollary, do the caves throw any light on the evolution of the surface landscape?

Ideas on the evolutionary history of the cave systems have previously been reviewed (Ford, 1966, 1977) and the caves themselves have been described (Ford, 1977; Beck, 1980; Cordingley, 1986, all of which contain references to much detailed literature in caving club journals). In the last ten years the possibility of dating stalagmites by uranium series methods has become available and this has necessitated a fresh look at the whole Derbyshire scene (Ford, Gascoyne and Beck, 1983) (Table 2). At the same time, concepts of the origin and development of cave systems in general have seen something of a revolution (D.C.Ford 1971; D.C.Ford and R.Ewers, 1978, Palmer, 1984) and the dating of the various climatic phases of the Pleistocene glaciations has been refined, so that a new look at some of our familiar old caves seems desirable.

Controlling Factors

A study of the evolution of cave systems anywhere must take into account a number of basic factors: the age and nature of the enclosing rocks; the date at which these rocks become exposed to karstic processes; structural controls on hydrological drainage patterns; climatic effects on precipitation and percolation; and changes in the surface topography caused by outside factors.

Some of these are easy to outline: others are not so easy. The rocks, of Lower Carboniferous age, were deposited when a deeply buried Lower Palaeozoic/Precambrian massif was transgressed by the Dinantian seas resulting in some 1600m of carbonate sediments of which only the top 500m or so are exposed. In effect this means that little is known of the deeper parts of the karstic regime. the limestones vary greatly in the lithology, being in essence a lagoonal massif filled with calcarenites bordered by marginal reef complexes. Rare thin shale partings are present. Occasional outpourings of basaltic lavas divide the lagoonal limestones but hardly penetrate the reefs: thick "wayboard" tuffs are scattered through the limestones: both provide local hydrological barriers constraining downward percolation. The limestones were covered by Upper Carboniferous classic sediments, marine shales at first and later deltaic sandstone/shale cyclothems totalling some 2 to 3 km in thickness. They rest with pronounced unconformity, locally with basal boulder beds, on an eroded surface of the limestone (Simpson & Broadhurst, 1969), with palaeokarstic developments (Ford, 1985).

An episode of faulting seems to have occurred at the end of lower Carboniferous times, as shown by the wrench faults later developed as mineral veins (rakes), none of which appear to extend into the surrounding Upper Carboniferous sediments, though later re-activation affected the latter to a minor degree. The main Armorican movements affected all the Carboniferous strata with folding, including the upwarping of the South Pennines, and widespread faulting. Whilst the latter had little direct affect on the limestones south of Castleton, the folding imposed a gentle easterly regional dip. Subsequent tectonic effects are somewhat limited: the re-opening of the mineral vein faults in latest Carboniferous, Permian and Triassic times, and the intermittent upwarping of the Pennine anticline.

How much Permian and Mesozoic stratigraphic cover once rested on the Carboniferous is uncertain; some estimates put it at 2km or so, but it is likely that a large part of the Upper Carboniferous cover had been eroded off before the Permian Magnesian Limestone was deposited across the South Pennine area (George, 1964). It is also somewhat uncertain how many folding phases occurred to elevate the South Pennines into their present broadly anticlinal form. There is little doubt that the uplifts were episodic, occurring in late Carboniferous to early Permian times, again in early Triassic, probably late Cretaceous, certainly mid-Cenozoic, with final upwarping in late Cenozoic times (Walsh et al., 1972). Suffice it to say here that the Carboniferous Limestone of the Castleton area was first exposed to surface karstic processes in mid-Carboniferous times and has been exhumed from beneath its cover only since mid-to-late Tertiary times. Most of the Brigantian Stage of the Carboniferous Limestone was eroded off the Castleton area in the mid-Carboniferous and the present cave systems are almost entirely within the Asbian Stage limestones, little more than 100 m thick. The depth to the base of the

Footnote: this review is a modified version of the Presidential Address delivered to the East Midlands Geological Society on February 2nd 1985, published in their Mercian Geologist, vol.10, no.2, pp. 91-114, (1986) and reproduced in this modified form with their permission.

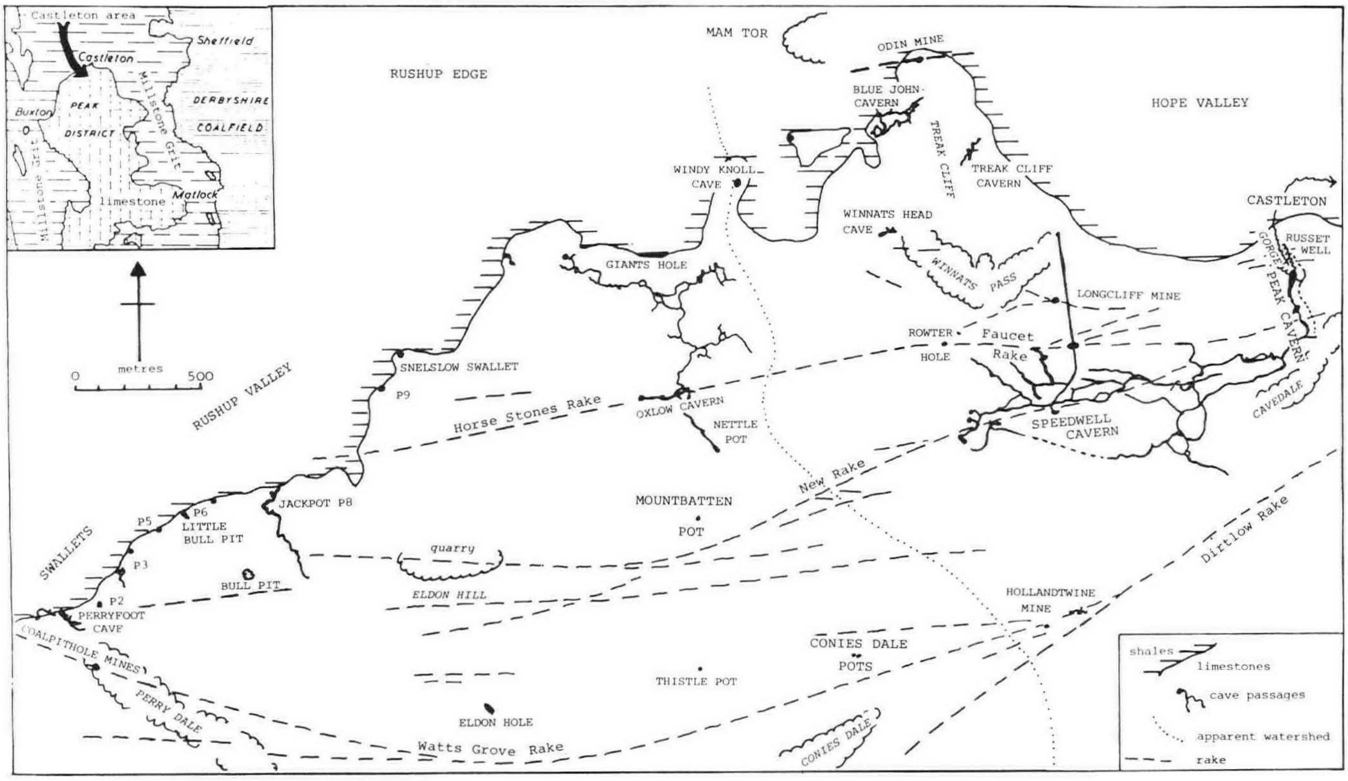


Figure 1. Sketch map of the Castleton area showing the limestone outcrop and its boundary in relation to mineral veins and cave passages.

limestones is unknown in the immediate area of Castleton but is likely to be more than 1 km. Subsurface processes operated in latest Carboniferous and Permo-Triassic times in association with mineralization.

The structural situation resulting from the above is a gentle easterly regional dip, diversified by strongly lenticular bedding in the reef complexes on both NW and NE margins of the limestone massif, with steep outward dips. Faulting and mineralization yielded a series of more or less east-west mineral veins across the Castleton area from late Carboniferous to Permo-Triassic times (Ineson & Mitchell, 1972; Quirk, 1986) which have affected the hydrological systems ever since.

The changes of climate in the Pleistocene glacial-interglacial cycles undoubtedly affected the amount and kind of precipitation and the degree to which run-off could percolate into the subsurface. Concomitant with this climatic regime was the incision of the major drainage of the area, the River Derwent, along the eastern margin of the limestone massif and the River Wye across it to the south of Castleton. The incision of these valleys and of their tributaries, some of the latter now being dry valleys, influenced the contemporary local base levels of underground drainage within the limestone.

Applying the above factors specifically to the Castleton area, a sequence of events is outlined in table 1 as a basis for later discussion.

1. Deposition of the Lower Carboniferous limestones, with intervening lavas, thin tuffs and shale bands as aquicludes of varying significance.
2. A mid-Carboniferous phase of palaeokarst, with limited tectonics and early cave development in the reefs.
3. Burial by Upper Carboniferous sediments.
4. Folding, upwarping and faulting in the late Carboniferous and early Permian.
5. Faulting and mineralization, overlapping in time with Triassic renewal of upwarping.
6. Cover by an unknown amount of Mesozoic (to early Tertiary?) sediments.
7. Very slow deep phreatic circulation probably initiated during 4,5 and 6 above and continuing into 8 and 9.
8. Main upwarping of South Pennine anticline in the Miocene (?).
9. Stripping of Mesozoic and Upper Carboniferous cover during and since the Pliocene.
10. Alternation of glaciations and interglacial phases with progressive incision of Derwent, Wye valley systems and their tributaries with resultant intermittent lowering of base level at Castleton in the Pleistocene.

Table 1. Outline sequence of events.

Approaches

The related problems of establishing a sequence of events and dating them require the correlation of a number of different approaches: (a) the morphology of the caves themselves: do they show a sequence of developments of differing cave passages and types? Can this be related to external factors? (b) the establishment of a sequence of external events from geological evidence such as erosional events deduced from river terrace levels, glacial tills, solifluction deposits, loess sheets etc; (c) the dating of speleothems (stalagmites); these should place at least minimum dates on the evolution of some cave passages and features; (d) the dating of external events; (e) a look at the time factor: could the processes visualized have resulted in the observed cave features in the time available?

Uranium Series dates

Studies of uranium/thorium isotope ratios in Derbyshire caves in general have shown a reasonable correlation with the climatic oscillations shown by oceanic cores (Ford, Gascoyne & Beck, 1983). What the age determinations do not tell is how long a cave has been above water-table before growth started and they provide no correlation with the classic Pleistocene Stages, Hoxnian etc., as hardly any of these have provided dateable material. Reference to these stages herein is given on the uncertain conventional basis only as a help to the reader. In turn the age determinations provide no correlation with the river terraces of the Derwent (Waters & Johnson, 1958) as none of these has been dated by direct means.

Age determinations for the Castleton caves extracted from Ford, Gascoyne & Beck (1983) are given in table 2A and these are supplemented by determinations from Pilkington's Passage of Speedwell Cavern in table 2B.

Uranium-series dates on speleothems from Castleton caves
(extracted from Ford, Gascoyne & Beck, 1983)

		Ka B.P.
Giant's Hole	- on solifluction fill near entrance	3.4±0.1
	- flowstone near entrance	17.0±2
	- flowstone near Maginn's Rift	54.0±2
	- flowstone overlying last-named	48.0±1
	- flowstone at Giant's Windpipe	125.0+22/-19
	- stalagmite in upper series	3.6±0.2
	- flowstone in upper series	2.2±0.2
Peak Cavern	- broken flowstone in canyon	59.0±3
	- eroded flowstone in canyon	59.0±3
	- eroded flowstone in Victoria Gallery	51.0±2
	- flowstone on mud-fill	1.1±0.1
Speedwell Cavern	- broken flowstone block in fill near Bung Hole stopes	96.0±4
	- flowstone cementing boulders at choke near Bung Hole stopes	17.0±1
Treak Cliff	- flowstone on collapsed block in Aladdin's Cave	125.0±6
	- ditto	131.0±6
	- ditto	126.0±3
Winnats Head Cave	- broken flowstone in upper series enclosing fallen stalactite	186.0±7
	- broken flowstone	191.0+15/-13
	- broken stalactite	176.0+8/-7
	- broken stalactite in Fox Chamber	9.0±2
	- flowstone veneer in Fox Chamber	54.0±3

Table 2A

Speedwell Cavern - Pilkington's Passage
(results from D.C. Ford, McMaster University)

Pilkingtons	1	48m above Stream Cavern level	91.0±5.5
	2	40m "	115.0±12
	3	76m "	63.0±3
	4	115m "	12.6±0.5

