Cave Science

The Transactions of the British Cave Research Association

BCRA

Volume 18 Number 3 December 1991

Cave Science

The Transactions of the British Cave Research Association covers all aspects of speleological science, including geology, geomorphology, hydrology, chemistry, physics, archaeology and biology in their application to caves. It also publishes articles on technical matters such as exploration, equipment, diving, surveying, photography and documentation, as well as expedition reports and historical or biographical studies. Papers may be read at meetings held in various parts of Britain, but they may be submitted for publication without being read. Manuscripts should be sent to the Editor, Dr. T. D. Ford, at 21 Elizabeth Drive, Oadby, Leicester LE2 4RD. Intending authors are welcome to contact either the Editor or the Production Editor who will be pleased to advise in any cases of doubt concerning the preparation of manuscripts.

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Cover: A splendid cascade of terraced gour pools in the main passage of the Akiyoshi-do tourist cave in the Akiyoshi Plateau karst at the southern end of Honshu island, Japan. By Akiyoshi-do Museum.

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Cave Science is published three times a year by the British Cave Research Association and is issued free to all paid up members of the Association.
1991 subscription rate to Cave Science is £16.00 per annum (postage paid).
Individual copies, back issues and details of annual subscriptions to Cave Science, and of Association membership, can be obtained from the BCRA General Administrator, 20 Woodland Avenue, Westonzoyland, Bridgwater TA7 0LG.
The Association's permanent address is: BCM BCRA, London WC1N 3XX.

ISSN 0263-760X

CAVE SCIENCE Vol. 18, No. 3, December 1991
Transactions of the British Cave Research Association

Studies at Rats Nest Cave: Potential for an Underground Laboratory in the Canadian Rocky Mountains

C. J. YONGE

Abstract: Rats Nest Cave is a four-kilometer long system on the flanks of the Bow Valley where the latter cuts through the Front Ranges of the Canadian Rockies. The cave was likely part of a mature karstic system draining basal water from the now-absent Bow Valley Glacier. It is a relict phreatic system showing almost no subsequent vadose activity, and contains speleothems throughout its known length. A pit at the entrance contains extensive bone deposits that date from the last glacial retreat.

The concept of the cave as an underground laboratory followed a preliminary survey of the site for the Alberta Government (during which it was declared a Provincial Historic Resource). It is now apparent that the cave can tell us a great deal about the Quaternary history of the region whose glacial chronology is poorly known. Speleothems date from an estimated 750,000 years to the present day, and bone dates span the last 7000 years.

In addition to its Quaternary deposits, the cave also contains bushy-tailed wood rats (hence its name), bats and other smaller fauna. It is also a well visited cave that demands management, and it is currently being considered for educational purposes.

Rats Nest Cave (also known locally as Grotto) contains more than 4 km of known passageways (figure 1), and is formed within Grotto Mountain lying to the East of Canmore (site for the Nordic events during the 1988 winter Olympiad; figures 2 and 3).

The cave is unique to the Canadian Rockies in that it is below treeline and highly accessible (1 km from the highway). It can be reached and entered at any time of the year, being neither threatened en route to the entrance by heavy snows nor inundated with spring melt-water inside (to mention the worst hazards likely to be encountered).

The cave system is currently the eighth longest in Canada, but the known passages hint at a much larger complex related to the now extinct Bow glacier. The cave is a fossil phreatic system with its entrance in a small canyon 250 m above the Bow River. The legacy of this abandonment is an accessible cave containing a 2 m thick bone bed of postglacial origin in a 15 m pit at the entrance, and copious mineral and clastic Quaternary deposits throughout its length.

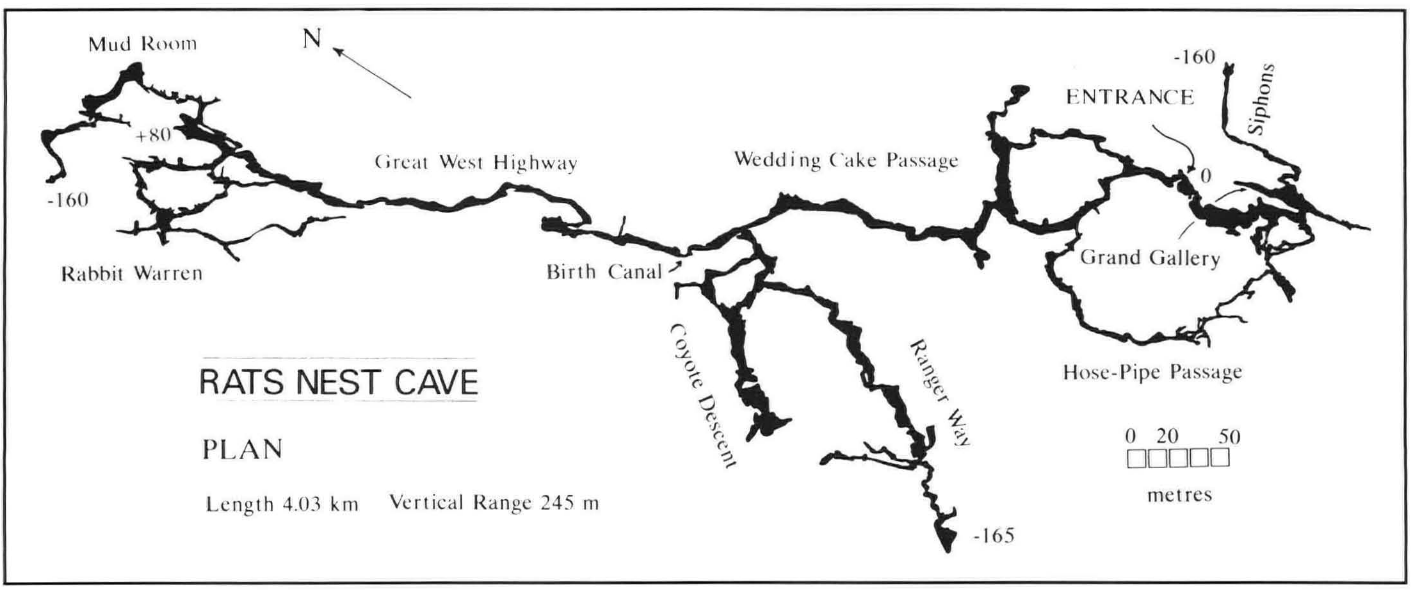
The cave has been known about for at least 2000 years judging by just two human artifacts recovered from the Bone Bed. However, most of the activity in the cave has been recent, principally visits by local mountaineers who referred to the cave as "Grotto", and by the Alberta Speleological Association (ASS), who explored most of the cave and dubbed it Rats Nest Cave after the bushy-tailed wood rats (or pack rats) that live there. Grotto comes from the name of the mountain in which the cave system lies. However, Grotto Mountain was not named after the cave, but for the many holes on its south flank above Bow Valley which were seen in the early 1900s by Europeans travelling through the area (as yet, none of these other caves have been found to be extensive). In any event, Rats Nest Cave cannot be seen from the Bow Valley.

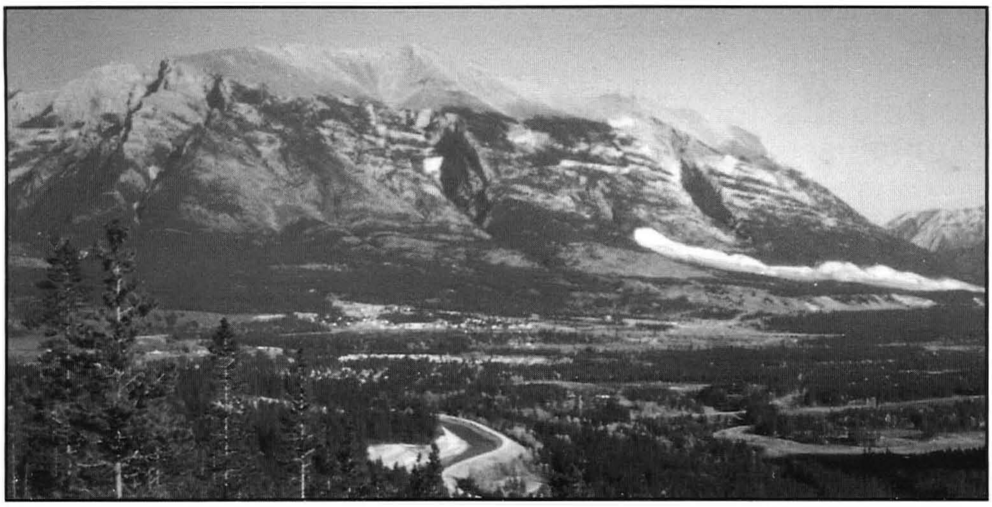
Early in the 1970s, the ASS gained access to the main part of the cave by pulling out a pack rat nest from a side lead at the top of the entrance shaft. The latter was plugged but was later dug out. Exploration continued to the Grand Gallery and Grotto, and arduous trips as far as the Wedding Cake via the Hose Pipe Passage (figure 1). The Hose Pipe Passage is narrow, made all the more miserable by a low duck halfway along its length, and is in marked contrast to the beauty of the Wedding Cake Passage which follows it. The ASS also conducted a number of dives through the Siphon Series stopping finally at Sump Four.

During the ASS explorations, and particularly after the entrance pit was dug out, people began visiting the cave in greater numbers despite the ASS ethic of keeping it secret. Visits even included guided tours. Since none of this was formally documented, it is hard to know exactly what was done. The first part of the Ranger Way was however explored by staff from the adjacent Bow Valley Provincial Park. The last phase of exploration has been completed during the period of work described now in this paper. Here the Birth Canal was dug out to give access to 1.5 km of passage beyond, and the Ranger Way was extended. These last two forays more than doubled the length of the cave to its present 4 km.

The study came about because of concern for the cave. Increased visitation over the years has degraded the cave, including the removal of some speleothems, and industrial leases over about 20% of the cave system have threatened it with quarrying. The cave has formed within a very pure carbonate band that is highly prized by the limestone industry. To be fair to the multi-national company involved (Continental Lime Limited), they have fully supported protection of the cave. The culmination of the inventory study and other lobbying has been to protect the cave, and one square mile around under Alberta Culture's

Figure 1. Rats Nest Cave.





Southern flank of Grotto Mountain (2667 m). The cave entrance is in a valley close to the right (eastward) skyline just above the quarry face. The town of Canmore in the Bow Valley is in the foreground. (Photo: C. Yonge).

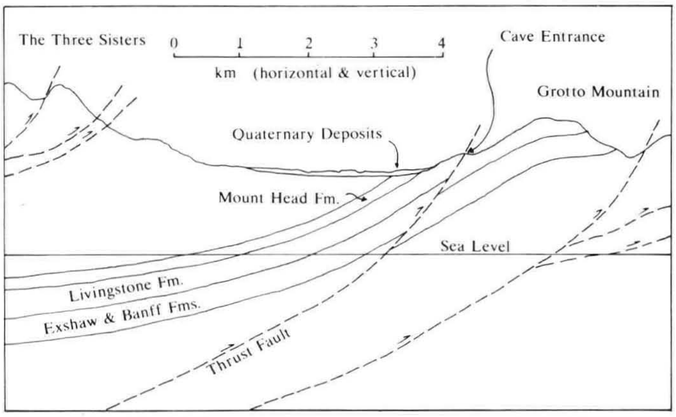


Figure 2. Location of Rats Nest Cave on Grotto Mountain.

Provincial Historic Resources Act. Alberta Culture fully supports the work on the cave, an important basis for securing the cave as an underground laboratory for both research and educational purposes.

What follows is an account of the Rats Nest Cave Project so far: of what is known of the cave, what it contains of scientific value, and where work might be directed in the future.

ORIGIN OF THE CAVE

Geological Setting

The entrance to Rats Nest Cave is situated in a small canyon on the south-east flank of Grotto Mountain (2670 m; figure 2). The cave is contained in the Livingstone Formation of Mississippian age (320 to 369 Ma) which forms the southern aspect of the mountain (figure 3). The rock ranges from a light grey skeletal calcarenite and calcarenitic limestone through to a cherty limestone to dolomite (good exposures of the skeletal calcarenite can be seen in Ranger Way, and cherty limestone in the Rabbit Warren). The Livingstone Formation is underlain by the Exshaw and Banff Formations and overlain by the Mount Head Formation. These sandwiching units contain less pure limestone than the Livingstone composed as they are of more argillaceous limestones or silty dolomites (Geological Survey of Canada, 1959). The Livingstone Formation therefore acts as the speleogenic unit, being more readily soluble. Lapping the Livingstone outcrops are the Quaternary tills of the Bow Valley which form benches along its flanks. Most of the cave system lies above, but close to the bench levels, suggestive of its cogenesis with the Bow Valley Glaciation.

The cave appears to have developed along a thrust fault that has been mapped south-eastwards into the Bow Valley where it passes under the Quaternary bench tills. However, the fault may be illusory, as it is hard to distinguish it from the major beddings in the area that broadly form a monocline down-dipping from the northeast to southwest. Dips in the cave range from 20° in the upper passageways to 60° in the lower sections, roughly mimicking beds exposed by quarrying on the mountain. Thrusting commonly occurs along bedding partings in the eastern Rockies, and the few slickensides in the cave make the distinction between low-angle thrust faults and bedding planes difficult. Nevertheless, other thrust faults that run in echelon to the Grotto Mountain thrust have been mapped with more certainty. These extend from Cougar Creek stepping northwards up the Fairholme Range with their upthrust to the southeast.

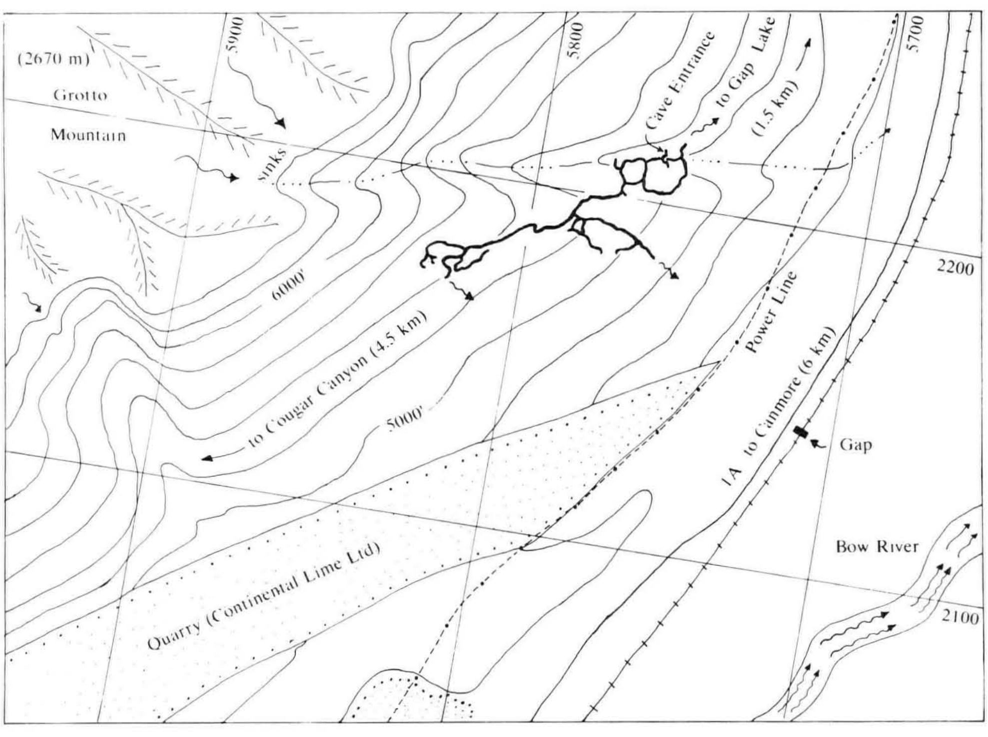


Figure 3. Rats Nest Cave in relation to the Bow Valley.

Speleogenesis

The bedding/fault feature along which the cave has formed could have provided a hydraulic route for water entering Grotto Mountain at its northwest end and reappearing somewhere on the southeast flank of the mountain. The recharge location corresponds to where the Bow Valley, turning eastwards, breaks through the Fairholme Range. The major valleys in the Rocky Mountains (e.g. Athabasca, Bow and Old Man rivers) were initiated during the Miocene 6 to 12 million years ago (Gadd, 1986), thereby giving caves considerable time to form. Ford *et al* (1981), using speleothem dates, have estimated that present ridge lines in the Canadian Rockies were at the level of valley floors at this time (valley down-cutting rates of between 0.15 to 0.50 m/ka). Although the "protocave" may have formed in this period, the principal phase of development, as with a number of Rockies caves, seems to be associated with the Quaternary glaciations (eg. Castleguard Cave under the Columbia Icefields; Smart, 1983, and Porcupine Cave in the Small River area; Yonge and Lowe, 1984). Lauritzen (1990), in a good review of literature concerning the Tertiary origins of caves, goes on to consider but fails to find Tertiary conduits in Hammarnesgrotta. Other caves in Norway appear to contain Tertiary conduits and these have both dimensions greater than 3 m and are at least 240 m above modern base levels. Rats Nest Cave meets these criteria (noting that valley deepening rates in the Rockies match those of Norway). However, interglacial phreatic conditions can generate 3-4 m diameter cave passages within 50 ka (Ford and Williams, 1989), but Lauritzen, in a detailed modelling of pre-glacial, glacial and interglacial erosion rates of valley deepening and conduit wall retreat, finds that the speleogenesis *in senso stricto* of Hammarnesgrotta commenced at 1.2 Ma, and ended around 320 ka. This period is nicely confirmed by U-series dating of bulk corroded speleothems in the cave. Speleothem dates from 3.8 ka to greater than 766 ka (the latter also corroded calcite) from Rats Nest cave are consistent with speleogenesis during the Quaternary glacial cycles, as are passage dimensions that are around 3 m in the main portions of the cave.

The cave appears therefore to be mature karst system, and as discussed is an essentially relict feature. It is noteworthy that relict caves tend to exist in the Rockies where major rivers breach the mountain ranges; active springs may then be found at valley level below them (e.g. Disaster Point cave on the Athabasca River, Wapiabi Cave on Chungo Creek and Eagle Cave with Crowsnest Spring in the Crowsnest Pass; Thompson, 1976). Such hanging, truncated systems of principally phreatic tubes appear to be related to glaciations. According to Ford and Williams (1989) and Ford (1983), ice caps superimposed on a karst aquifer can enhance karstification by increasing the hydraulic head. A good example of the raising of a piezometric surface due to the presence of glaciers may be seen in the phreatic components of Porcupine Cave (Yonge and Lowe, 1984). Major valley breaches of mountain barriers would provide an outlet for subterranean glacial water by unloading the strata and, with subsequent down-cutting of valleys and glacial retreat, ground water would follow lower routes to springs at present valley levels.