Table 2B

The topographic situation

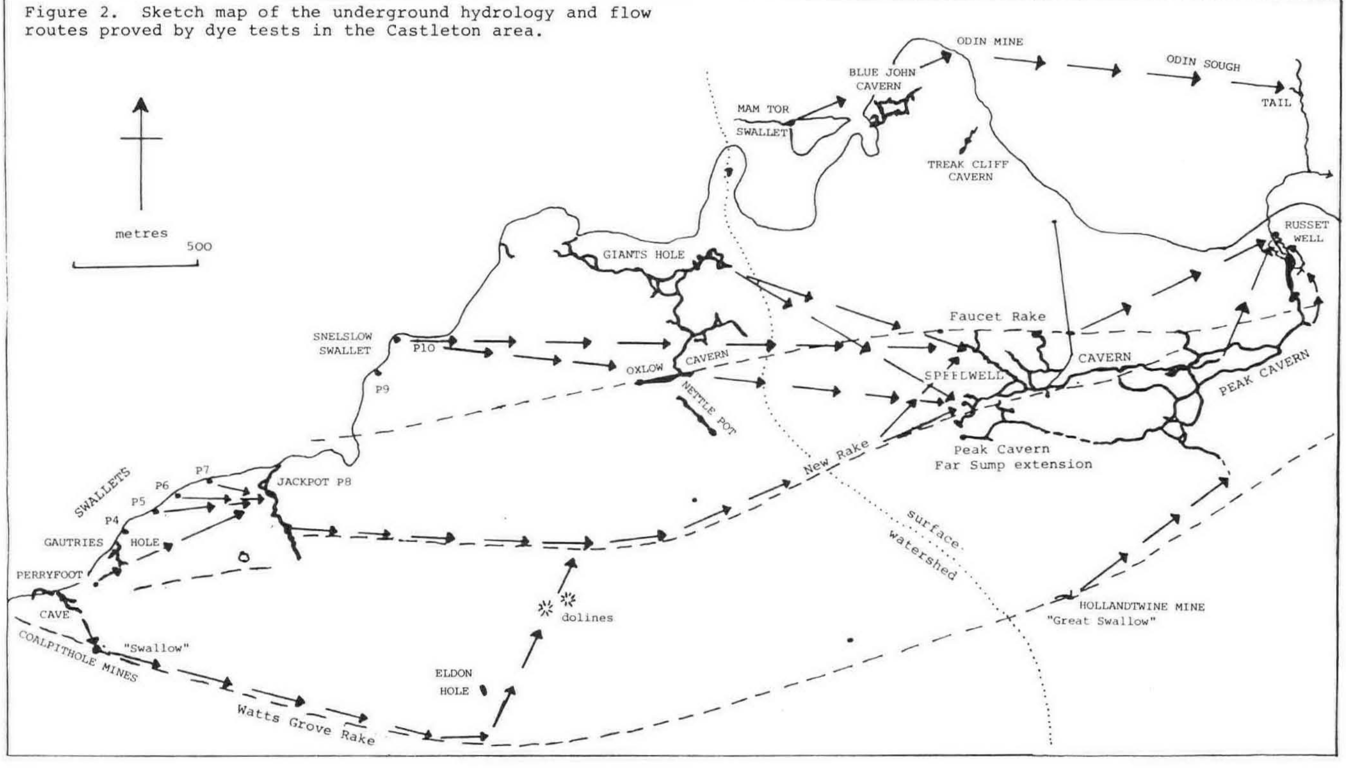
The most northerly point of the Carboniferous Limestone outcrop is at the north end of Treak Cliff where the reef limestones disappear beneath the shales and sandstones of Mam Tor. To the west the reef belt trends generally WSW along the Rushup Valley, with streams draining off the Millstone Grit of Rushup Edge and sinking at or close to the limestone boundary at altitudes of 310 to 370m (Fig.6.) The underground drainage penetrates the reef belt into the lagoonal limestones with their generally gentle easterly dip, and the water resurges in Castleton either at Russet Well or outside Peak Cavern at about 195m O.D. at the head of Hope Valley (Fig.1). The drainage thereby crosses beneath the surface watershed between the apparent topographic catchment areas of the Rivers Wye and Derwent and there is little doubt that at least part of the intervening route is of deep phreatic (sub-water-table) nature following mineral vein fissures. The main mineral veins trend WSW-ENE or W-E and circulation may extend some hundreds of metres below water-table within these.

The general easterly direction of the underground drainage pattern has been known for a long time as mid-19th century mine working at Coalpithole Mine near Perryfoot discoloured the water resurging from Russet Well.

In more recent years dye tests have confirmed the fact that all the swallets drain via Speedwell Cavern to Russet Well (Ford, 1966; Christopher et al., 1981), with flood waters backing up in the lower part of Speedwell and overflowing into Peak Cavern (Figs. 2 and 10).

With the highest point of the limestone plateau at Eldon Hill, 470m O.D. , being 100m or so lower than the surrounding Millstone Grit scarps there is a question of the amount of lowering by solution weathering having taken place since exhumation from beneath the Millstone Grit cover. Pitty (1968) argued for a very large part of this lowering being in Pleistocene times, but this overlooked the nature of the sub-Namurian unconformity, whereby almost all beds of Brigantian (D2) age were stripped off before the Edale shales were deposited. The thickness of the missing Brigantian is difficult to estimate but it may well account for most of the 100m of apparent lowering i.e. the lowering is largely a mid-Carboniferous palaeokarstic erosion feature.

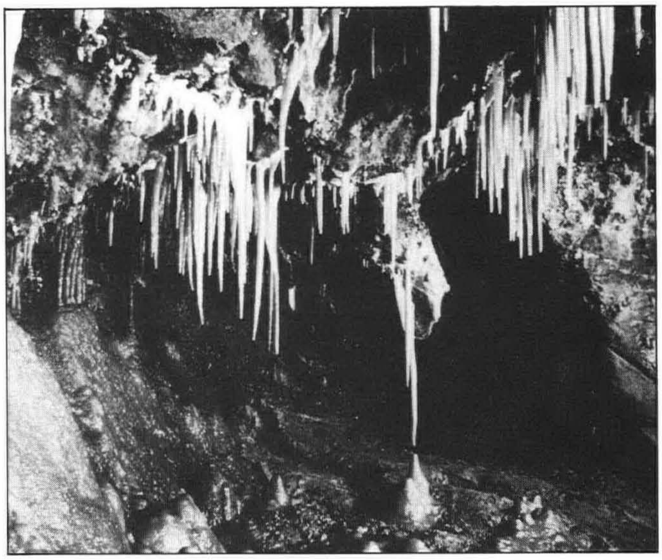
Figure 2. Sketch map of the underground hydrology and flow routes proved by dye tests in the Castleton area.



The Millstone Grit outcrops at present are of course the current stage in the progressive erosion of the former cover. Understanding the evolution of the cave systems necessitates consideration of the state of affairs at previous greater extents of this cover before it was stripped back. This can be done firstly by considering the evidence of the mid-Carboniferous unconformity and what significance it might have had in cave development, and secondly by consideration of the sub-surface effects of mineralization on early cave development. To examine these problems the caves of Treak Cliff are a useful starting point.

TREAK CLIFF AND ITS CAVES

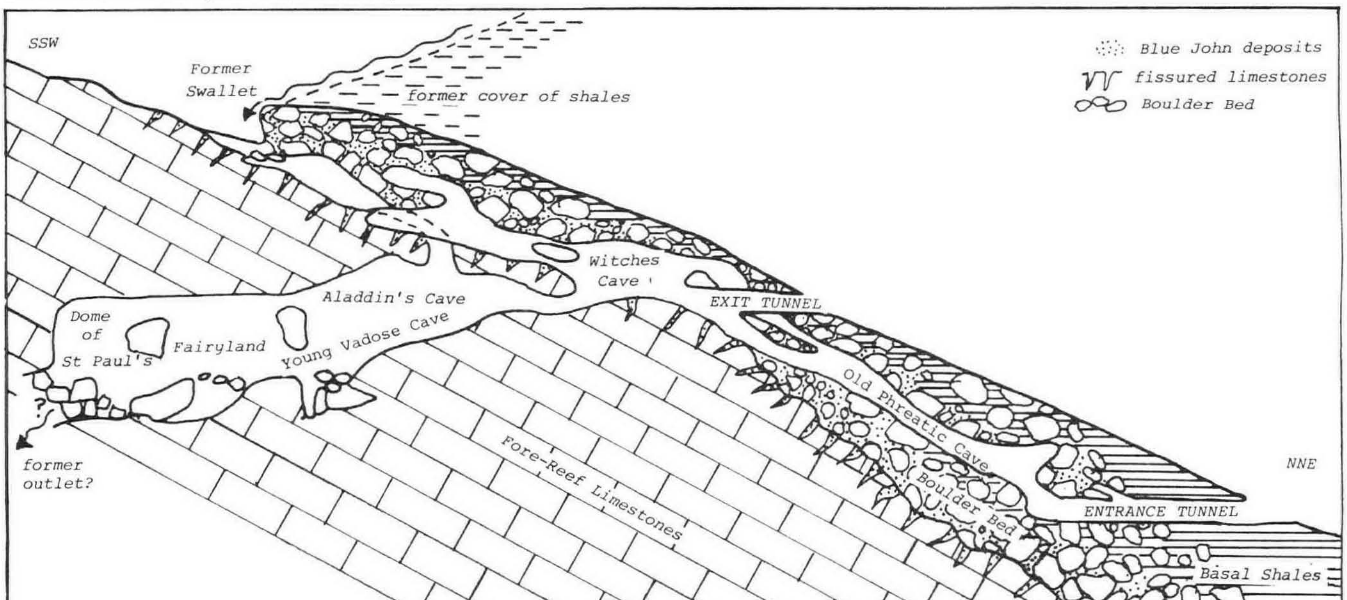
In the middle of the Carboniferous period, the Dinantian reef complex and the margins of the lagoonal massif limestones were uplifted and deeply eroded to provide the boulder beds flanking the fore-reef limestones and covered by shales as described by Simpson & Broadhurst (1969). Almost all Brigantian beds were removed so that the most exposed limestones around Castleton are of Asbian Age. During this period there can be little doubt that at least part of the limestone massif was subject to subaerial karstic erosion: fossil clints and grykes are in evidence at Windy Knoll and what appear to be early phreatic caves were developed at various levels within Treak Cliff itself. Late and post-Carboniferous mineralization (Ineson & Mitchell, 1972; Ford, 1969) affected these so that the original speleological and surface karst features have been partly obscured. However, the boulder-filled gryke fissures at Windy Knoll are well-known and voids between boulders lined with Blue John fluorspar in Treak Cliff Cavern are the main source of the semi-precious mineral variety (Fig.3). Blue John is also found lining what appears to be small tube and bedding caves of general phreatic form in the Blue John Caverns and in the Old Tor mine in the Winnats Pass. However, no evidence has been found of ancient stream cave systems of mid-Carboniferous age.



Treak Cliff Cavern showing the speleothems of the Dream Cave, with stalagmites resting on the derived loessic clay floor.

The further development of Treak Cliff Cavern appears to have been as a swallet cave draining off a former extent of the Millstone Grit cover halfway up the face of Treak Cliff utilizing the ancient mineral cavity systems (Fig 3). At first this fed water into a deep phreatic system in what is now the Old Series of caves near the surface and former shale cover, partly in the pre-Namurian Boulder Bed. Later the former Treak Cliff swallet fed water deeper into the fore-reef limestones to resurge at an unknown site possibly somewhere near the foot of the Winnats Pass. Falling base level permitted the incision of a vadose canyon, now abandoned and well decorated with many stalactites and stalagmites, some growing on a clay fill derived from loess while others are now beneath fallen blocks. Some of the latter were dated (Table 2A) as 125,000-131,000 years B.P. correlating with isotope stage 5e, probably the Ipswichian Interglacial. At present no stalagmite lying on the loessic fill has been dated so it cannot be deduced whether this is pre-Ipswichian or not.

Figure 3. Diagrammatic section through Treak Cliff Cavern showing the probable position of the former Treak Cliff swallet in relation to the former extent of the Namurian shales cover, the relationship of the Cavern to the pre-Namurian Boulder Bed and Blue John mineralization, the later vadose cave extending into the fore-reef limestones (modified after Simpson & Broadhurst, 1969)



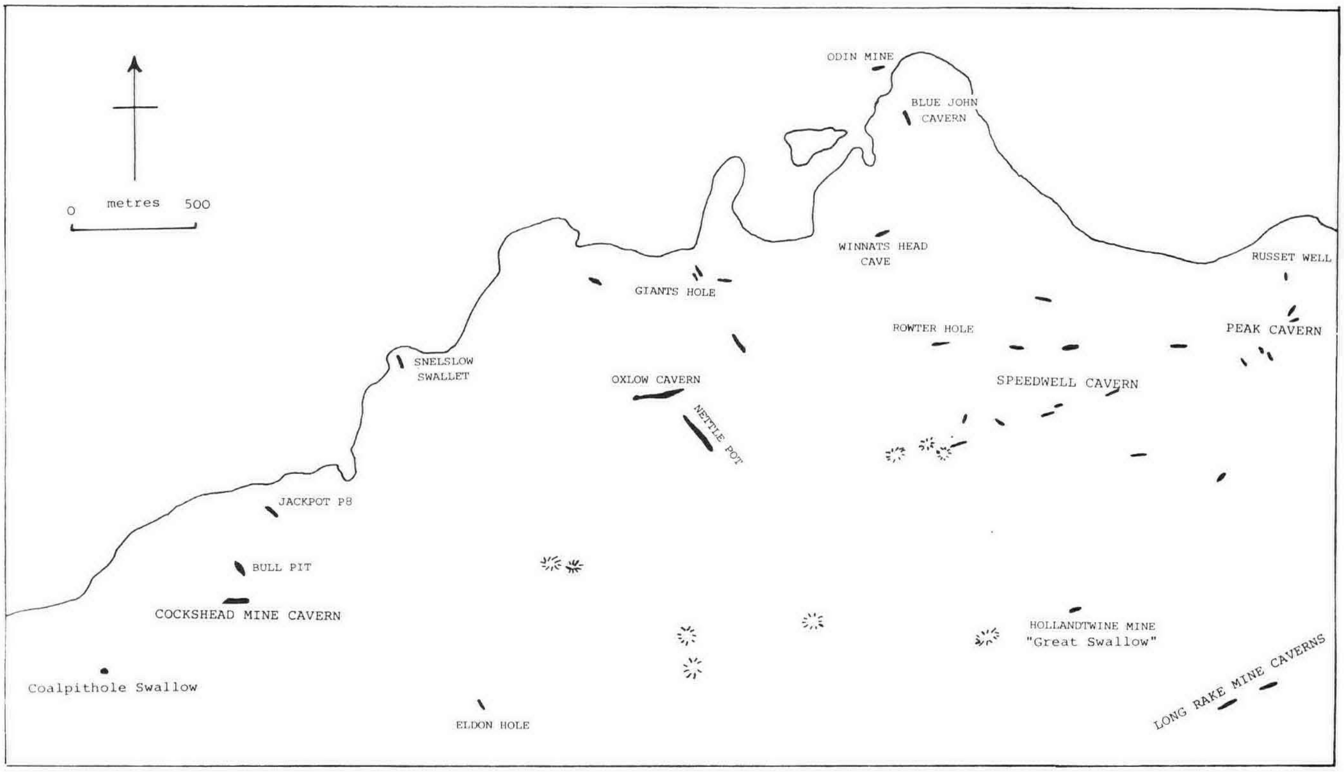


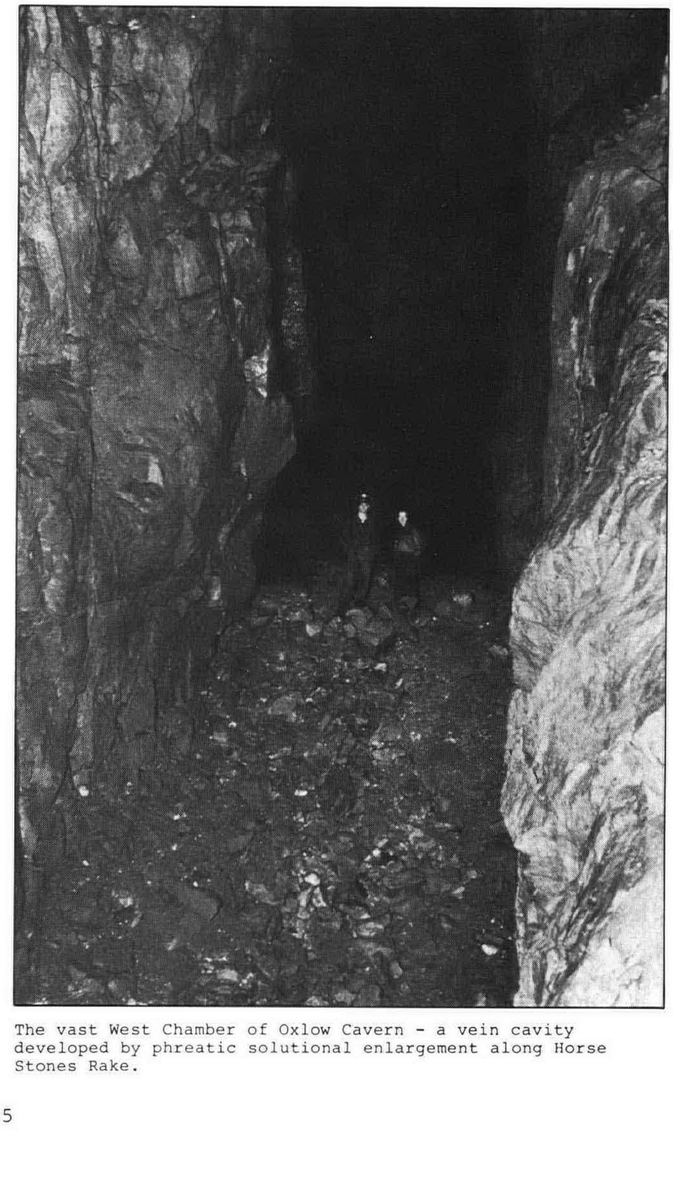
Figure 4. Sketch map of the distribution of vein cavities and similar caverns developed along faults and major joints, and of dolines which may overlie comparable cavities.

The Blue John Cavern is similarly a vadose cave system to a minor extent developed from a mineralized mid-Carboniferous palaeokarst, with a former input close to the present shale boundary. The large vadose canyon suggests a major input at some time, though the present catchment area hardly seems adequate. The termination of the cave in a minute impenetrable sump provides yet another enigma. Run-off from a former ice-margin near Windy Knoll may account for the large vadose canyon.

MINERAL VEIN CAVITIES

The major mineral veins (rakes) crossing the Castleton area broadly on a WSW-ENE trend are characterized by two types of ancient cavity. The first results from the fact mineral deposition did not always fill the space available in the fault fractures, leaving crystal-lined vugs in the centres of veins. It is reasonable to suppose that the last crystals in these were deposited by the last phase of mineralizing fluids, and that the latter must have had some degree of an integrated plumbing system to permit fluid flow to supply the minerals. Although such primary mineral-lined vugs must have been found frequently during mining few are accessible today. The mineralizing fluids also appear to have been aggressive at times and small parts of the limestone wall-rocks were dissolved, yielding pipe-caverns, later lined or filled with mineral deposits.

The second type of cavity is due to posthumous solutional enlargement of the vugs. Although all the mineralizing effects were deep-seated, with temperatures commonly around 80-100°C, under a cover of possibly 3 km of younger strata, any speleogenetic processes would have been minimal owing to the very slow movement of fluids. Once the Upper Carboniferous cover was breached by erosion at a much later date probably mid-late Tertiary (see below) the potential could arise for hydraulic gradients to accelerate the flow through the vugs and pipes of the mineral vein system (Ford & Worley, 1977). Ideally the cover would have to be breached in two places at different altitudes, so that a hydraulic gradient could be established. Under these conditions it is likely that large solution caverns



The vast West Chamber of Oxlow Cavern - a vein cavity developed by phreatic solutional enlargement along Horse Stones Rake.

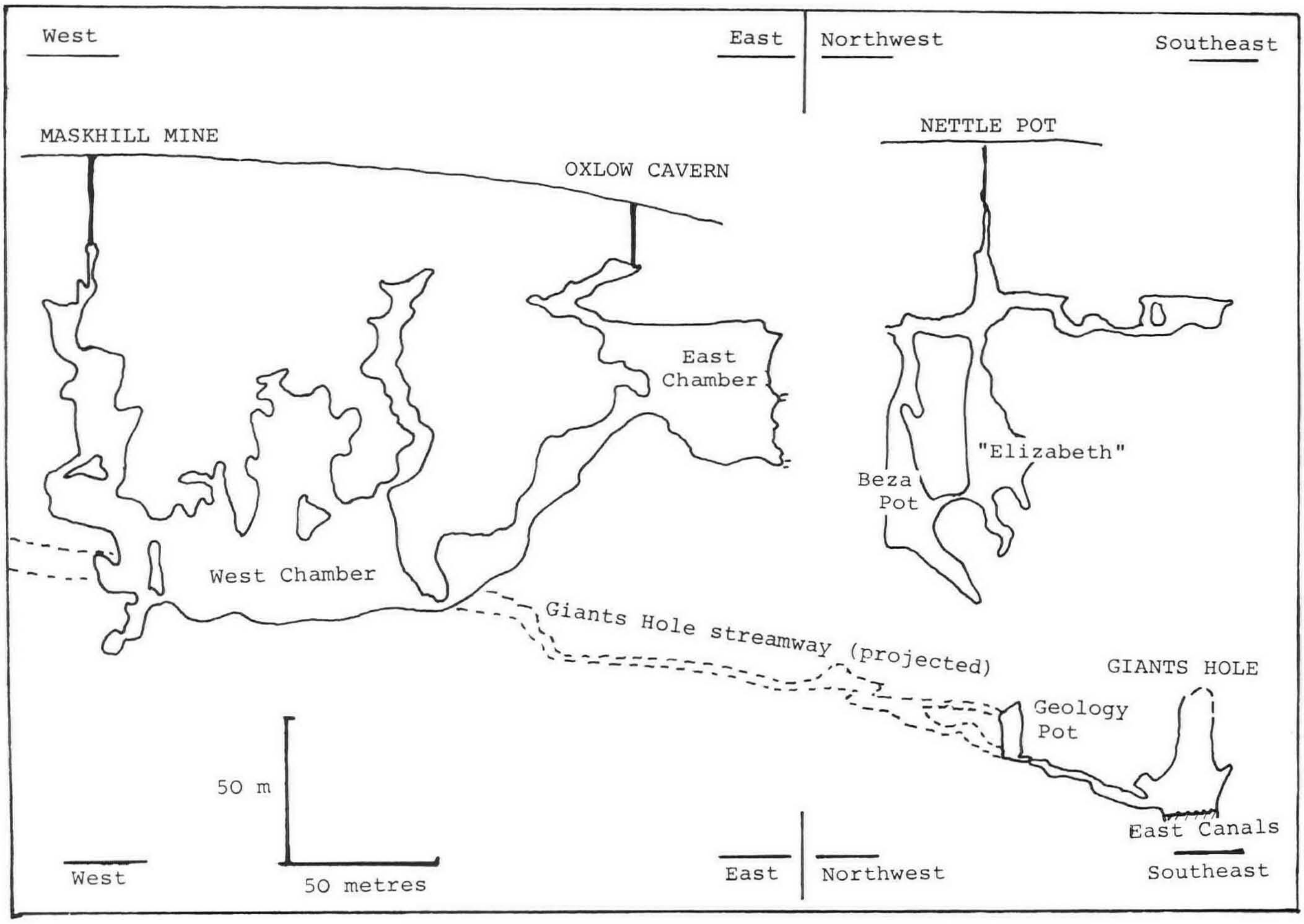
(vein-cavities) were developed by solutional enlargement of vugs and pipes. The sites of inputs and outlets are unknown but likely places for early engulfment would be on Eldon Hill and the moor to the east whilst outlets might have been in or near Peak Cavern gorge as predecessors of Russet Well and Slop Moll or in the Pindale -Bradwell area. Several such caverns are well-known e.g. the Bottomless Pit Cavern in Speedwell Cavern, Long Rake and Venture Mine Caverns on Bradwell Moor and Oxlow Caverns, later linked to the dry upper abandoned tube-system of Giant's Hole (Fig.4). Oxlow and the associated Maskhill Mine Caverns show a vertical amplitude in Horse Stones Rake of around 150m above present water table, with fill concealing any deeper extension.

The width rarely exceeds 5m but the long profile shows a strong up-and-down oscillation characteristic of deep phreatic loops (Fig.5). At the eastern end, the east-west Oxlow system intersects (though there is no accessible connection) the NW-SE fault-guided Nettle Pot. Though obscured by collapse debris this also shows evidence of solutional development. There is little vadose modification in either cave so that the vein cavities seem to have been drained by a rapidly falling water-table. Other vein or fault-guided deep phreatic solution cavities include Eldon Hole, Ghost and Maginn's Rifts and Geology Pot in Giant's Hole, Victoria Aven in Peak Cavern and the entrance shaft of Longcliff Mine. Mining records suggest the presence of others, such as "The Great Swallow" in Hollandtwine Mine and a "swallow" in Coalpithole Mine, which still feed water into the underground systems. The "Swim Hole" on an 18th century plan of Odin Mine may indicate the presence of one such cavern still beneath the shale cover. Russet Well, the outlet to most of the subterranean drainage, is in a thin mineral vein and water rises from a totally submerged vein cavity system. A feature of all such cavities is that their genesis was entirely by phreatic solution which could be at any depth below a water-table, and in fact is probably still going on beneath the present day water-table, e.g. in the canals at the bottom of Giant's Hole, and in the Main Rising of Speedwell Cavern. A critical question is when was the cover breached sufficiently to permit the establishment of this vein-cavity drainage? Other than saying that it was "early" and could have been before most of the Millstone Grit cover was stripped off there is no way of putting a date on this event. At best, in general terms, it was probably after the final upwarping of the Pennine anticline (Miocene?) and before the moulding of the present landscape by the Pleistocene glaciations, so that the initiation of vein cavity drainage can be conceived as "Pliocene or earlier".

A scatter of deep dolines on the limestone plateau suggests the presence of other vein-cavities now partly or wholly collapsed (Fig.4). These are mostly near or on mineral veins and also lie above the drainage routes from the swallets to Castleton resurgences. Taken with the known vein-cavities these suggest a more complex, integrated, vein-controlled phreatic complex than has generally been considered hitherto.

The evolution of the mineral vein cavities from the deeply submerged slowly-moving solutional phase to the hydraulic U-tube systems envisaged above can be compared directly with the Bathyphreatic and Deep Phreatic stages of D.C.Ford & R.Ewers (1978), and various parts of the Castleton drainage system are seemingly in each of these at present.