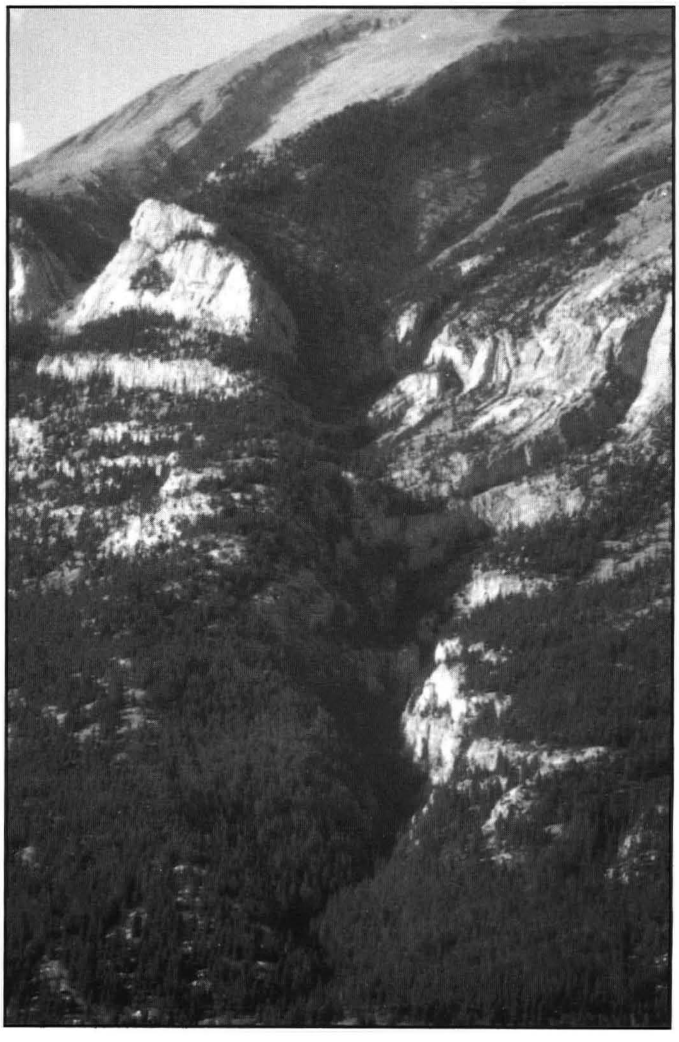
Found so far, the phreatic passages in Rats Nest Cave show very little vadose development. Classic vadose features such as stream-derived shafts and canyons are absent. Canyon and shaft-like forms such as the 30 m high aven in the Grand Gallery and the 50 m high fissure between sumps 3 and 4 appear to be phreatic enhancements of prominent joints, possibly by mixing corrosion (Plummer *et al.*, 1979; Bögli, 1980); vadose entrenchments with the corresponding graded flow paths are absent.

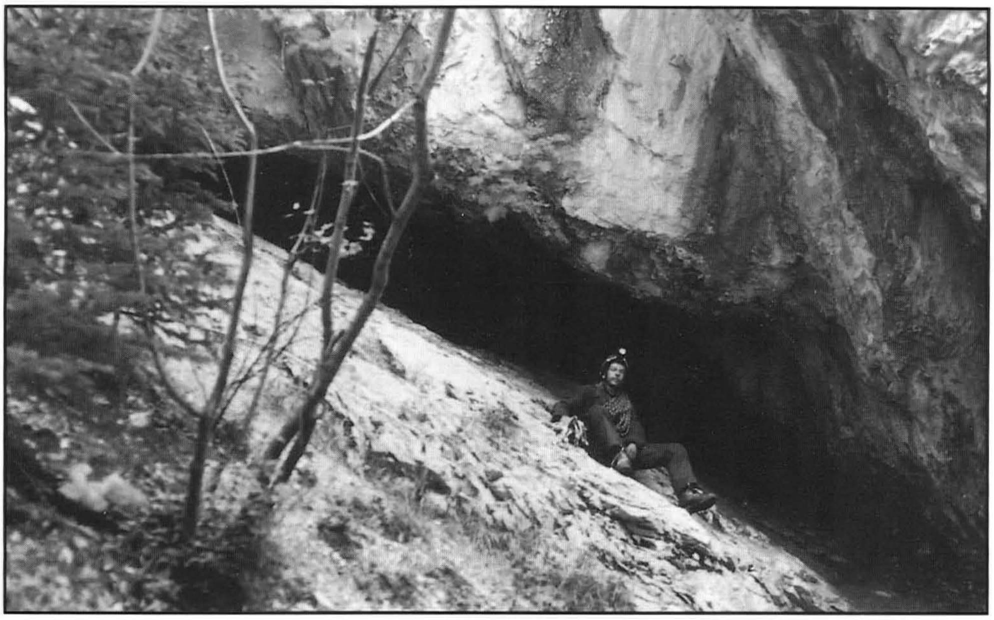
Some sizable entrenchment has occurred above the Slimy Climb in the Great West Highway where an upper siphon has drained to a lower one, and the scale of the entrenchment suggests that this went on for a long time. Otherwise vadose features are minor such as the entrenchment at the end of Ranger Way which has developed from an underfit stream similar to those seen in the cave today. Entrenching of upper segments of phreatic loops during piezometric lowering has been noted in Castleguard Cave where drainage levels are linked to the extent of ice cover on the overlying Columbia Glacier (Ford and Ewers, 1978). It therefore seems likely that during punctuated retreats of the Bow glacier, the cave was rapidly dewatered leaving the phreatic conduits unmodified by vadose stream action.

Rats Nest Cave is a bathyphreatic system with water having lifted at least 150 m through a series of lifting chimneys, to rise 80 m above the present entrance at the northwest end of the cave (figure 1). Deep groundwater circulation is very common in the Rockies because of high regional dips (e.g. Banff Hot Springs

Solutional scallops at the −150 m level of a lifting system in the northwest end of the cave.

Grotto Mountain viewed from the southeast. The cave entrance is below the sunlit outcrop low down in the canyon. (This and all other photos by Dave Thomson).





Entrance of Rats Nest Cave.

A 20 m lifting chimney along a vertical joint en route to the Grand Gallery.

25 km to the east boasts circulation to a depth of 2 km; Gadd, 1986). It is unlikely that the entrance was the only outlet (scalloping on a slab just outside the entrance shows that it has been a spring). Higher entrances may well yet be located that are associated with older valley levels or with constrictions in the system due to till-mantled springs for example. One possible candidate is being excavated 100 m above the entrance.

The deep phreatic flow under a substantial head was quite slow, 1 to 5 cm/s, according to scallops up to 0.5 m across (e.g. White, 1988). This suggests flow rates in the cave of up to 0.5 m^3/s in the largest passages, which is probably a conservative estimate because the cave is made up of parallel routes confined essentially to the bedding/thrust feature. Other unknown parallel conduits are likely to exist. Interestingly, Lauritzen (1990) comments on the headward linking of phreatic loops along strike within the dipping, but igneously confined aquifer of Hammarnesgrotta.

It is intriguing to speculate on the true extent of the cave system. Using a model of Bögli (1980) for deep phreatic karst in which lift is related to the input/output distance. The 5 km distance northwest to southeast across Grotto Mountain would suggest a vertical range of 750 m for the cave (245 m presently realized). Worthington (1990) presents a very different model for the Crows Nest Pass hydrological system in southern Alberta and BC, coming up with the relationship: D = 0.08 L sin(A), where D and L are the depth and length of the aquifer system, and A the stratal dip. Using 23° for the average dip, and the current depth of 245 m, an aquifer length of 8 km is obtained for the Rats Nest system; a lower limit that is significantly more than the presumed 5 km. Doubling the cave depth to 500 m, not perhaps unreasonable, places the input 16 km away to the northwest in the Ghost River drainage. This is most interesting since the Bow once drained through this valley system (see *Age dating and glacial periods* below for further discussion). Worthington's model therefore points to large regional flow systems in the Rockies, perhaps of much greater extent than even indicated here. In any event, 4 km of cave have been realized in a straight-line distance of 0.7 km; the complete system therefore could, at a minimum be around 30 km in length. Its scale would certainly match that of Canada's longest cave, Castleguard with 20 km of passage recorded.

Of the cave's present hydrology, two active streams have been found at Sump 4 and at the end of the Pearly Way. These appear to come from seasonal streams that sink in minor draws high on Grotto mountain (figure 2), and they are assumed to connect to the active springs below at the level of the Bow River. One spring which flows very steadily is estimated to be around 0.1 cumecs, otherwise groundwater emerges in Gap Lake to the east in sufficient volume to keep a portion of the lake ice-free. Apart from minor sinks above the cave, karst is not well-developed on Grotto Mountain. Glacial scour has probably obscured or removed karst features leaving only recently developed micro-karren. One feature of glaciokarst is common, perhaps classic here, and that is the prevalence of tributary canyons to the Bow Valley (Grotto Canyon at the east end of Grotto Mountain being a spectacular example). Sweeting (1973) suggests that meltwater flowing on the surface both from glacier and "dead" ice gives rise to conspicuous meltwater gorges. The present cave entrance is located in a canyon, but the canyon is probably not related to the cave. The canyon, like the cave, may have been established along the thrust/bedding weakness thereby intercepting the cave, and forming the present entrance.

ISOTOPE STUDIES OF THE CAVE

Age dating and glacial periods

Both bone collagen and speleothems have been dated from Rats Nest Cave. The carbon-14 dates on bones from the Bone Bed are described later, the uranium-series dates on speleothems are discussed below.