Figure 5. Diagrammatic section along the vein cavities of Oxlow Caverns (including Maskhill Mine Caverns), Nettle Pot and the East Canals of Giants Hole, (modified from a diagram by J. S. Beck, 1980).



Eldon Hole - a 60 m deep pothole developed by solution and collapse along a minor northwesterly fault.

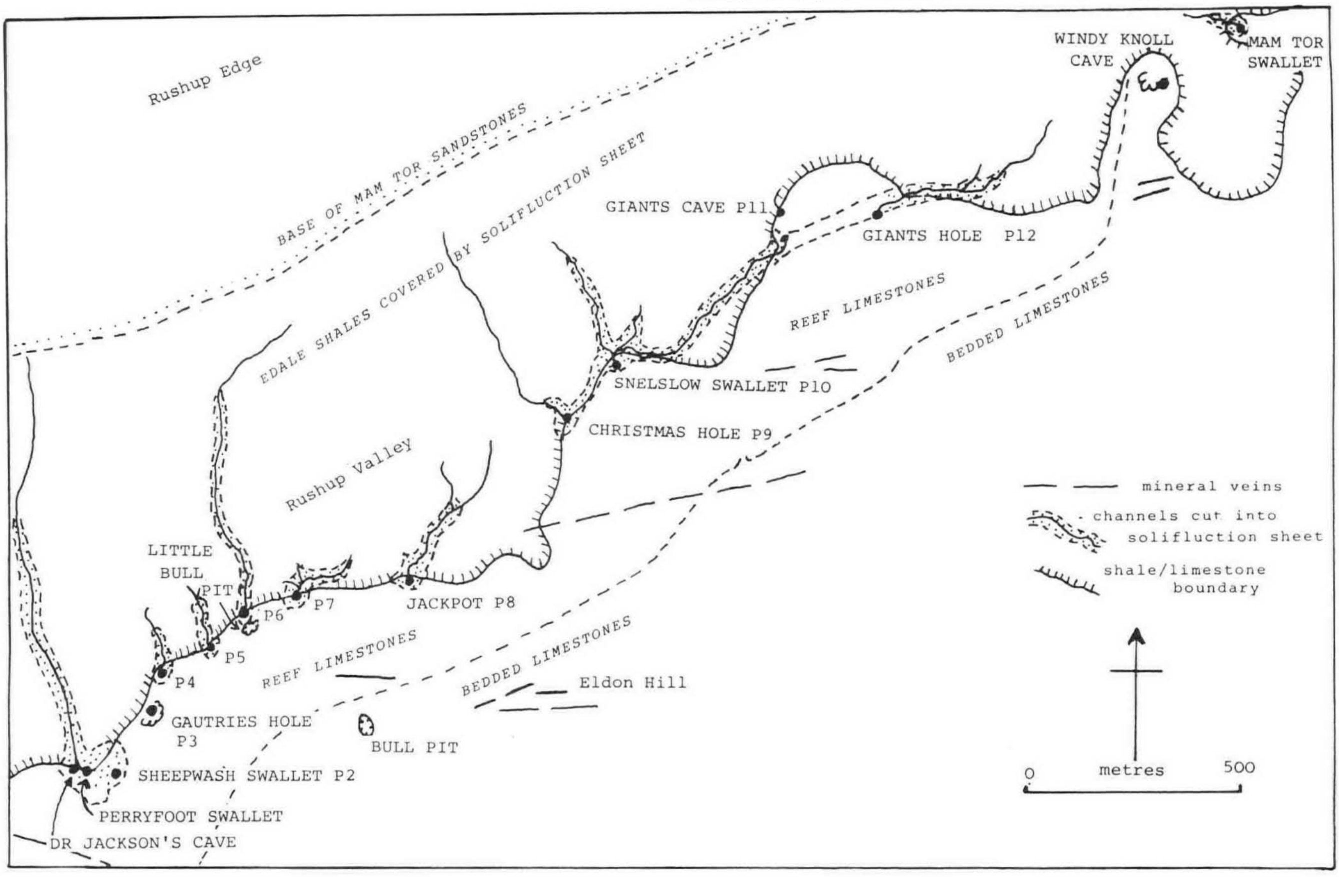
THE SWALLET CAVES

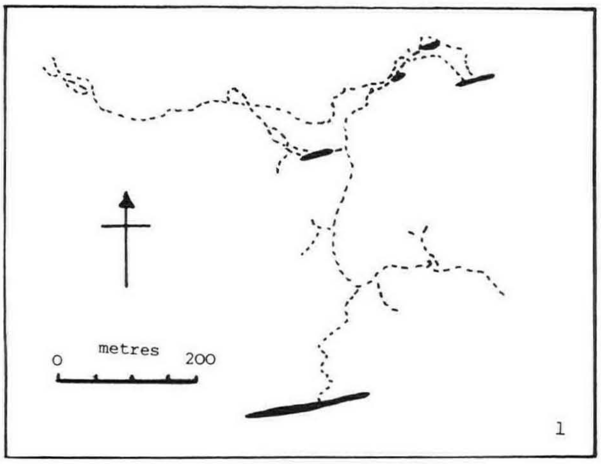
The present day swallet caves lie along the shale/limestone boundary in the Rushup Valley, taking in allogenic drainage from the streams running south off Rushup Edge (Fig.6). Descriptions can be found in Ford (1977) and numerous caving club publications. Few of the swallet caves can be followed for more than a hundred metres or so. All show a complex arrangement of generally small passages with their morphology controlled by an intersecting maze of bedding planes and joints. These are inclined at various angles, often contrary to the regional dip, owing to the lenticular character of the reef limestones. The surface stream channels leading to the swallets are incised some 5 or 6 metres into a solifluction sheet (Johnson, 1967) and much comparable fill can be seen in the caves themselves; indeed Giant's Hole has "old" passages completely filled with cemented solifluction gravels.

Relative chronologies for the development of the two major swallet caves have been worked out. Smith & Waltham (1973) outlined a sequence of passage developments in Jackpot (P8) whereby a series of early phreatic passages were progressively enlarged by vadose downcutting and then abandoned during falling base-level. Even so the accessible cave is only 800m long and soon reaches a depth of 50m in a high "rift" along a NW-SE fault. Divers have shown that the cave continues for another 700 m, beyond which pitches descend to a streamway currently being explored. As yet no speleothem uranium-series dates have been obtained for this cave.

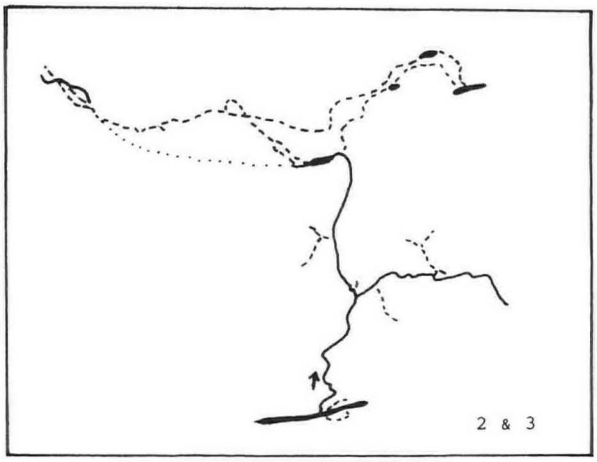
A comparable chronology has been worked out for Giant's Hole by Westlake (1967) and with some modification, is shown in Figure 7. The "old" cave again shows a complex of ramifying passages through the belt of reef limestones, with several "fossil" passages completely full of solifluction gravel suggesting former entrances near the

Figure 6. Sketch map of the distribution of swallets, caves, solifluction sheet and incised channels in relation to the limestone - shale - sandstone solid geology of the Rushup Valley (modified after Johnson, 1967).



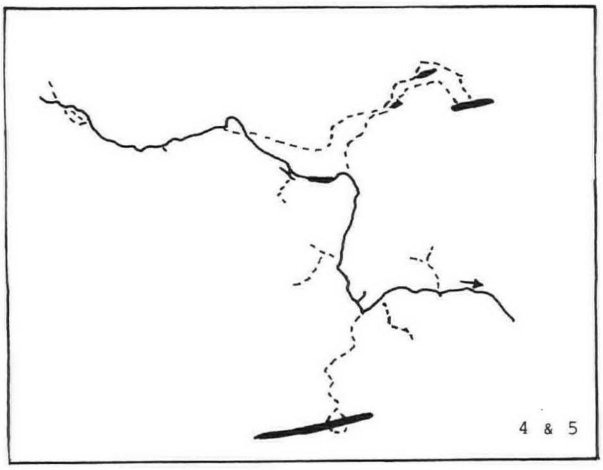


1. Pliocene to early Pleistocene-vein, fault and joint cavities opened by deep phreatic solution.



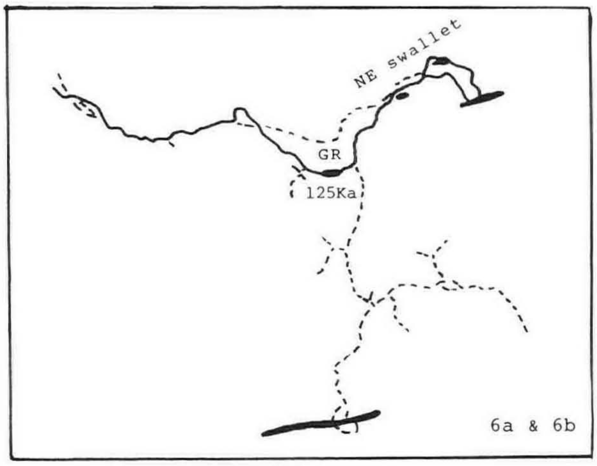
2. pre-Anglian? First swallet enters by upper levels of old Giants Hole and flows via choked tube to near Ghost Rift, then through the link to sink near North Chamber of New Oxlow Caverns.

3. Anglian glaciation? all passages filled with fluvioglacial sediments.

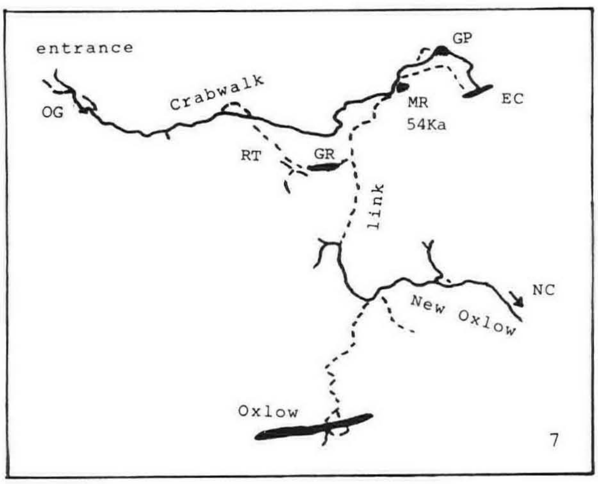


4. Hoxnian. drainage of Stage 2 re-established and then diverted along the roof tube of the Crabwalk through the link to sink near North Chamber, in New Oxlow Caverns.

5. Wolstonian glaciation. Entrance passages again filled with fluvioglacial sediment, little run-off owing to frozen ground at glacial maximum.



6a. Late Wolstonian to Ipswichian - blocked passages cleared. Drainage via Giants NE swallet to East Canals. Maginn's and Ghost Rifts drained. Link dry. Present entrance established. Rapid downcutting in Crabwalk. Lower Complex drained. Flowstone in Ghost Rift 125000 years old.
6b. Early Devensian - solifluction gravels fill entrance passages; some loessic clay in high level tubes.



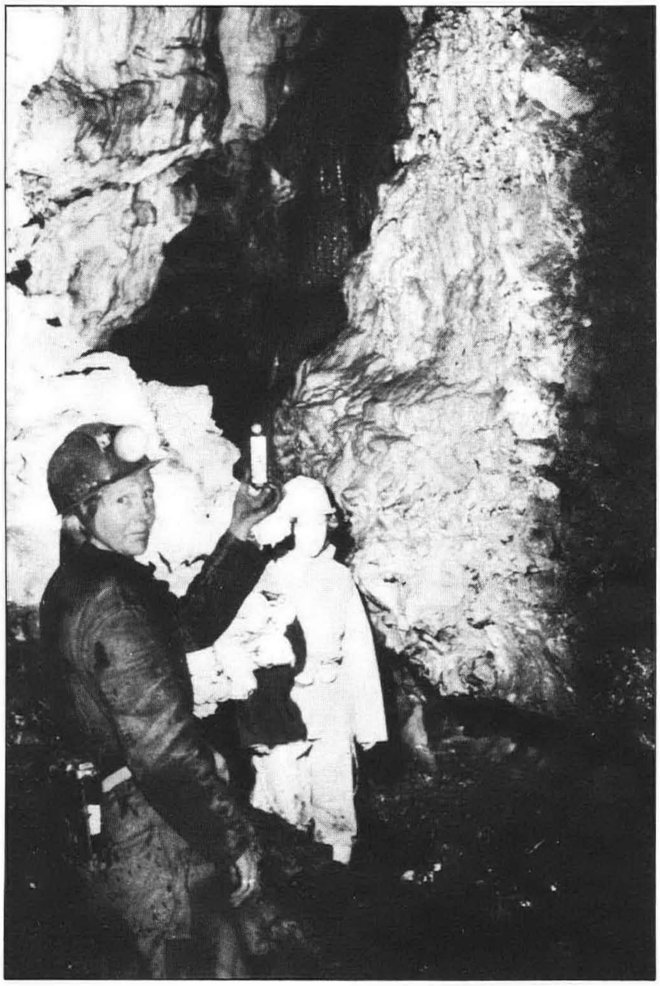
7. Mid-Late Devensian - solifluction fill partly removed. Further incision of Crabwalk. Minow inlet from branch of link to New Oxlow. Another lower minor inlet in bottom of Oxlow Cavern. Flowstone 54000 years old in Maginn's Rift.

OG-Old Giants; MR-Maginn's Rift, GR- Ghost Rift
NC-North Chamber; GP-Geology Pot; RT - roof tube

Figure 7. Diagram of the possible sequence of phases of development of Giants Hole and Oxlow Cavern system (modified after Westlake, 1967).

present one. Beyond the entrance series, the cave changes character. At Base Camp Chamber and the adjacent avens, there is evidence of alignment along a NW-SE fault (and evidence of a former fill of gravel), whilst below Garlands Pot striking vadose incision of the Crabwalk into the floor of one of a maze of small phreatic tubes has taken place. Westlake has suggested a sequence of morphological development of these tubes in relation to vein-cavity drainage in Oxlow Cavern which the stream no longer uses. Instead it follows the regional dip more or less ESE down an intricate meander belt (along local joints) into a group of larger joints in Maginn's Rift, Geology Pot and the East Canals some 150 m below the entrance, close to the altitude where the water re-appears in Speedwell Cavern. Westlake suggested a relative sequence of events without any fixed dates, but thanks to uranium-series dating it is now possible to say that the water-table had fallen far enough for stalagmite growth to start in the Giant's Windpipe near Ghost Rift by 125,000 years B.P., i.e. in the last interglacial (Ipswichian), and growth had started in the lower Maginn's Rift by 54,000 years B.P. (Chelford Interstadial).

Together these dates suggest that the main part of Giant's Hole was already much in its present form by the Ipswichian Interglacial; tentative suggestions can be made concerning possible dates for the establishment of earlier drainage routes in now-abandoned phreatic tubes at high level, through to the North Chamber of New Oxlow Cavern. Following the development of the present drainage route, a rapidly falling water-table, perhaps controlled by the lowering of Hope Valley floor, resulted in the drainage of the largely phreatic lower Giant's complex from Geology Pot to East Canals. There may have been more than one phase of fill by fluvioglacial sediments but only the last Devensian phase of solifluction gravel has been recognised and the cave stream has trenched through this in late to post-glacial times, in a fashion comparable to the incision through the solifluction sheet on the surface.



Near Base Camp Chamber in Giants Hole: the right-hand wall is largely flowstone-covered solifluction gravel once attached to the boss behind the caver on the left. The present stream has cut a channel through the gravel fill in the centre.

A few small passages in the swallet caves are filled with sticky yellow clays and silts. It seems likely that these were derived from a former cover of loess, wind-blown dust of periglacial character, though as yet we have no evidence for the age of such material. Although loess on the limestone plateau is mostly of Devensian age (Pigott, 1962; Burek, 1977), there is no inherent reason why some should not be considerably older (Pigott 1962b).

A direct implication of the present form of the swallet caves is that the outlet end of the drainage system was within 50 m of its present altitude by the last interglacial, and thus that Hope Valley had been incised to that depth by the Ipswichian. A second implication is that the Millstone Grit cover had been stripped back to more or less its present position before the Ipswichian, for the vadose incision by allogenic streams to have occurred. This leads to the corollary problem of what happened when the cover had not been stripped back so far? Theoretically there should be one or more earlier generations of old swallets further back up the flanks of the limestone plateau. None can be found. Some may of course be buried under solifluction deposits, loess or even boulder clay, but no evidence has come to light of an earlier generation of swallet caves, presumably taking allogenic input from a larger catchment of Millstone Grit than the present Rushup Edge. Can an explanation be offered other than saying "they are buried"? The only possiblity that comes to mind is that during one of the early glaciations, Anglian or Wolstonian*, the cover was stripped back very rapidly, and thus the underground drainage systems went from the breached vein-cavity stage to the present swallet stage very quickly. However, there is little evidence of glacial stripping on this scale either.

The isolated Windy Knoll Cave lies exactly on the watershed between the Derwent and Wye drainage basins. It is developed close to the shale/limestone boundary and its roof is in the pre-Namurian boulder bed. The lower walls show solutional facetting characteristic of phreatic conditions but its situation suggests that a swallet once existed here. This could only have operated with a reasonable catchment where the Rushup Valley is today (Fig.6) i.e. before the Millstone Grit shale cover had been stripped back where the present swallets are. Regrettably the cave is choked with solifluction debris a few metres inside so that no further evidence is available, but it does look as though this might have been a very early stage in the evolution of the underground drainage system.

Winnats Head Cave may also have acted as an early, pre-Winnats Pass, swallet but again too little is known of its extent to provide much evidence.

A number of high-level abandoned phreatic tube passages link the Giant's Hole system with the vein-cavities of Oxlow Caverns, and others by-pass the Giant's Hole streamway. Beck (1980) has suggested that these may have developed at a time of high base level in pre-Hoxnian times. They appear to have been fed from sinks at or close to the present swallets so that there is an implication of a stage of development when the

*Footnote: although current opinion is increasingly to the effect that the traditional Wolstonian and Anglian glacials are one and the same event in different parts of Britain, the older terminology is retained for simplicity. If the new opinions were accepted then "Wolstonian" could become an invalid term and could be replaced by Anglian throughout Britain, with the corollary that "Anglian" glaciation as used herein could become "pre-Anglian".

Millstone Grit cover had been stripped back in the Rushup valley but when Hope Valley was nowhere near as deep as at present. There is a hint of phreatic tube development at more than one level, but whether this represents phases of falling base levels or whether it is simply a matter of picking out favourable shale partings is unknown.

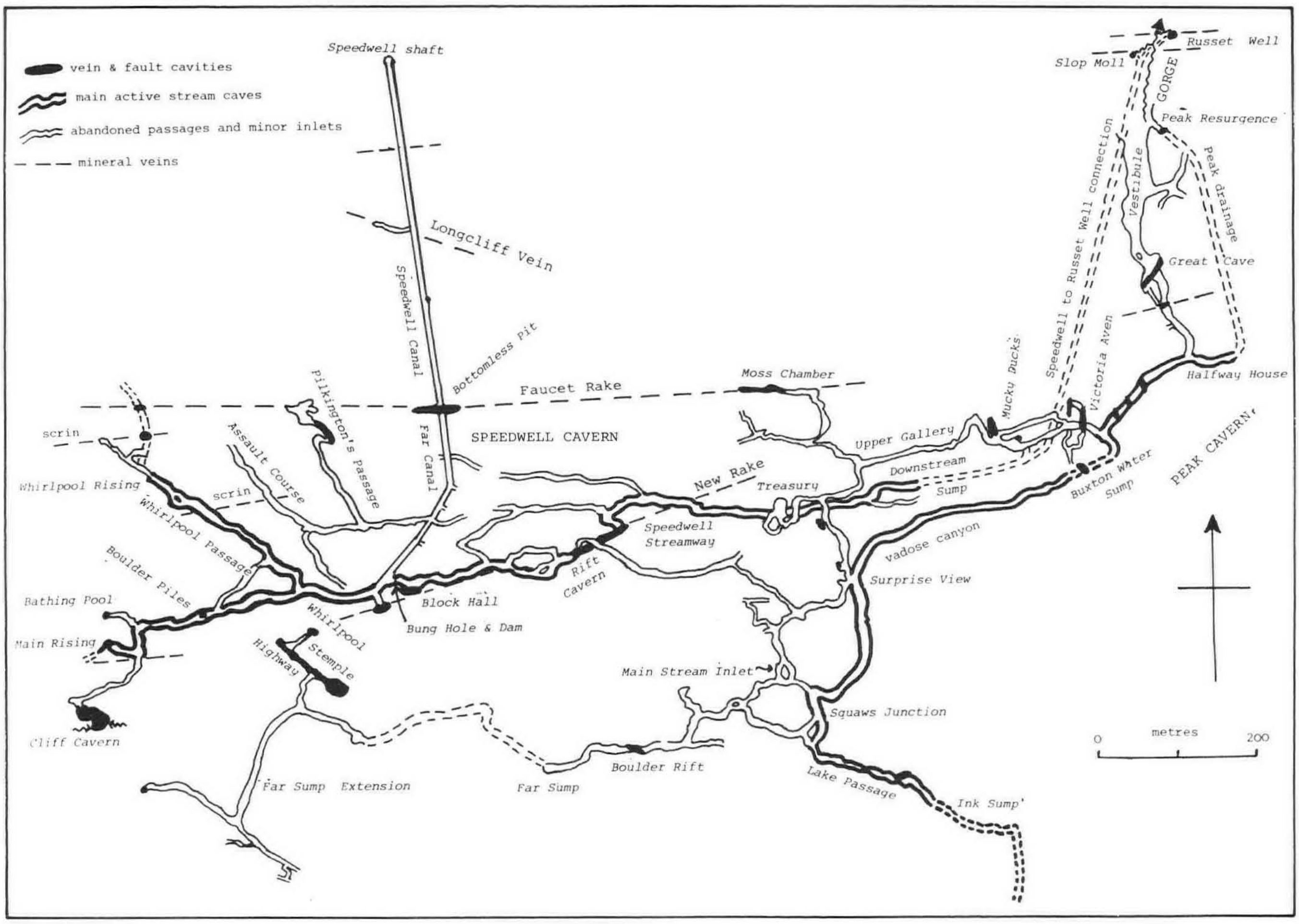
The active swallet caves can be regarded as Drawdown Vadose caves in the classification of Ford & Ewers (1978). To some extent they may also be invasion vadose caves since the sinking streams run off a solifluction sheet, though this only transgresses the limestone margin by a few metres at most, and fossil passages are very limited.

PEAK CAVERN

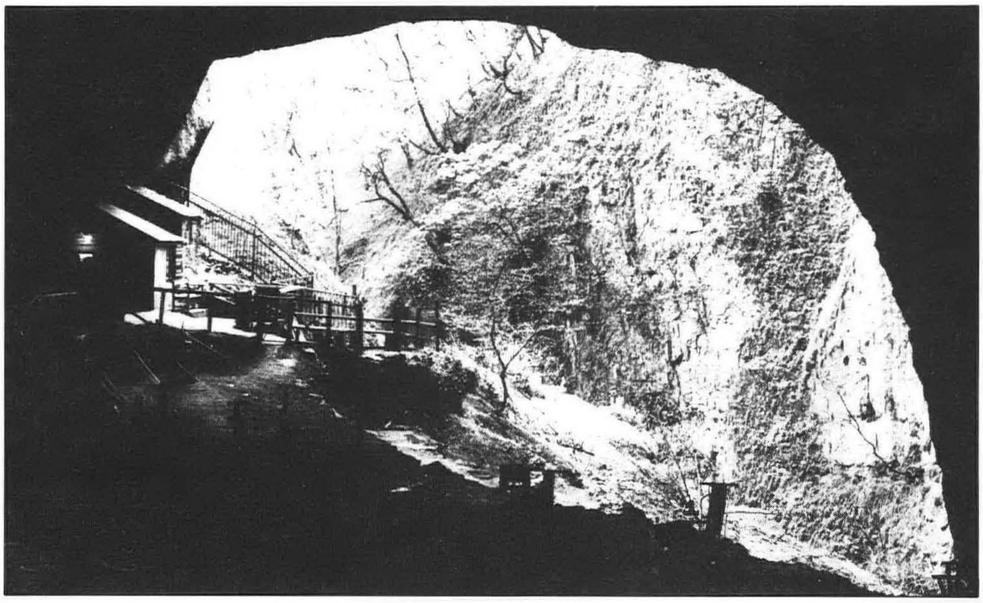
With its vast entrance, the largest in Britain, Peak Cavern looks as though it ought to be the natural outlet for all the subterranean drainage of Castleton, but it is not at present. Under normal flow conditions its stream is a minor one largely composed of percolation water from the limestone plateau around and west of Cavedale. The entrance and outer passages show changes of morphology as one passes through the reef belt, but from the Devil's Staircase onwards the cave is in bedded lagoonal limestones and the greater part of the system follows a single bedding plane with a shale parting some 14 m above that in the Speedwell Cavern. Indeed the two cave systems lie closely parallel, with one series of Peak passages actually crossing above Speedwell's Lower Bung Hole series (Fig.8). Although there is very restricted cavers' access between the two cave systems, flood waters back up in Speedwell and overlow into Peak (Fig.10). Speedwell Cavern now carries the bulk of the allogenic drainage. In Peak Cavern strong joints, possibly minor faults, generally trending NW-SE, have resulted in impressive caverns such as Victoria Aven, but they are crossed with little deviation by the cave. A network of phreatic tubes in the bedding plane is still partly filled with clays and silts derived from loess. The stream has excavated an impressive vadose canyon through much of its length. At the downstream end (immediately upstream of Buxton Water Sump) the form of a phreatic tube is maintained with a beautifully symmetrical tube some 6 m in diameter, but upstream a long profile develops where a vadose trench has been cut into the floor of the tube by some 15 m in places. The tributary Upper Gallery, above Surprise View, is a similar tube with but a 2 m deep narrow slot in the floor. Further up the main stream in Boulder Rift a mass of collapsed boulders has created a dam, holding back Far Sump. Recently explored by the Cave Diving Group (Farr, 1981, 1982; Cordingley, 1986), this 385m long submerged section is but a continuation of the great tube and trench partly filled with sediment behind the dam. The phreatic tube, with segments of vadose canyon in its floor, continues into Far Sump Extension, some 500 m of cave fed from small sump inlets (though the old 18th century lead miners had been in before).