Dates from the cave are important because of the paucity of dates on regional glaciations. Surficial deposits have been

Table 1a. Sample locations, descriptions and uranium series dates of speleothems from Rats Nest Cave

Sample Calgary	Number McMaster	Location	Description	Age +/−	(ka) 1σ
871122	RN87/22	Birth Canal	Calcite floor well laminated dirty base; 38g	6.1	0.8
881015(1)	RN88/15T	Junction to Ranger Way	Top of tight clean stalagmite; 25g used	8.4	0.8
	RN88/15B		Basal flowstone; 30g	—	—
881020	RN88/20	50m north of Slimy Climb	Well laminated calcite floor with detritus at base and top 20g used	123	11
81006II	RN81/6 CAR	Alcove in Grand Gallery	Carapace of stalagmite, hard calcite vuggy; 23g	200	130
	RB/86T		Hard with clay layers; 13g	>350	
	? B			250	?
880220	RN88022T	In rubble in Grand Gallery	Tight, partly translucent calcite from stalagmite; 22g	324	+46−83
	RN88022B		Tight but dirty basal calcite; 26g	>350	
	(Based on (234U/238U) from top date			450)	

Table 1b. Uranium series dates of stalactite 881010 by alpha and mass spectrometry. This sample was found 50 m north of the Slimy Climb in the Great West Highway. It is a stalactite with several hiati showing resolution and clastic interlayering indicative of cyclical flooding (Figure 5).

Sample		230Th/234Th Ages (ka) Alpha Count (1σ)	Mass Spec. (2σ)	234U/238U Age*
V	J (top)			
	J (base)		3.8 0.1**	
Detrital layer d				
IV	H1 (middle)	129 +12−13	180 +24−25	213***
	H1 (base)		157 2**	
Detrital layer c				
III	G2 (top)		116 1**	
	G2 t1	159 +255−126		215***
Detrital layer b				
II	G2 b1	159 +255−126	216 +5−3	
	G2 (base)		212 3**	
Detrital layer a				
I	Core E (top)		692 +?−165	605 +?−304
	E (middle)			669 23
	E (base)			659 21
	D		568	681 22
	C		620 +267−82	766 24
	B		600	745 22
	I (i)	350		
	II (ii)	350		

* Based on an initial 234U/238U activity ratio of 3.0
** Detritally contaminated sample
*** Based on an initial 234U/238U activity of G2 b1

partially removed or completely obliterated by successive glacial advances, and what remains is hard to piece together and often gives ambiguous results. In contrast, the cave has preserved evidence of past climatic events in the form of clastic sediment sequences, bedrock morphologies indicative of changing water tables, flora and faunal remains and the chemical and isotopic composition of speleothems. Four glacial advances have been recognized in the Bow Valley Corridor (Rutter, 1972; Gadd, 1986), and events recorded in the cave appear to relate to these glacial advances.

Although only a few dates are available so far, their range from 3.8 ka back to 766 ka bodes well for the greater quantity of material awaiting analysis. The uranium series dating has been done both in the Geography Department at McMaster University by alpha-counting (Gascoyne *et al.*, 1978), and solid source mass spectrometry (Li *et al.*, 1989). Even at this preliminary stage, the

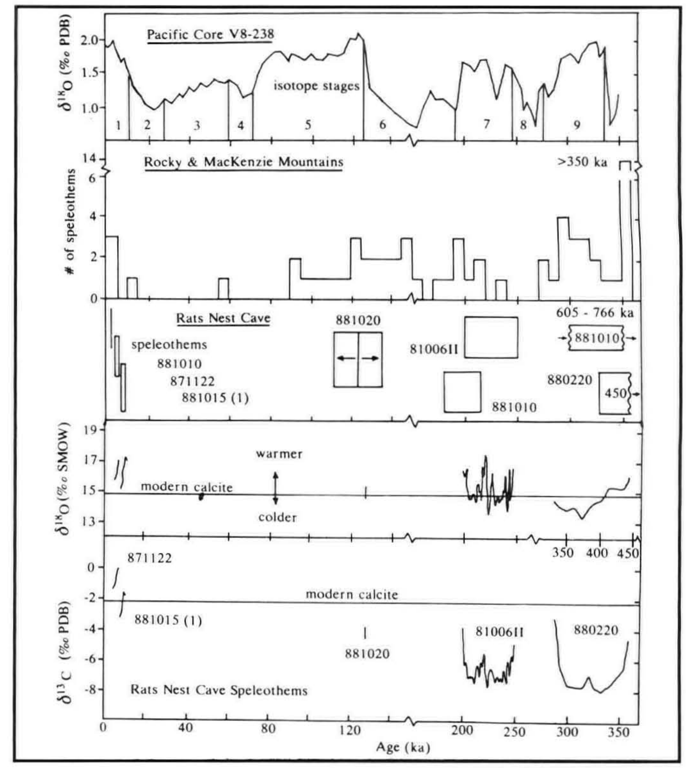


Figure 4. Comparison of Rats Nest Cave speleothem ages and stable isotope ratios with the frequency of speleothem ages from the Rocky and MacKenzie Mountains (Harmon et al., 1977), and the $\delta^{18}O$ variations and isotope stages of the deep-sea foraminiferal core V28-238 (Shackleton and Opdyke, 1973).

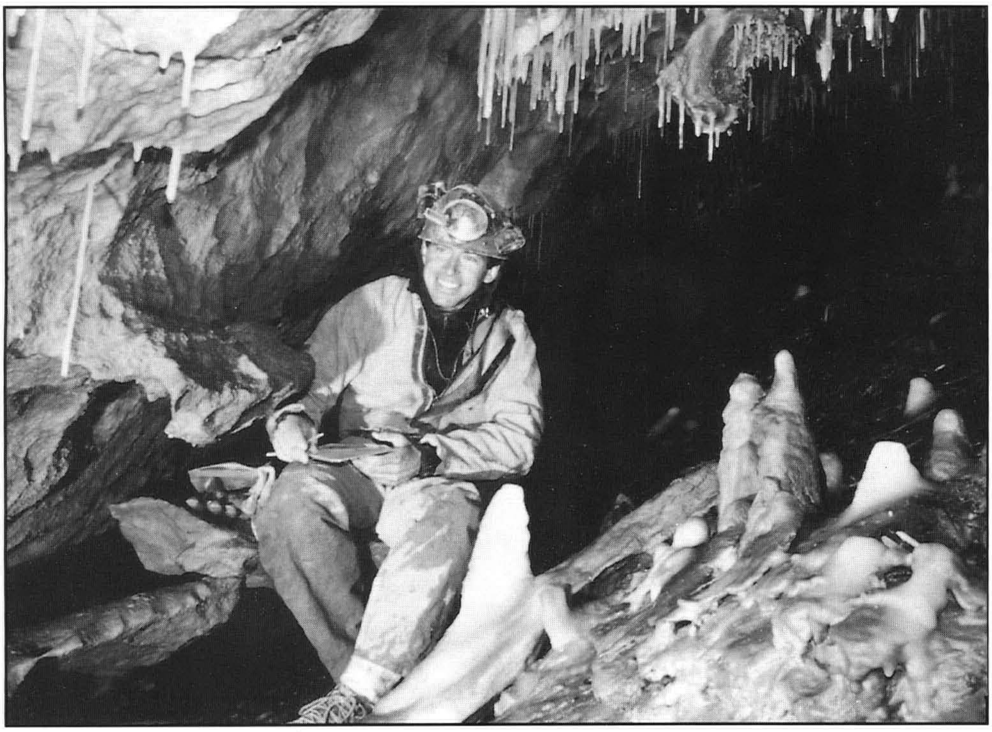
suite of ages matches that of any cave in Canada, and may yet yield the most complete Quaternary record of any site, cave or otherwise, in the region.

Dates greater than 620 ka have been inferred assuming initial $^{234}U/^{238}U$ values calculated from the datable portions of speleothems (Table 1). Accepting the older dates, then tentatively speleothem growth periods range from 766 ka to 605 ka, from 405 ka to 324 ka, from 250 ka to 180 ka, around 123 ka and at intervals during the Holocene from 8.4 ka to the present. These periods of speleothem growth compare favourably to the record obtained from caves in the Canadian Rockies and the McKenzie Mountains (Figure 4), thus supporting the view that speleothems form only during interglacial periods when the ground was not frozen.

The earliest period of speleothem growth, represented by the core of 881010 (766-605 ka), is matched by few local records. Only the Wascana Ash and associated clay deposits (around 600 ka) from the Wascana Creek site near Regina, Saskatchewan coincide with the cave dates and define the Wascana Nonglacial Interval (Fenton, 1984). In continental chronology this early speleothem grew within the Aftonian Interglacial (770-590 ka) between the Nebraskan (earlier) and Kansan Glacials. The earliest Bow Valley glaciation may relate to this time; a poorly defined glacial till overridden by later deposits has been recognised, but it really can only be dated as pre-Early Wisconsin (Rutter, 1972).

Stalagmite 880220 (450-324 ka) can tentatively be correlated to the pre-Illinoian, Yarmouthian interglacial (480-370 ka). But again the Yarmouthian is poorly represented in other records locally except in deposits ascribed to the Redcliff Nonglacial Interval at Medicine Hat, Alberta. Stalagmite 81006II may have formed after the Illinoian Glaciation (also known as the Great Glaciation; 370-240 ka) during the Sangomanian interglacial (240-120 ka) but the dating systematics are problematic. Whereas the base date of 250 ka is concordant with 190 ka for a carapaced overgrowth, the top date is greater than 350 ka.

Returning to stalactite 881010, as discussed, its core predates 605 ka, but later records cyclical flooding events (resolution horizons terminating in a clastic layers) between a series of calcite overgrowths (Figure 5). The overgrowths, bar the outermost of Holocene age, date from 215-180 ka based on the most reliable dates of Table 1. For these more recent dates comparisons are made with the more-detailed, proxy isotope records: specifically, the Hell Hole flowstone (Winograd *et al.*, 1985), marine foraminiferal cores (Shackleton and Opdyke, 1973) and polar/Greenland ice cores (Jouzel *et al.*, 1987). In figure 4, only the foraminiferal record is included although it is complemented by the ice records. Interestingly, the best dated record is the Hell



Looking northwest along strike in the Great West Highway.