Without going into a full description of the intricacies of Peak Cavern's 5 km of passages, some of the main morphological features may be summarized thus. A network of bedding-controlled phreatic tubes, mostly filled with inwashed loessic clays and silts, is largely beneath the "umbrella" of the Cavedale Lava, so that there is little percolation input in the accessible cave. The chemistry of the waters indicates percolation origins so the inputs must be further west, where the lava thins out. Only in flood conditions does swallet water reach the system, and even then it is not clear how (Chrisopher et al., 1981). Avens rise above the phreatic network by as much as 90 metres, but only little has been found of old high level abandoned passages - a feature which correlates with the lack of an early generation of

Figure 8. Sketch plan of the cave passages of the Speedwell and Peak Cavern systems (modified after a compilation by J. S. Beck, 1980).



The entrance arch of Peak Cavern, looking out from the terrace with the remains of the old ropeworks. (Photo: John Cordingley)



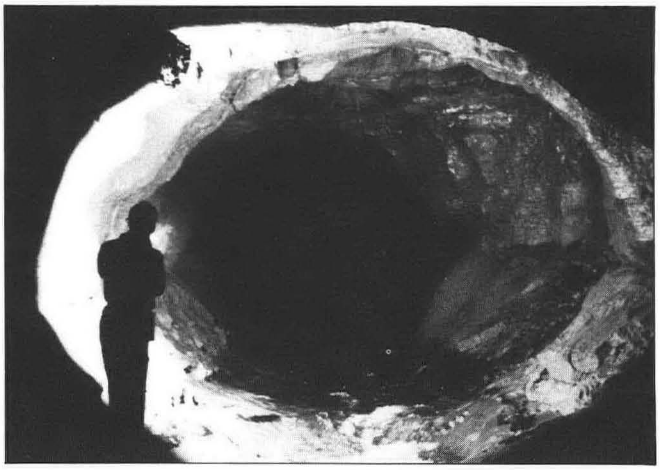
swallets. One part of the tube system was enlarged preferentially and yielded the roof tube of the main streamway, as well as the Upper Gallery. Invasion by the Speedwell stream via mineral veins doubtless supplied an extra input of aggressive water (still active under flood conditions) within the phreatic network. The last stage of erosion was the incision of the vadose trench. This is large enough to suggest that far more water flowed through the Peak Cavern drainage than can be accounted for by percolation alone. One can only surmise that there has been a major change in the drainage pattern below the swallets since then, with Speedwell Cavern taking the bulk of the water today (Fig.8).

Stalactites are few and far between in Peak Cavern, but samples from fallen blocks in the streamway, below deposits on the shoulder of the vadose trench and from corroded flowstone in the Upper Gallery, have yielded dates of 51,000, 59,000 and 73,000 years B.P. broadly the Chelford interstadial. Together they indicate that the phreatic network had been drained to within 20 metres or so of present resurgence level by then, and that most of the vadose incision had already taken place.

The entrance to Peak Cavern and its gorge outside present some problems. The Vestibule slices through lenticular reef limestones, with high narrow avens extending up master joints above, but again with few known high-level side passages. The gorge outside cuts through the fore-reef limestone and is graded to the present valley floor. The present stream has abandoned the main cave for its last 500 m and flows to one side in an immature bedding tube to resurge in the gorge just outside the entrance. The establishment of the initial phreatic cave can only have taken place when the valley floor was much higher than at present and it seems likely that the major outlet for the underground drainage was in the form of a vauclusian spring, rising from the present entrance up through a vertical flooded pothole to the valley floor. Its lip has been cut away by the stream adjusting to falling valley floor levels, in turn reflecting the migration upstream of knick points and the development of river terraces in the Derwent Valley, as discussed later. Doubtless the removal of this lip was assisted by the upwelling of phreatic water through mineral vein cavities at what are now seen as Russet Well and its overflow spring, Slop Moll (Fig.8).

Assigning dates for the development of phreatic drainage via Peak Cavern with its vauclusian spring, and for the conversion to something approaching the present vadose conditions is difficult, though Ford, Gascoyne & Beck's (1983) interpretation of Waters & Johnson's (1958) terrace sequence suggested that the formation of the Hathersage terrace was a critical factor at least in the conversion. A Hoxnian interglacial date can be suggested. Beck (1980) has noted that the lower ends of canyon-type incision in both Peak and Speedwell Caverns is apparently graded to the projected Hathersage terrace (Fig.9). Subsequent incision to the slightly lower level of the Hope Terrace, possibly in Ipswichian times, has been responsible for draining the greater part of the large phreatic tube in Peak Cavern, and equivalent bedding tube in Speedwell Cavern, though any terrace development in the valley is masked by the solifluction sheet. Subsequent incision to the slightly lower level of the Hope terrace, possibly in Ipswichian times, has been responsible for draining the greater part of the large phreatic tube in Peak Cavern, and equivalent bedding tube in Speedwell Cavern, though any Terrace development in the valley is masked by the solifluction sheet.

Whilst the Devensian glaciers do not have appeared to have reached Castleton, the cold phase yielded a cover of loess, with some washed down to fill (or re-fill?) the phreatic tube network. In the gorge there can be little doubt that much frost-shattering took place and the gorge was partly filled with scree damming up water in the cavern, leading to para-phreatic solution enlarging some parts. Post-glacial outflow, particularly in flood conditions, has cut through the fill, re-exposed the resurgence and left the deposits in the vestibule into which the rope-walk terraces were cut. A detailed profile through



The phreatic tube at the lower end of the main stream cave of inner Peak Cavern. Developed by solution outwards from the central bedding plane, it has been drained in recent geological times and now has a misfit stream on the floor.

these could be very informative but none is available as yet. A temporary dam in the Inner Streamway near Lake Passage resulted in a local sediment fill with current bedding indicating flow southeast. Preliminary palaeomagnetic results suggest a date of 5,000 B.C. for this fill stage (Noel, in prep). The dam of collapsed boulders in Boulder Rift has created Far Sump and diverted the normal flow drainage into an adjacent bedding plane now discharging water from a 5 cm high slot in the clay-filled tubes above Squaw's Junction. This and input from Ink Sump in Lake Passage now provide most of the stream in Peak Cavern: the latter gets its water from vein cavities in Dirtlow Rake or a branch thereof at present being investigated by divers.

One final comment on Peak Cavern: a phreatic tube in the roof above Boulder Rift heads off towards Dirtlow Rake and Pindale, but it is completely choked with sediment after 100m or so at Picnic Dig. Could it be that the phreatic drainage once discharged through an unknown resurgence in Pindale?

Being at least partly fed by water rising from phreatic passages (Ink Sump, Minor Sump in Far Sump Extension, and the overflows from Speedwell) the main part of Peak Cavern can be regarded as the crest section of an extended phreatic loop, with vadose downcutting of the trench section, in the classification of Ford & Ewers (1978).

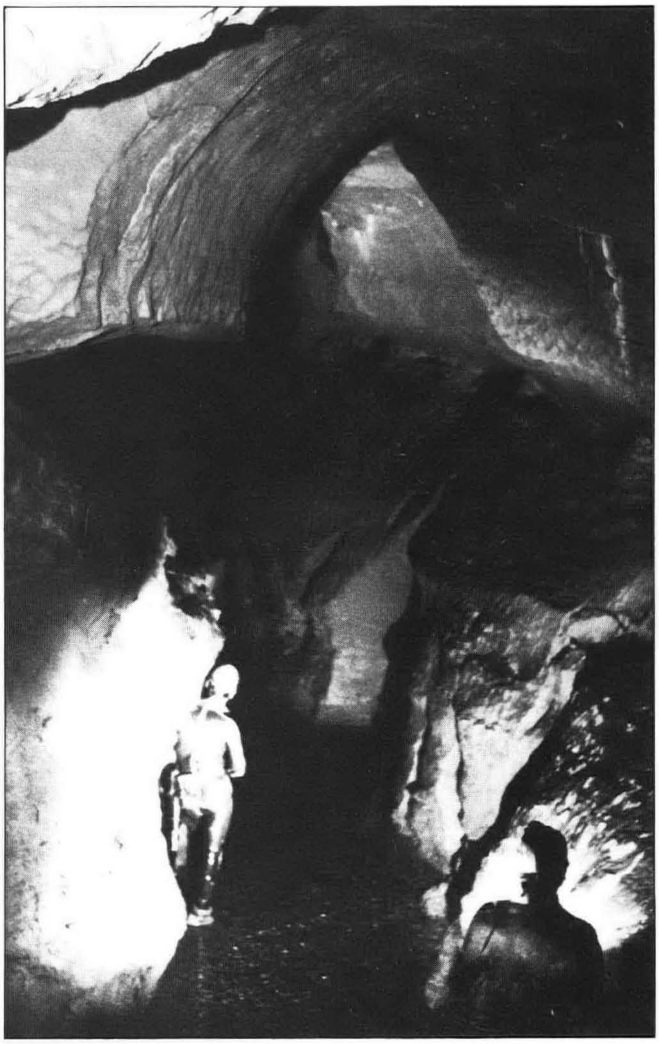
SPEEDWELL CAVERN

The history of the intersection of the extensive natural stream caverns by late 18th century lead miners has been told elsewhere (Rieuwerts and Ford, 1985) and need only be summarized here. A canal tunnel driven south from the foot of the Winnats Pass to intersect several E-W mineral veins first encountered the Bottomless Pit Cavern, some 430 m south of the entrance. This is a large vein-cavity extending some 50 m upwards and 16 m downwards. Clearly of phreatic solution origin, it developed by enlargement from vugs in the calcite-rich Faucet Rake, but this requires both an input opening and an outlet. The input opening is buried under collapse debris and the outlet is beneath the "lake" in the bottom of the Bottomless Pit. This takes overflow water from the canals but the outlet is constricted and flood water soon backs up. An interesting point is that the present water level is some 13 m above the altitude of the final resurgence at Russet Well, so that there must be a vadose stream cave somewhere between, as yet unentered by cavers. The Bottomless Pit Cavern may thus be typical of a fairly early stage in the phreatic enlargement of a primary vein cavity, now partly drained by falling water-tables.

Beyond the Bottomless Pit Cavern, the Far Canal swings more to the southwest and intersects the stream caves in the controlling bedding plane

The main stream passage in Peak Cavern, in this section with a shallow vadose trench and some clastic infill below the phreatic tube.
(Photo: Paul Deakin)

The main stream passage of Speedwell Cavern near the entrance to Cliff Passage: a phreatic tube in the roof and a vadose canyon below.



some 14 m below that of Peak Cavern (Fig.8). Upstream from the Whirlpool junction the main stream passage is a classic phreatic tube in the roof with a vadose trench up to 6 m deep. A blocked aven developed through pipe vein cavities appears to have once led to high level passages similar to those in Far Sump Extension in Peak Cavern, but these are now inaccessible. The upstream end, to the west, is something of a surprise - turning a corner the roof suddenly comes down to water level, and the floor drops into a flooded pothole. Developed in a minor mineralized joint this has been dived to a depth of 36m and continues as a large submerged vein-cavity system explored for about 100m southwestwards so far. This Main Rising is the main outlet for the streams draining off Rushup Edge into the swallet caves (Fig. 2).

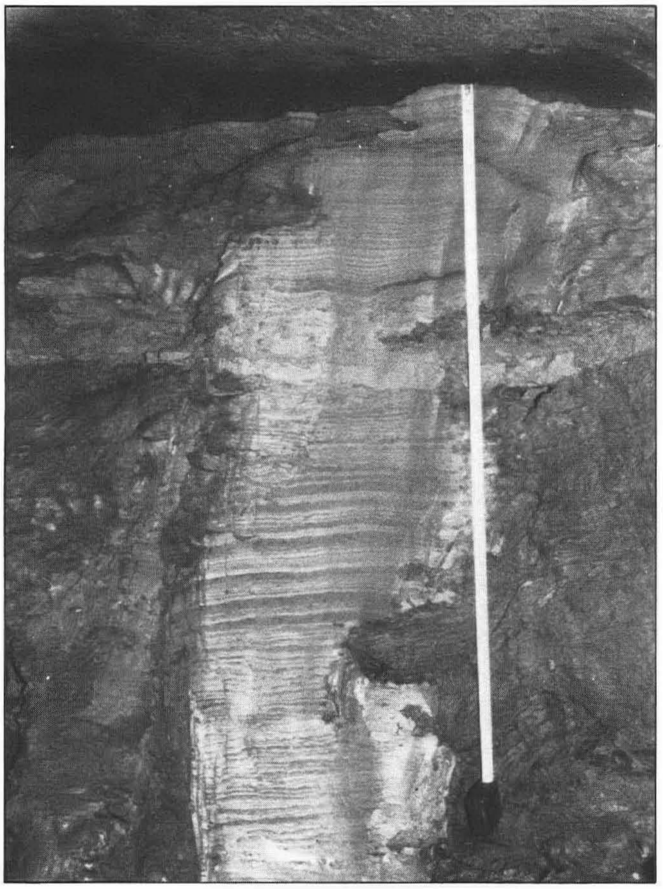
Nearby two branch passages both lead along tubes with minor vadose trenches into vein or fault cavities. Cliff Cavern rise spectacularly in joint intersections for at least 50 m, whilst the Bathing Pool is flooded and has been dived to 18 m. Both discharge only minor streams.