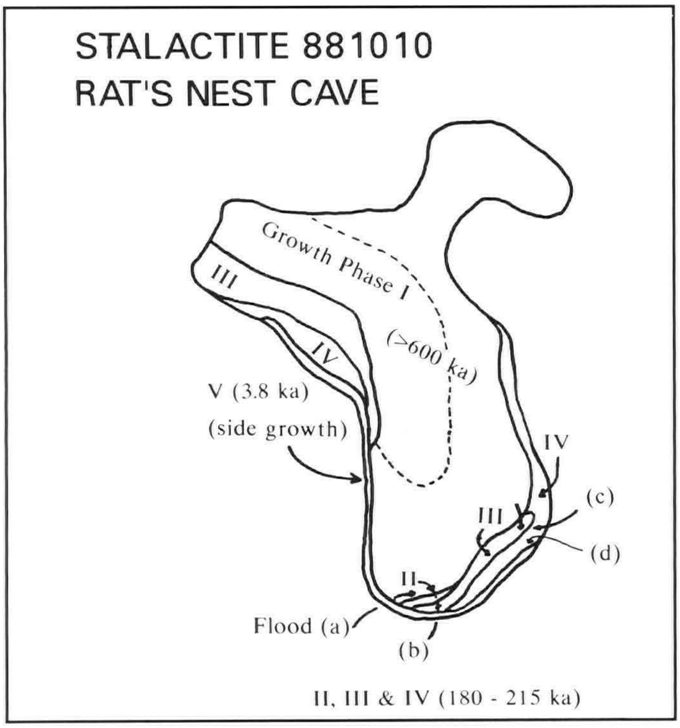


Figure 5. Cross-sectional schematic of stalactite 881010 showing cyclical flooding events a,b,c, and d in between calcite overgrowths I, II, III, IV, and V.

Hole flowstone and this lags the other records significantly enough to challenge conventional wisdom (i.e. Milankovich Hypothesis) on the causes and timings of glacial cycles. More appropriately, the Rats Nest Cave dates may be compared to the well established records since most studies are presently based on these.

Hence, in the ocean record a warm period is encountered from 245 ka (Termination III) to 185 ka (Isotope Stage 7). The warmest event occurs at 215 ka followed by a slight decline in temperature to a further warm peak at 190 ka. The latter events correlate well with the cyclical flooding of 881010 and the overall warming period (245-185 ka) might be represented by 81006II if one accepts only the concordant dates (250-190 ka). What is intriguing is the possibility that the cyclical inundations of 881010 around 200 ka occurred when the Bow was dammed and its flow diverted northwards through Lake Minnewanka and out into the Prairies via the Ghost River. This event is recognised in the glacial sedimentary record but when it occurred is not known (Rutter, 1972).

One of the firmest dates from the cave (123^{+-}11 ka) comes from 881020, a 1-cm thick piece of calcite flooring that overlies rhythmite sediments. This date corresponds precisely to the end of the Illinoian Glacial and is marked by the beginning of isotope stage 5. A recently-acquired date, based on a tephra deposited just after the warming maximum (116^{+-}16 ka), pins the maximum to 123 ka (van den Bogaart *et al.*, 1989). This warming event is also marked by sea levels 5-10 m above those of today, implying a significant melting of the ice caps (Fairbanks and Matthews, 1978). The rhythmites below 881020 may well yield pertinent regional information of events leading up to the warming maximum. In terms of the local glacial chronology, the lowest of the Bow Valley tills may bracket this warming event, but again uncertainty results through the lack of datable materials in the glacial sediments. Other Albertan records fall in this period such as the Watino non-glacial gravels and the Mitchell Bluff Formation (Fenton, 1984).

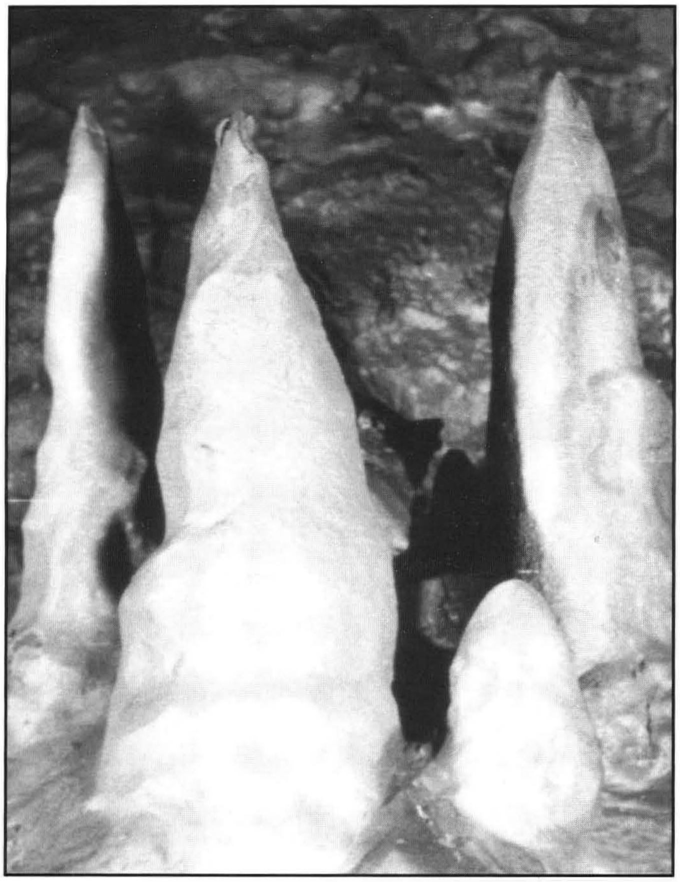
No speleothems apparently grew during the last three glacial advances along the Bow Valley. The nomenclature and best estimates for the advances are: the Bow Valley (75-64 ka; Early Wisconsin), the Canmore (26.6 ka) and the Eisenhower Junction (less than 18.3 ka); the latter two occurring during the Late Wisconsin (Rutter, 1984). The lack of speleothem growth regionally testifies to the intensity of this last glaciation (Ford *et al.*, 1981).

The remaining dates from the cave fall in the Holocene. The oldest of these, 881015, has an upper date of 8.4 ka, but the base date was affected by detrital contamination from the underlying clastics and was lost. This is unfortunate because the deposit may contain information pertinent to Wisconsin deglaciation. Of interest here is the possibility of recording the Younger Dryas, a period of rapid natural temperature change (Fairbanks, 1989). The significance of the one date on 881015 and the date of the next Holecene speleothem (flowstone floor; 871122) of 6.1 ka is that they both fall at the time of the two Holocene Altithermals (Fulton *et al.*, 1984). The youngest radiometric date from the cave is 3.8 ka on 881010. The successive inundations and concommitant resolution of stalactite 881010 around 200 ka caused it fall to the floor where later it received the Holocene overgrowth at 3.8 ka. The cave contains active speleothems and it is hoped that a complete record of the Holocene might be recovered. The principal concern here is the study of recent climate change via stable isotope measurements which is discussed next.

Stable isotopes and the paleoenvironment

Stable isotope ratios were measured on calcite, water and vegetation from the cave. The ratios are expressed in the δ-notation where for example for carbon

$$\delta^{13}C = (R_x/R_s - 1)\ 10^3$$



Redissolved stalagmites in the Great West Highway.

R_x and R_s refer to the ratios $^{13}C/^{12}C$ in the sample and an international standard respectively (Hoefs, 1987). Besides carbon, the ratios D/H (δD) and $^{18}O/^{16}O$ ($\delta^{18}O$) were also measured; carbon and oxygen came from the speleothem calcite and hydrogen and oxygen from water.

The $\delta^{18}O$ speleothem record

As shown in figure 4, $\delta^{18}O$ of ancient calcite fluctuates around the values obtained for modern calcite in the cave. In general this is what would be expected for speleothems deposited during interglacials where climatic conditions broadly resemble those of today's interglacial. As discussed above, the dates suggest that speleothem growth indeed did take place during the interglacials. Thus far, it is difficult to separate the $\delta^{18}O$ data from background in some speleothems (only slightly smaller variations being found along individual growth layers in both 81006II and 880220). With a further 26 speleothems awaiting analysis, some may better satisfy the criteria established by Hendy (1971) for calcite having grown in thermodynamic equilibrium with its host seepage water. Nonetheless, one can perhaps glean the following information, at least from one of these deposits. A significantly low trough occurs in the record of 880220 (450-324 ka). Accepting its insecure base date, a cooling of the climate during the Yarmouthian interglacial may be indicated, terminating just prior to isotope stage 9 in the Pacific Core record. The O-18 data for 881020 are taken from a single layer and the spread is relatively small and straddles the modern calcite line. The foraminiferal record above indicates that the 123 ka date for 881020 is the last time that temperatures were similar to those of today, thus concurring with the speleothem isotope record such as it is.

The Holocene speleothems analysed exhibit a similar equilibrium to 881020, and some conclusions can be drawn from the isotope data. Dating places 881015(1) and 871122 at the first and second Holocene altithermals. Both records show a decline in $\delta^{18}O$ during speleothem growth suggestive of cooling trends following the initiation of growth at the height of the altithermals. These records are now being analysed in much greater detail; in principle hundreds of analyses can be made as modern techniques demand only a milligram or so of calcite for each measurement.

The $\delta^{13}C$ speleothem record

Speleothems 81006II and 880220 exhibit U-shaped troughs in their carbon records, and all of the ancient deposits have $\delta^{13}C$ values significantly different from modern and Holocene calcite in the cave (figure 4). Although the carbon chemistry in ground water is affected by many factors which usually preclude its use in climatic interpretation (Hendy, 1971), it is perhaps broadly possible on photosynthetic pathways (Hoefs, 1987). The bicarbonate in groundwater tends to be a mix of the high and low values. One might thus conclude that the ancient deposits were associated with greater biological activity than the modern deposits (hence warmer?). Further, the troughs might indicate initial post-glacial conditions (higher values, greater role of bedrock) giving way to interglacial conditions (lower values, biogenic soil dominated), and finally going back to the more glacial conditions where biological activity is reduced again. Assuming this to be a correct interpretation, perhaps the rate at which soil is developed over glacially-scoured bedrock might be determined (3,000 to 5,000 years indicated here). However, one is still faced with interpreting the rather high, i.e. close to zero, values for the Holocene (interglacial) speleothems.

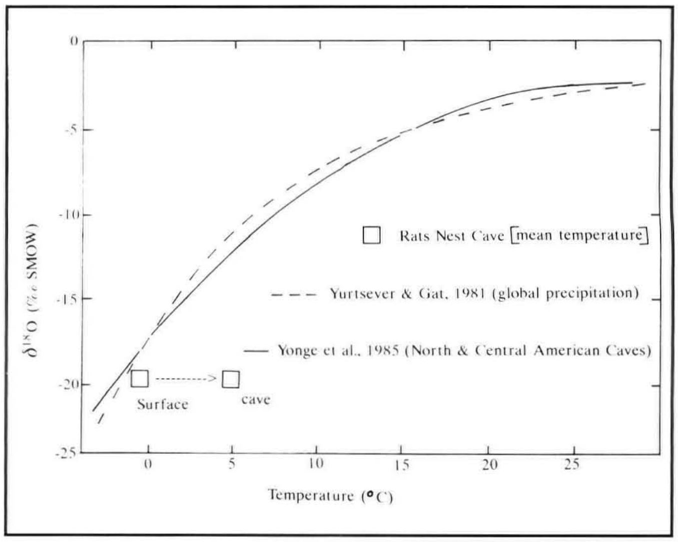


Figure 6. Variation of $\delta^{18}O$ of mean annual precipitation (dotted line) and vadose seepage water (solid line) as a function of mean annual surface temperatures (MAT's). The Rats Nest Cave seepage data is included (squares); if the cave temperature is used rather than the MAT, the "cave" line would yield higher gradients at the lower temperatures.

The δD and $\delta^{18}O$ of cave water

Globally these isotopes vary in a parallel manner in precipitation and in subsequent ground water. Furthermore, the values are temperature dependent and are the basis for climate interpretation in proxy isotope records such as ice cores (Dansgaard, 1964). Figure 6 shows $\delta^{18}O$ plots of mean annual temperature versus mean annual precipitation, or seepage water both for world-wide meteorological stations (Yurtsever and Gat, 1981) and caves (Yonge *et al.*, 1985). In general, low δ-values are associated with low temperatures (calcite δ18O's are usually interpreted in this way although other effects can reverse the trend). Of interest is that seepage water in Rats Nest Cave falls below the global curves; other Rocky Mountain caves do likewise. The implication here is that these caves do not reflect mean annual temperatures as suggested by (Wigley and Brown, 1976) but are either recording past warmer temperatures, or more likely, that geothermal heating of the caves becomes noticeable in these cooler climes. Geothermal heating at Castleguard was thought to be aided by the blanketing effect of the overlying Columbia Icefields (Ford and Williams, 1989), but now it appears that the presence of ice is not necessary.

Radon and the cave atmosphere

Radon has been very much in the news lately where attention has focused mainly on buildings (e.g. 1500 deaths annually are attributed to radon in Britain; Gunn *et al.*, 1989). However the systematics of radon are not fully understood, and caves serve as controlled environments (essentially constant temperature, humidity and air movement) where it may be studied. Studies, notably by Gunn, have been extended to monitor the threat of radon to cavers, and this is of course relevant to Rats Nest Cave if it is to be used as an underground laboratory and interpretive site.

Radon is the product of uranium decay, arising after a series of alpha emissions. Some uranium is transported to the cave as dissolved complexes in ground water and is subsequently

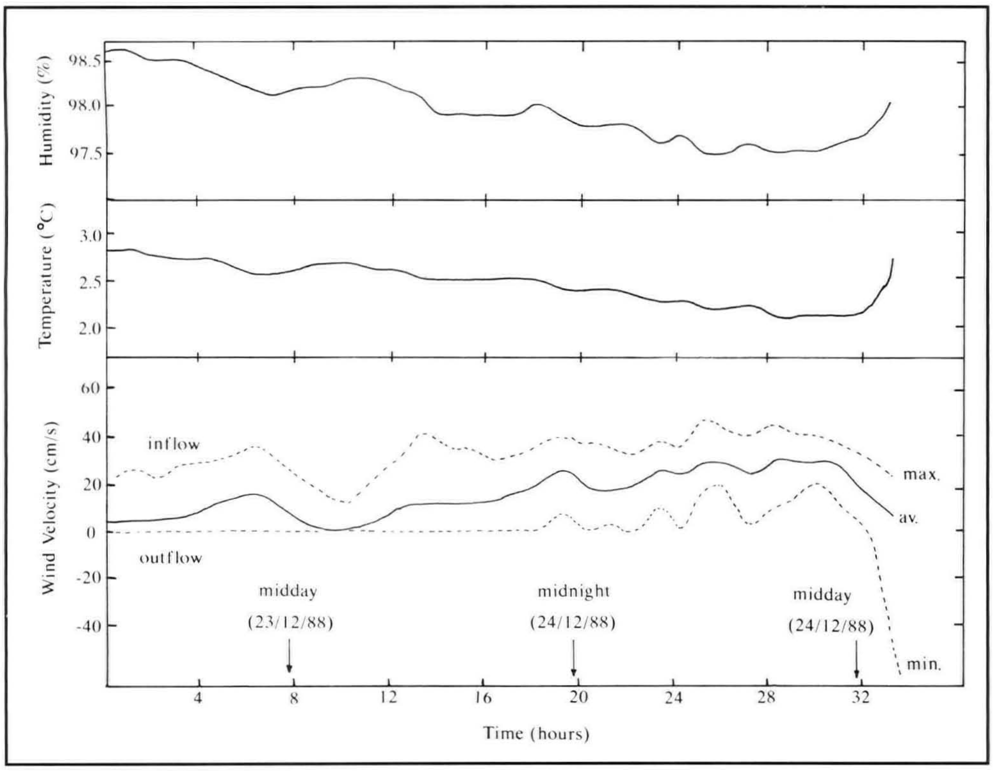


Figure 7. A 34-hour record of temperature, humidity, and wind velocity at the Bone Bed in December 1988.

Sampling rhythmites for paleomagnetism near the Birth Canal. A layered block has been lifted from the cracked mud floor in the background.

precipitated out in speleothems. Uranium also exists in the walls of the cave and in clastic sediments. Radon itself is highly soluble in ground water and may be liberated in the cave. Radon decays to give the short-lived lead isotopes, polonium and bismuth which also emit alpha particles. The alpha particles from radon decay when breathed in irritate the lungs and can initiate lung cancer (Gunn *et al.*, 1989; Nazaroff and Neroy, 1988).

The study at Rats Nest Cave was in collaboration with Ann-Lise Norman and John Bland from the department of Physics and Astronomy University of Calgary. Two approaches to monitoring radon were adopted, both utilizing charcoal cannisters to collect the gas. The first method assumes that the radon daughters are in equilibrium with the parent radon. Airflow, temperature and humidity were therefore neglected, and the value obtained around 2 WL (working levels). In assessing the risk to health it is necessary to compute dose or working level hours (WLH), and 204 WLH per year is considered safe. At Rats Nest Cave this translates to only 102 hours underground in any one year. The second method takes into account the daughters' chemical and physical parameters (e.g. deposition rate) which requires airflow and temperature measurements. Five cannisters were placed between the Bone Bed and the start of the Wedding Cake Passage, and a micrometeorological station was installed at the base of the Bone Bed to measure airflow, humidity and temperature. The station ran for 33 hours in December before it was upset by visitors. The results, figure 7, show a strong positive correlation of temperature with humidity, these parameters exhibiting a negative correlation with wind velocity. The airflow is mainly inwards in winter due to chimney wind effects (Wigley and Brown, 1976), although some reversal of flow is indicated by hoar frost at the entrance during this time. Measurements of airflow and temperature with an estimate of cave volume (50,000 m^3) gives a radon exposure level of about 1.87 WL, a value similar to the first.

The radon levels are quite high but may well be an overestimate due to the normally high humidity one encounters in caves. Furthermore, the cannisters were not sealed tightly to the cave surfaces which may have resulted in an increased absorption of radon. Perhaps relevant too, is the fact that radon levels in the cave pools were found to be almost undetectable. Work is currently going on to develop a new calibration technique to account for the efficiency of these kinds of detectors in the cave environment.

CAVE SEDIMENTS

Speleothems

Calcite deposits are found throughout the 4 km of known cave, and their importance has been discussed above with respect to paleoclimatology. But apart from the usual varieties of speleothems some perhaps merit further note. Unusual subaqueous coralloids have been observed in a pool at the Mud Room. These forms are irregular-shaped needles, clustered with their axes vertical and sandwiched between planar calcite layers. In fact, the predominance of sub-aqueous coralloids and cave pearls in long-standing pools is a feature of the cave which might be interesting to investigate, perhaps with reference to the below-treeline water chemistry (most caves occur in the Rockies above the treeline in alpine areas).