The passage to Cliff Cavern intersects two old phreatic tubes completely full of laminated (varved?) silts and clays in one case resting on old flowstone. Palaeomagnetic data here may give a date on the fill, which must post-date the flowstone and this in turn must post-date draining the passage.

The main Speedwell tributary is the Whirlpool Passage, some 350 m long. Again, it is a classic phreatic tube with vadose trench, rarely more than 2 m high, partly developed along pipe-vein cavities up to 2m in diameter. The stream rises from a flooded pothole and an underwater extension has been followed for some 200 m at only a few metres depth, with avens rising into vein or fault cavities. This is also fed with water from the swallets, particularly Giant's Hole, and in medium to high flood levels resurges with an intermittent action of pulses every few minutes. Though the Whirlpool Rising is 8 m higher than Main Rising both receive water from the same sources by an as yet unknown course. Studies of the variations of flow from both over the years suggest that flood waters can move sandbanks around and temporarily block one or other system as a result of flooding in the inaccessible passages.

Downstream of the Bung Hole (and Miners' Dam), the stream flows in a continuation of the phreatic tube plus vadose trench, by-passing a vein cavity, the 75 m high Block Hall, and traversing Rift Cavern along a part of New Rake. Vadose trenching in the further reaches is less well developed, at times being only a series of swirl holes in the stream floor. Beyond the Treasury Connection, the last 150 m before the Downstream Sump is simply a wide phreatic tube along the controlling bedding plane. Like the streamway in Peak Cavern, there has been no vadose incision beneath a point some 16 m above final sump level. The water flows directly to both Russet Well and Slop Moll, being joined by Bottomless Pit water en route. Russet Well is on the east side of Peak Cavern gorge whilst the Speedwell Cavern is to the west so that the drainage passes under Peakshole Water in a U-tube fashion via vein cavities, Russet Well having been explored to a depth of 27 m by divers (Fig. 10).

In flood conditions water backs up in the Bung Hole series and rises through the Treasury Connection to overflow into Upper Gallery in Peak Cavern, thence discharging via the Peak Cavern stream to the Peak resurgence.



A 0.5 metre section of laminated silts and clays in an old phreatic tube near Cliff Cavern probably representing repeated inflows of derived loess from the surface some 200 metres above Speedwell Cavern.

The miners evidently broke into caverns above their Bung Hole workings though the route is now blocked with fallen debris. Amongst it a sample from a large block of stalagmite yielded a uranium-series date of 96,000 years B.P., i.e. early Devensian or late Ipswichian.

A significant part of Speedwell Cavern is Pilkington's Cavern. Discovered during sinking a shaft on Faucet Rake some 200 m south of the Winnats Pass, (Pilkington 1789) and only recently re-entered (owing to the shaft having been filled in; Shaw, 1983a and b), a series of natural vein cavity-type caverns led downwards via five vertical pitches to a long narrow winding tube plus trench passage, apparently in the same bedding plane as that which controlled Peak Cavern. A further vertical drop of 14 m entered a series of small tube-plus-trench passages tributary to the main Speedwell stream way. The significance of this tributary system of passages is that water must have gone underground under phreatic conditions to feed a bedding plane and tube system and associated vein cavities at an early stage, before water tables had fallen to anywhere near their present level. Subsequently there was sufficient input for small vadose trenches to develop. But as the input point for these was only 200 m south of the gorge of the Winnats Pass, it is difficult to conceive of the Pass being in existence when water was being engulfed into Pilkington's Cavern. This has implications for the stages in stripping back the Millstone Grit cover, and for the development of the Winnats Pass (Ford, 1987).

The Speedwell Cavern's stream caves thus provide evidence for the early phreatic development of vein cavities, later utilization of a controlling bedding plane, a silt-and-clay fill stage and vadose trenching gradually draining the vein cavities. As there are few speleothems, few dates are available, except in Pilkington's Cavern, where dates of 63,000; 91,000 and 115,000 B.P. indicate stalagmite growth in Ipswichian, early and mid Devension times. As Speedwell's main stream cave is fed by water rising from a deep phreatic system it may also be regarded as the equivalent of an extended crest section of a phreatic loop, perhaps comparable with stage 3 of Ford & Ewers (1978) classification. In the Downstream Sump to Russet Well section it re-enters the phreatic zone.

SURFACE FEATURES

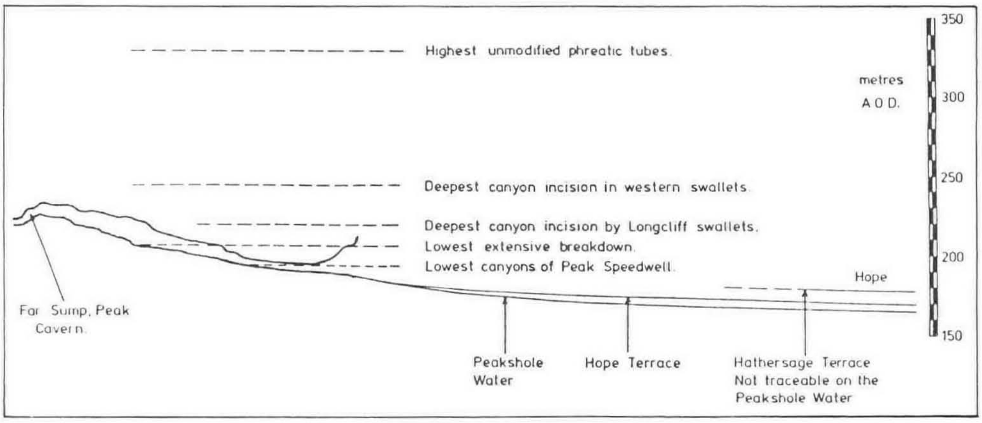
No detailed geomorphological or morphochronological study of the Castleton area has yet been published, so that only a review of some important observations can be attempted here, with emphasis on those bearing on the evolution of the caves.

The Rushup Valley is floored with a solifluction sheet of gravels, sands and silts washed off Rushup Edge (Fig.6.). At its maximum this sheet covered the sites of the present swallet caves (Johnson 1967), and with the ground being frozen under periglacial conditions drainage must have been by a surface stream. The only possible outlet is the now dry valley system of Perry Dale. With its continuations of Dam Dale, Hay Dale and Monks Dale, this drained to the Wye Valley at Millers Dale, and the thalweg is largely graded to the present level of the River Wye though with interruptions due to the presence of igneous rocks. In turn the River Wye near Bakewell has been incised some 50 metres below a terrace (the Hathersage Terrace according to Waters & Johnson, 1958) covered with several metres of boulder clay, generally thought to be of Wolstonian Age. The implication here is that the Perry Dale dry valley system has been incised to its present depth since the Wolstonian glaciation (Warwick 1964), and that the incision could have been as much as 50 m below a Hoxnian valley floor. The question arises: has there been enough run-off in late Wolstonian deglaciation, the Ipswichian interglacial and the periglacial effects of the Devensian to account for this amount of incision? And does this fit with the preceding analysis of the caves' morphology? Or, could the incision have been started in earlier Pleistocene phases and simply been rejuvenated in Wolstonian to Devensian times? Was it a dry valley, as today, in each of the interglacials?

The dry valley of Conies Dale is a tributary of Perry Dale and must be taken into account as well. Its fresh appearance suggests that it could have been incised or trimmed from previous incision in the same way as Perry Dale. But on the plateau above Conies Dale, there is a loessic soil cover of a metre or so of yellowish silty clay, seen in temporary excavations in the Portway "Gravel" Spar pits (SK 128 811) and in on an old lead mine working close to the summit of Eldon Hill. The age of this loessic clay is uncertain. Since it does not blanket Perry Dale or Conies Dale, it could be regarded as Devensian in age, with periglacial meltwater run-off keeping those dry valleys clear. Or, it could be regarded as older, i.e. Wolstonian, or even Anglian, with the dry valley network incised through a loessic blanket as well as into limestone. If the latter view is correct it is surprising that the loessic

The Main Rising of Speedwell Cavern: water draining from the Rushup Valley swallets rises from a 30m deep pothole in a minor mineral vein - a still evoloving vein cavity section of the hydrological system.

Figure 9. Diagrammatic profiles of the Peak Cavern and Speedwell stream passages to show their possible relationships to the Hathersage and Hope terraces (reproduced from J.S. Beck, 1980, with permission).



cover has survived so well; and since the Wolstonian and Anglian glacial limits are far to the south in Middlesex why is there no till associated with those ice sheets around Castleton as there is around Stony Middleton and Bakewell, some 12 km to the south? The last difficulty can be "explained away" by observing that there are traces of till with a few striated erratics in fissures in the Hope Cement Works Quarry, possibly as relics of a more extensive sheet, and also that it is likely that the Castleton area, lying in the lee of Kinderscout and the main Pennine Range, was by-passed by the main ice streams anyway, leaving more or less stagnant ice over Castleton, with little resultant till. A late Wolstonian ice tongue standing in Rushup Valley with its margin close to Windy Knoll offers a reasonable explanation for the vadose canyon passages in Blue John Cavern and the excavation of Winnats Pass (Ford, 1987).

The western end of Hope Valley is bordered by the fore-reef limestones of Cowlow, Long Cliff and Treak Cliff on one side and by the sandstones of the lower Millstone Grit on the other. Its floor is in early Namurian shales covered by a solifluction sheet through which the present day streams are incised by a few metres. The spectacular landslip of Mam Tor seems to have no relevance to the cave systems, though of course an ancestral Mam Tor may have had earlier landslips off its flanks, e.g. down the front of Treak Cliff. The floor was interpreted by Waters & Johnson (1958) as being the upstream continuation of the Hathersage Terrace, of "Older Pleistocene" date. Burek (1977) and Ford et al. (1983) suggested that this was probably of Hoxnian age (and covered by Wolstonian till at Bakewell), but the incision noted at Bakewell has no comparable incision in the Hope Valley owing to its knick point having been held up by the thick Kinderscout Grit near Grindleford. Minor incision in the Ipswichian yielded the Hope Terrace only some 10m below the Hathersage terrace in the lower end of the Hope Valley, but the masking sheets of solifluction deposits in the head of the valley mean that two terraces cannot be defined at Castleton itself, and only the relative extents and altitudes of vadose canyons and phreatic tubes in the caves suggest any distinction.

Slicing through the reef limestone belt and separating the main part of the limestone massif with its contained Speedwell and Peak Caverns from Treak Cliff with its caves partly developed in mineral veins is the Winnats Pass. This steep, deep gorge presents something of an enigma concerning its origin and consequently its relationship to the evolution of the caves. Various ideas have been proposed for its origin and the evidence and implications have been analysed by the writer (Ford, 1987).

In short, the Winnats Pass is a culmination of superimposed developmental stages: a late Asbian to early Brigantian inter-reef channel was deepened during the pre-Namurian palaeokarstic phase to yield a cross-reef-belt valley some tens of metres deep at the most. It was then filled with shale and appears to have been still infilled at the time of development of Pilkington's Cavern, probably pre-Wolstonian. It appears to have been cleared of shale and graded to Hope Valley floor as a result of ice-margin run-off in late Wolstonian times, when the ice margin stood near Windy Knoll. Apparently a dry valley during the Ipswichian interglacial, it was trimmed during the

Peak Cavern Resurgence in the gorge outside Peak Cavern seen in flood conditions. Water rises from a still-active phreatic tube.