Clastic sediments

The cave contains much clastic material which probably entered the system carried by glacial meltwater. The sediments are mainly of the rhythmite type grading from clay to sand sized particles. Organic material is evident in the layers. Clay grains cling to all surfaces indicating inundations of muddy water or a total filling of passages with clastics. As discussed above, speleothem 881010 indicates repeated flooding episodes associated with clastic deposition.

Table 2. Preliminary List of Species from Rats Nest Cave (after Burns, 1986)

Provenance	1	2	3	4	5	6	7	8	9
Insectivora (Shrews, etc.)									
Sorex cf. *arcticus* (Arctic Shrew)							x		
Sorex sp. (Shrew)		x							
Chiroptera (Bats)									
Lasionycteris noctivagans (Silver-haired Bat)	x								
Unidentified Bat							x	x	x
Lagomorpha (Pikas, Hares, etc.)									
Ochotona princeps (Pika)		x					x	x	
Lepus americanus (Snowshoe Hare)	x		x	x		x	x	x	x
Rodentia (Rodents)									
Marmota caligata (Hoary Marmot)	x					x		x	
Spermophilus columbianus (Columbian Ground Squirrel)	x		x		x			x	
Eutamias sp. (Chipmunk)								x	
Tamiasciurus hudsonicus (Red Squirrel)							x		x
Peromyscus maniculatus (Deer Mouse)		x					x	x	x
Neotoma cinerea (Bushy-tailed Wood Rat)	x		x	x		x	x	x	x
Clethrionomys gapperi (Red-backed Vole)							x		
Phenacomys intermedius (Heather Vole)		x		x			x	x	x
Microtus sp. (vole)				x		x	x	x	x
Erethizon dorsatum (Porcupine)					x			x	
Carnivora (Carnivores)									
Ursus americanus (Black Bear)						x			
Canis lupus and *C. latrans* (Wolf and Coyote)	x	x	x	x	x	x	x	x	
Vulpes velox (Swift Fox)						x			x
Mustela vison (Mink)			x						
Martes americana (Pine Marten)									
Gulo gulo (Wolverine)	x					x			x
Taxidea taxus	x				x				
Mustelidae sp (Weasel)								x	
Lynx canadensis (Lynx)	x								
Unidentified							x		
Artiodactyla (Even-toed Ruminants)									
Odocioleus sp. (Deer)	x	x		x	x		x		
Cervus elaphus (Wapiti)								x	
Bison bison (Bison)	x	x	x	x	x	x	x	x	x
Ovis canadensis (Bighorn Sheep)	x	x	x	x		x	x	x	x
Aves (Birds)		x		x		x*	x	x	x
Pisces (Fish)	x	x					x	x	x
Amphibia (Frogs and Salamanders)		x							
Reptilia (Snakes)		x					x	x	x
No. of taxa in each unit	13	12	7	9	6	11	18	20	14
No. of mammalian taxa to genus	12	8	7	8	6	10	14	16	10
Total mammal taxa to genus: 26									

* incl. *Aquila* (Golden Eagle)

** Key to provenances
1 — Disturbed area leading to upper bone bed (DA, preliminary report)
2 — Surface of upper bone bed (SP, preliminary report)
3 — 90-100cm below datum, upper bone bed
4 — 140-150cm below datum, upper bone bed
5 — 170cm below datum, upper bone bed
6 — surface of lower bone bed
7 — Sample No. 1, surface lower bone bed
8 — Sample No. 2, 0-20cm below surface, lower bone bed
9 — Sample No. 3, 20-30cm below surface, lower bone bed

Apart from samples taken for geomagnetic analysis for which results have not been returned, the clastic sediments remain unstudied. Much may be gleaned as datable speleothems lie in favourable stratigraphic relationships to the rhythmites. In addition, palynological observations on the organic material may reveal something of the local fluctuations. The phreatic nature of the cave has resulted in thick rhythmite sequences deposited in U-tube traps making excellent sites for study.

The Bone Bed

The work described here has mainly been undertaken by Dr James A. Burns, curator of Quaternary Paleontology at the Alberta Provincial Museum. His work has focused on the Bone

Detail of the Bone Bed strata showing numerous bone fragments. J. Burns of the Alberta Provincial Museum is sampling the deposit.

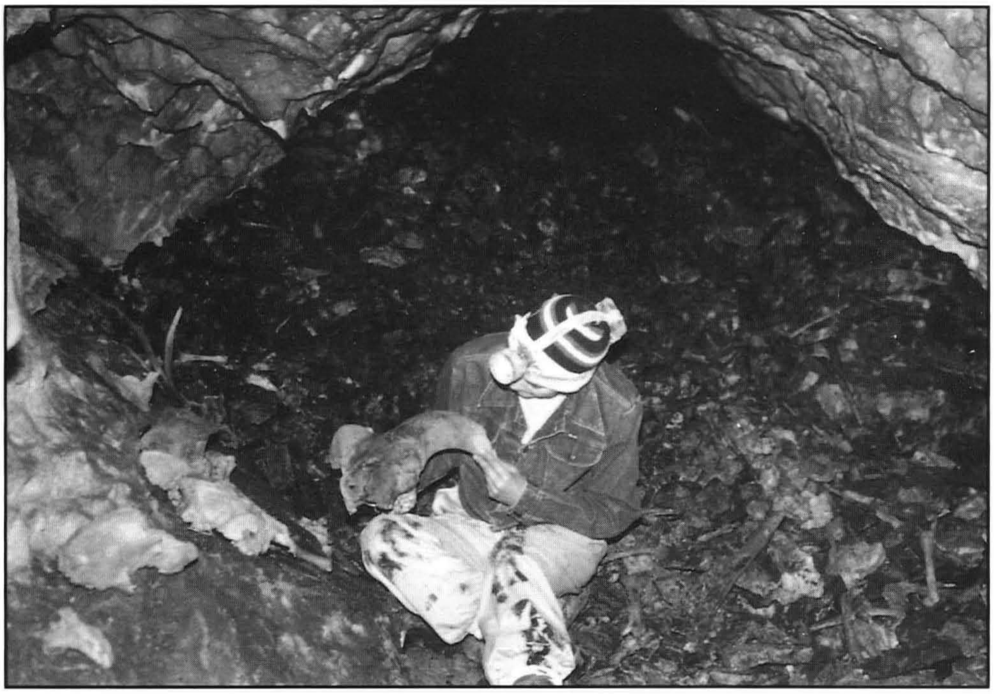
Bed, a 2 m thick sequence at the base of the 15 m entrance shaft, although some observations deeper in the cave are also included. A summary of two reports to Alberta Culture and Multiculturalism follows (Burns 1986a and 1986b). A synopsis of this work has been published in *Canadian Caver* (Burns, 1989).

It appears that the Bone Bed has potential for a continuous environmental record for the last 6000 to 7000 years (table 2). The most recent excavation by the museum has recovered a large sample of subfossil material, including: vertebrate bones, teeth and scales (all vertebrate classes present), pollen, plant macrofossils (twigs, needles, seeds and cone bracts), and insect parts, of the vertebrates alone, it is anticipated that perhaps 20,000 specimens will be catalogued and indentified.

Despite good samples from earlier excavations, there is concern that the repeated pass of cavers has disturbed the sediments and mixed up the record. Nevertheless, 34 mammalian species, including the swift fox which is locally extinct, have been recovered. Many remains of birds, fish, snakes, and several amphibians are also present. The 34 species of mammal identified, 3 found recently in new material, represents a high proportion of mammals regularly occurring in the region (e.g. 34 out of a possible 51; Burns, 1989). In addition, the identification of a passenger pigeon (amongst a number of presently unidentified avian bones) fits in with historic records of this essentially eastern bird occurring in Alberta and British Columbia, including Eagle Cave in the Crowsnest Pass. Passenger pigeons became extinct in 1914.

Two prehistoric indian arrow heads have been found, one regrettably lost years ago, and the other has been identified as Pelican Lake style, 2000 to 3000 years old. Carbon-14 dating by the Alberta Environment Radioisotopes Laboratory, Vegreville has given a range of dates from 7060 to 2480 years. Due to mixing of the sediments, these dates cannot yet be assigned to specific strata or faunal components. Thus the Bone Bed site, with its multiple lines of evidence, has the potential to provide the best documented, ostensibly continuous mid- to late-Holocene record of environmental change anywhere in Alberta. The altithermals may be represented here as they are in the speleothem record, whereas on the plains flora and faunal records are non-existent (McKinnon and Stuart, 1987; Wilson, 1989).

Despite the potential of the Bone Bed, much painstaking work remains to be done to establish its true value as a Holocene site. Meanwhile, pollen is being analysed by the Archeological Survey of Alberta, Edmonton, and insects by Dr Alan Morgan of the



Base of the Bone Bed where the bone deposits have spilled out into a horizontal passage. Note the skulls to the left, one of which is a bear, and skull of a bighorn sheep being handled.

University of Waterloo.

In addition to the Bone Bed, bone and other organic debris is scattered through the cave. Some material has been identified but not in detail. Many of the bones have been carried into the cave by pack rats who chew on them for calcium. Otherwise bones have accumulated from animals that entered the cave and died there, such as a Coyote (at the end of Coyote Descent almost 1 km into the cave), some bat remains and numerous pack rat skeletons.

Elk bones a long way into the Ranger Way suggest another entrance, perhaps preglacial, to the cave. Tenacious as pack rats are, it is hard to imagine them dragging these large bones all the way from the present entrance. If another entrance existed, it is now more than likely blocked by extensive glacial terraces that lap the flanks of the Bow Valley. However, fresh pack rat skeletons and the presence of bats at the end of the Great West Highway, which is above the glacial terraces, suggests an entrance currently open.