Mid Carboniferous:	Limited palaeokarstic development; shallow Winnats channel.
Late Carboniferous, Permian Triassic:	Mineralization accompanying faulting hydrothermal enlargement of palaeokarstic caves, mineral vugs, mineral linings and fill under cover of partly eroded Upper Carboniferous.
Mesozoic:	No evidence
Mid-Tertiary to early Pleistocene:	Uplift and breaching of Upper Carboniferous cover; establishment of slow vein cavity deep phreatic circulation and solution.
Early Pleistocene:	Initiation of early phreatic tube drainage via bedding planes into vein cavity system.
Cromerian Interglacial:	Possible swallets at Windy Knoll and Winnats Head, and perhaps Pilkington's Cavern. No Perry Dale; Winnats still a shallow channel filled with shale.
Anglian Glaciation:	Possibly some stripping back of shale cover and initiation of Rushup Valley; abandonment of Winnats Head and Windy Knoll swallets? Some development of Hope Valley at high levels?
Hoxnian Interglacial:	Deepening of Hope Valley to Hathersage Terrace level; initiation of Peak Cavern vauclusian spring; Treak Cliff Cavern swallet off former extent of Mam Tor? Speedwell and Peak Cavern phreatic tubes operative. Perry Dale shallow valley draining Rushup Valley roughly along swallet line. Some deepening of Winnats Pass. Vadose canyon phase in caves initiated.
Wolstonian Glaciation: (largely under waxing and waning phases)	Headward incision of Hope Valley (to Hope Terrace level?) Abandonment of Treak Cliff Cavern as a swallet. Deepening of Winnats Pass under peri-glacial run-off conditions. Some deepening of Perry Dale with extensive excavation of Rushup Valley. Vadose canyons further developed. Some clay fills derived from loess. Lip of Peak Cavern vauclusian spring lowered.
Ipswichian Interglacial:	Lower phreatic ends of Peak and Speedwell Caverns partly drained as lip of vauclusian spring is cut away. Speleothem deposition widespread in caves. Cave systems largely in their present form.
Early Devensian Glaciation:	No ice in immediate area, but much evidence of periglacial conditions. Partial filling of Peak Cavern gorge with frost scree blocked cave drainage. Loess washed in to pseudophreatic caves to yield clay fill. Dry valleys probably partly filled with scree and loess. Snow melt-water run-off. Solifluction deposits in Rushup Valley block swallets. Winnats and other dry valleys trimmed by limited snow-melt run-off.
Chelford Interstadial:	Partial drainage of caves again, renewed speleothem growth.
Late Devensian:	Progressive removal of fill from swallets, vadose canyons and Peak Cavern gorge. Incision of Peakshole Water trench into solifluction sheet.
Post-glacial:	Further removal of fills, dry valleys abandoned by drainage and swallets fully functional. Renewed speleothem deposition.

Table 3 A suggested sequence of events in the development of the Castleton Cave systems (partly based on Beck, 1980, and on Ford, Gascoyne & Beck, 1983)

peri-glacial episodes of the Devensian and is a dry valley once more today.

The above observations on the surface morphology indicate which features must be taken into account in any attempt to understand the evolution of the underground drainage but until a comprehensive geomorphological analysis is available the full significance remains uncertain.

DISCUSSION

It is pertinent now to ask how far the observations of surface and underground features support the sequence of events outlined at the start of this review. In general they do, but the shortage of absolute dates on speleothems and the uncertainties of the timing of the valley incision and terraces mean that only a tentative sequence can be presented at this stage (Table 3).

The mid-Carboniferous erosion phase certainly produced a karstic landscape on Treak Cliff and Windy Knoll and may have involved a shallow incision of the Winnats Pass by a few metres. Of any caves developed at this time, there are no recognizable relics except the Blue John-lined mineralization vugs of Treak Cliff. Some of these may have channelled water off the former extent of the Millstone Grit cover in earlier Pleistocene times into both Blue John and Treak Cliff Caverns, but their subsequent draining by falling base levels means that they cannot be related to the other cave networks.

Folding, faulting the mineralization were episodic in end Carboniferous, Permian and Triassic times. Mineral deposition tended to fill underground voids, as with the Blue John deposits, but crystal-lined vugs in the middle of rakes and scrins were almost certainly left open and were thereafter available for slow-moving phreatic waters. The solutional erosion of vein minerals and walls would have been minimal until uplift in the mid-Tertiary orogenic phase and the breaching of the Millstone Grit shale and sandstone cover permitted an increased flow rate with a hydraulic gradient from input to outlet.

No date can be placed on the breaching of the cover rocks but it is likely to have been in Mio-Pliocene times. Once breaching had been established at two points at different altitudes on the vein systems the movement of phreatic water through the mineral vein cavities would have been greatly accelerated and, with increased aggressiveness from run-off from the Millstone Grit, a series of complex U-tubes oriented more or less vertically along the east-west vein system would be the initial stage of speleogenesis.

From the establishment of the deep vein-cavity phreatic drainage to the stripping back of the cover to its present position and the initiation of the swallet drainage is a problem in that there are no dateable deposits on the plateau; also it is a period beyond the limits of the uranium series dating method (350,000 years) and no terrace remnants have been recognised above the Hathersage terrace of probable Hoxnian date in the Castleton area.

The resurgence underground drainage, then as now, was in or close to the entrance of Peak Cavern which must have operated as a vauclusian spring to a valley floor some tens of metres above the present Hope Valley floor, i.e. the spring may have overflowed well above the Hathersage terrace of the valley floor of Hoxnian date. Uranium dates on speleothems indicate that much of the cave system was drained by Ipswichian times, so that the lip of the vauclusian spring must have been cut away before the Ipswichian Hope Terrace, perhaps as a result of Wolstonian melt-water run-off. The steep head of Hope Valley must have been cut during this phase too. The development of the steep valley head had the effect of uncovering Treak Cliff, with an intermediate stage of allogenic flow into Treak Cliff Cavern, and thereby setting the scene for the periglacial run-off excavation of the Winnats Pass, probably largely in post-Hoxnian times.

The corollary of the incision of Hope Valley is that retreat of the shales from the limestone plateau margins across the reef complex seems to have rapid, as no earlier generations of swallets are known.

This sequence of events leads to a scenario of deep phreatic drainage via vein cavities followed by allogenic input into the limestone via the present swallets with drainage following bedding planes and joints into the vein cavities. This means that the limestones away from the veins went through an early bedding-controlled phreatic tube phase, but as soon as vigorous flow was possible, water-tables fell and vadose drainage was established down dip to the nearest vein cavity system.

A phase of infill by derived loess followed, filling many early tube passages apparently before much vadose incision had taken place. In fact, there may have been more than one phase of loessic infill. Re-excavation of the fill and incision into tube floors was effected almost down to present water-table by Ipswichian times, but there was a phase of solifluction infill to parts of Giant's Hole thereafter during early Devensian times. Phases of underground morphological change have been noted in Giant's Hole and P8 swallet, but at present these are of stream routes only, with no absolute dating available in the latter.

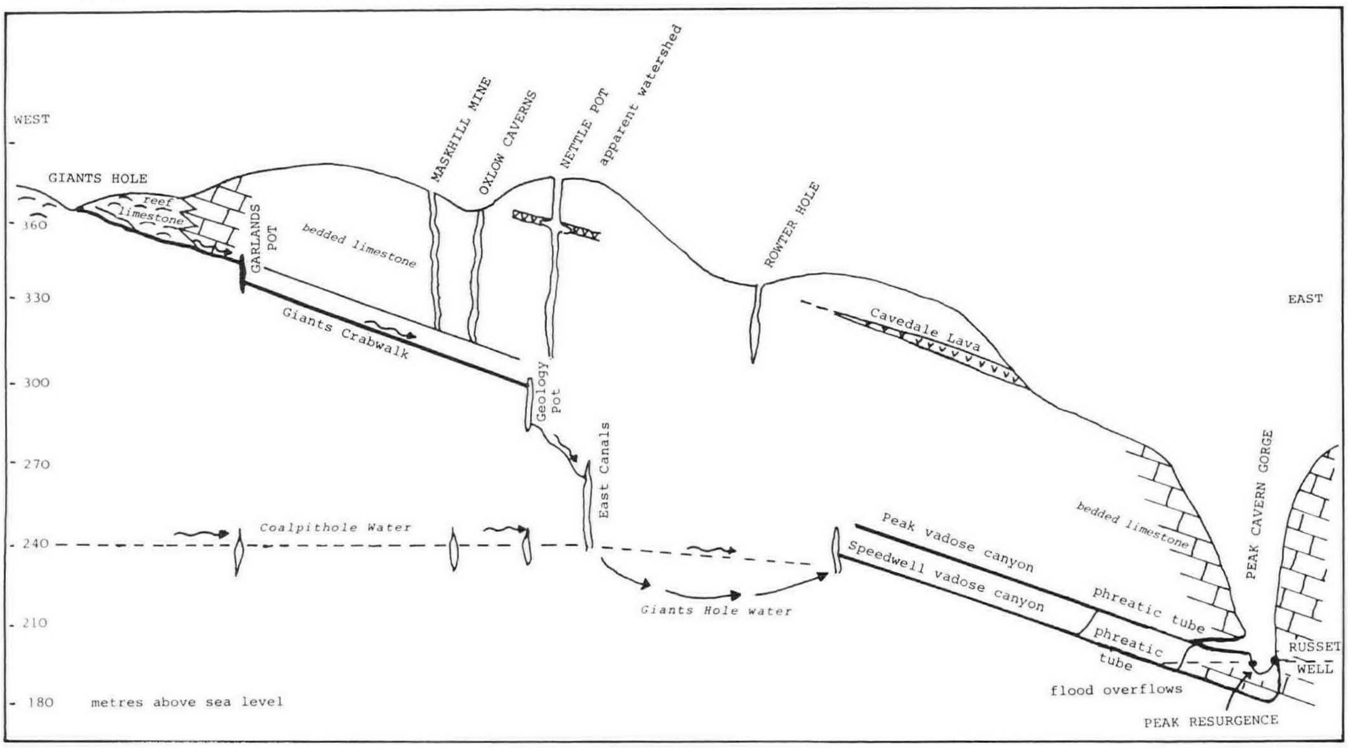
The limestone plateau with its cover of loess is also diversified by a series of shallow dry channels cut into the loess near Hazard Mine and by deep doline-like hollows with solution collapse features, as at Portway "Gravel" Spar pits. The channels clearly represent run-off flowing across loessic sheet in waning periglacial conditions, and they drain into hollows on the line of mineral veins, presumably overlying vein-cavities. In a few cases, as at Thistle Pot and Conies Dale Pot, the channels have cut through the loess cover and revealed the limestone beneath to have potholes going vertically downwards. Choked with boulders these require excavation and Thistle Pot is currently being dug at nearly 20m depth. The nearby Nettle Pot was dug through comparable fill to open at a 50m depth into caverns developed along a thin lava horizon, with vast fault-guided cavities extending below to a final depth of about 160m.

To the east Cavedale is incised into the plateau in much the same fashion as Perry Dale. Its lower reaches are graded into Hope Valley floor, i.e. the Hope terrace, but it appears to have a strong knick point (Knighton, 1975) about halfway. However, this is less likely to be a real knick point than a structural interruption for it occurs just where the thick Cavedale lava outcrops close to the inner margin of the reef limestones. Cavedale lies partly above Peak Cavern but this seems to be coincidental and no genetic connection between them has been proposed. True, there is a small stream in part of Cavedale which sinks on a thin mineral vein and re-appears as the heavy shower in Roger Rain's House beneath, but this seems to be fortuitous and of no genetic significance. Indeed, the Cavedale Lava lies in the limestones over much of the inner part of Peak Cavern precluding percolation reaching the passages 150m below. The wide amphitheatre of lower Cavedale lies directly above the Great Cave of Peak Cavern with only connection being a very narrow fissure, now blocked. Indeed the lack of relationship between Cavedale and Peak Cavern supports the concept that the dale is a young dry valley cut whilst the cave below was frozen.

A periglacial event during the Devensian may have been the final incision of Perry Dale, as a dry valley draining the Rushup Valley to a slightly lower altitude, but taking it into the River Wye catchment. This would have had the effect of accentuated shale-margin retreat at Perryfoot with the consequent development of the morphologically young swallets of Perryfoot Cave and Dr Jackson's Hole. These now feed water into the vein cavity system at Coalpithole Mine whence it resurges via Speedwell Cavern at Russet Well.

The present situation is of immature karstic

Figure 10. Diagrammatic long profile to show the relationship of the Giants Hole swallet to the deep phreatic drainage system, including the flow from the Coalpithole Mine "swallow" to the phreatic and vadose passages of Speedwell and Peak Caverns and to the resurgences in Peak Cavern gorge.



conduit drainage system partly utilizing vein cavities far below the water table, partly in vadose canyons and partly in phreatic tubes, collectively crossing beneath the topographic watershed from the Wye drainage basin into the Derwent's (Fig. 10). Various parts of the drainage system are currently in the bathyphreatic, deep phreatic, and mixed phreatic-cum-water-table-levelled stages of Ford & Ewers (1978). There is a long way to go before the ideal water-table cave from swallet to resurgence is reached.

CONCLUSION

Many years of study of the Castleton cave systems have revealed a complex history of speleogenic development from mid-Carboniferous times to the present. Unlike many karstic drainage systems there are additional factors which have affected both speleogenesis and geomorphological changes. These include the presence of the marginal reef belt of limestones with highly variable dip of bedding planes and widely spaced curved joints; the mineral vein cavity systems deflecting phreatic drainage to great depths; the pre-Namurian unconformity with attendant boulder beds and palaeokarst; and a multiglacial history with both depositional and erosional effects. The lowering of the Hope Valley floor was relatively rapid in pre-Ipswichian times; the Winnats Pass is an overdeepened mid-Carboniferous valley once partly filled with shales and scoured to its present depth by snow-melt run-off.

There is a need for many more speleothem dates to establish a full sequence of cave development, and there is a need for a more detailed geomorphological analysis of Hope Valley itself.

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