CAVE FAUNA

According to Peck (1988), little is known of the fauna of Canadian Caves. Apart from the paleofaunal work described above, Rats Nest Cave remains essentially unstudied. Included here are a few observations made as survey work proceeded in the cave.

Microorganisms

The cave contains moonmilk at a number of locations, but extensively within 30 m of the entrance and at the same level. Some moonmilk has been shown to have been derived from bacteria (Moore and Sullivan, 1978), but it remains to be shown whether this is the case or not in Rats Nest Cave.

Invertebrates

Covered by ice during a series of glaciations throughout the Quaternary, the cave may well contain organisms that predate glacial events as has been discovered at Castleguard Cave under the Columbia Icefields (Holsinger *et al.*, 1983). In such a refugium invertebrates may evolve divergently, independent of their counterparts on the surface. Apart from anecdotal reports, no invertebrates have been specifically observed in the cave pools. Some single strand filaments or webs have been seen in very moist portions of the cave, and these may be constructed by a tubular worm for predatory purposes (such worms may be seen in caves in the Ozarks, USA). Worm tracks, almost certainly unrelated to the tubular worms, are seen to criss-cross clean-washed silty deposits.

Insects

Calcified winged insects can be found in the Wedding Cake Passage but these await identification. At the entrance, overwintering harvestmen and mosquitos are also observed. The incidence of the former has been described by Angerilli and Holmberg (1984).

Bats

A small number of bats has been seen on occasions flying through the cave. The most common sightings have occurred in the passage complex at the end of the Great West Highway, in Coyote Descent and the Ranger Way. A bat skull has been identified by Dr J. Burns as a little brown bat, and one sick bat was retrieved and likewise identified by Chris Butler, a ranger from Bow Valley Provincial Park. The occasional sightings of bats points to a substantial roost and alternative entrance in some hitherto undiscovered part of the cave. Other Eastern-Slope caves such as Cadomin, 200 km to the north, contain large brown bat populations.

Bushy-tailed wood rats (pack rats)

These creatures can always be found around the cave entrance (and most other cave entrances in the Rockies), and they appear little disturbed by humans. The name of the cave is derived from the presence of these ubiquitous rodents. Large nesting piles have been built in crevices around the entrance, and these contain many items discarded or lost by cavers (hence, pack rat). Pack rats appear to have travelled up to a km or so into the cave although other entrances may exist.

Further observation of the live fauna by appropriately qualified experts may well bring to light a rich assemblage of life in the cave system. The cave's potential as a glacial refugium further make it worthy of study.

FUTURE WORK AT THE UNDERGROUND LABORATORY

The above discussion points to a number of diverse studies that are intended to be carried out at the cave. The University of Calgary's Kananaskis Centre For Environmental Research only 15 km from the cave is a possibility for a field base. Otherwise, analytical work will be undertaken at the main campus, supported by other institutions (see acknowledgements).

Ongoing work includes:

(i) Pleistocene studies of speleothems and the regional glacial history
(ii) Holocene studies of speleothems and recent climate change
(iii) Paleontological inventory of the Bone Bed
(iv) Speleogenesis
(v) Radon monitoring
(vi) Stable isotope studies of cave water and hoar frost.

Future work planned includes:

(vii) Fluid inclusion studies of speleothems
(viii) Macro- and micro-faunal studies
(ix) Cave and regional hydrology
(x) Cave sediments

(xi) Cave climate
(xii) Educational program

Although some topics are referred to in some detail in the text, a few comments should be made with regard to those topics that are not self-explanatory, or that have not been discussed above:

Of the ongoing work, item (vi) refers to the isotopic composition of hoar frost being studied in addition to the cave water. Large masses of hoar frost form at the cave entrance in winter, especially when arctic fronts ponded against the Rocky Cordillera penetrate southwards to the US border. This occurred for three weeks last winter driving temperatures down to −37°C. The hoar that forms reflects the humidity and temperature of the cave air and the adjacent surface air. The initial results point to a highly localised Rayleigh distillation process that mimics atmospheric precipitation processes (Yurtsever and Gat, 1981). Furthermore, the hoar frost experiment is assisting in a wider study of ice caves by graduate student Bill MacDonald of the Committee on the Resources of the Environment at the University of Calgary. Many ice caves are to be found in the Canadian and US Rocky Mountains, and the study aims to model the present and ancient ice in these caves.

The study of fluid inclusions (item (vii) of future work) adds additional parameters to speleothem paleoclimatology (Schwarcz *et al.*, 1976; Yonge, 1982). Here water trapped in the speleothem calcite fabric is extracted and measured isotopically. The composition of mean annual precipitation at the site and isotopic cave temperatures can be obtained in principle. Since cave temperatures reflect mean annual temperatures at the surface, isotopic temperatures give a direct temporal temperature record for the site.

Item (ix), cave and regional hydrology, will be followed up by the staging of streams and springs around Grotto Mountain for estimates of runoff, and the dye tracing sinks and cave streams to springs. The two large springs at the east end of the mountain, one emerging at valley level directly below the east end of the mountain and the other into Gap Lake require careful monitoring. In the latter case, monitoring can only be done at the lake outlet.

The education program, item (xi), will follow a management plan presently being worked out between this project, Alberta Culture and the industrial leaseholders, Continental Lime Limited. The management of Rats Nest Cave, and other caves locally, is being studied by Jon Rollins of the Department of Environmental Design at the University of Calgary and of the Alberta Speleological Society. Ultimately tours and field trips will be made to the cave, with a classroom follow up, to enhance understanding of the underground environment. Groups would comprise local interested societies, college students and schools. Eventually a centre may be built on site, depending on future leasehold conditions.

Comments and/or suggestions from the readership of *Cave Science* with regard to the ideas outlined above will be greatly appreciated.

ACKNOWLEDGEMENTS

Presently a three year project at the cave is being funded by the Alberta Environmental Research Trust for which this paper provides preliminary results. Speleothem dates have been provided by Dr D. C. Ford and his recently-departed student Joyce Lundberg of the Geography Department at McMaster University, Ontario. The stable isotope laboratory facilities have been freely extended to me by Dr H. R. Krouse of the Department of Physics and Astronomy at the University of Calgary. In addition, the work of Bill MacDonald, graduate student and Nenita Lozano, technical analyst, is very much appreciated during my time overseas.

Many have contributed to the study so far, and other than those mentioned in the text, I am very grateful to members of the Alberta Speleological Society, whose names may be found on the cave map, for many hours of field work in the cave, and especially to Dave Thomson, field assistant, who made numerous trips into the cave, often solo, taking photographs and collecting samples.

Thanks are finally extended to Dasho Zangley Dukpa, principal of Sherubtse College, Bhutan for the facilities of the college during the writing of this paper.

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CAVE SCIENCE Vol 18, No. 3, December 1991
Transactions of the British Cave Research Association

A New Survey of Råggejavri-Raigi and the Hellemofjord Karst, Norway

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Abstract: In order to accommodate the needs for a sampling programme, Råggejavri-Raigi (RJR), the deepest cave in Scandinavia, was resurveyed. We claim the present survey to satisfy BCRA standard 5C. The cave has a surveyed length of 1915 m, with an estimated total length exceeding 2000 m. The surveyed depth is 580 m with a through trip elevation of 579 m. The fiord entrance is situated at 80 m a.s.l. Several interesting leads still remain in the cave, and we hope future visitors may explore and survey them. The cave survey is stored on magnetic media for easy update. On the northern Noroldahkvarri plateau, several extensions in Østhullet were found, giving the cave a total length of 900 m. Several small caves and choked shafts were found, but none of them yielded cavities of any significant size, in spite of digging attempts. All Noroldahkvarri caves were still in their untouched, pristine state, whilst RJR shows signs of travel due to the intense attention the system has received during the past 20 years since its discovery. Finally, we suggest a standard nomenclature for RJR.

Råggejavri-Raigi (RJR), situated in the southern wall of Hellemofjord, North Norway, is the deepest cave in Scandinavia. The cave potential was first alluded to by Foslie (1942) who, during geological mapping, pointed to streams sinking into steeply dipping marble bands on top of the plateaus around Hellemofjord. Foslie associated them to the powerful submarine springs which occur at both sides of the fiord and suggested that immense caves must exist inside the fiord walls. He was indeed right, but it would take some 27 years to confirm his assertions. Foslie's ideas were later cited by Corbel (1957), but no penetrative exploration was done until British cavers, led by David Heap (1969, 1970) explored and surveyed the system. Being among the 30 deepest caves in the world at that time (Courbon 1972), and still providing No 7 of the deepest through-trips available (Courbon and Chabert 1986), the cave is a celebrated one and has experienced much attention ever since. Almost every year, caving groups from all over Europe have visited the cave. We gather that several hundred individual through-trips must have been made during the 20 years since its discovery.

In 1990, the Hellemofjord caves became subject to a closer morphological and stratigraphic study in order to obtain paleoclimatic and geomorphic information. The project belongs to the general "Global Change" Program, where the purpose is to provide a database for past climatic changes.

The original Kendal Caving Club (KCC) survey (Heap 1971) has proven remarkably accurate, in spite of the logistically difficult conditions prevailing at the time when it was made. However, 20 years' of visits has naturally revealed new details and routes. In particular, the connection to the fiord cave (Vouleb Råggejavre-Raige), and a much used high level route above Store Skrå (The Big Rift) necessitated accurate documentation. It was felt that the old survey did not allow us to locate our observations and sediment sections with sufficient accuracy, so we would in any case have to connect these locations to a new survey traverse. We therefore found it most convenient to re-survey the whole cave, thus providing new fixed stations for future extensions.

The purpose of this paper is to present our revised surveys and report some new findings on the northern, Noroldahkvarri plateau.

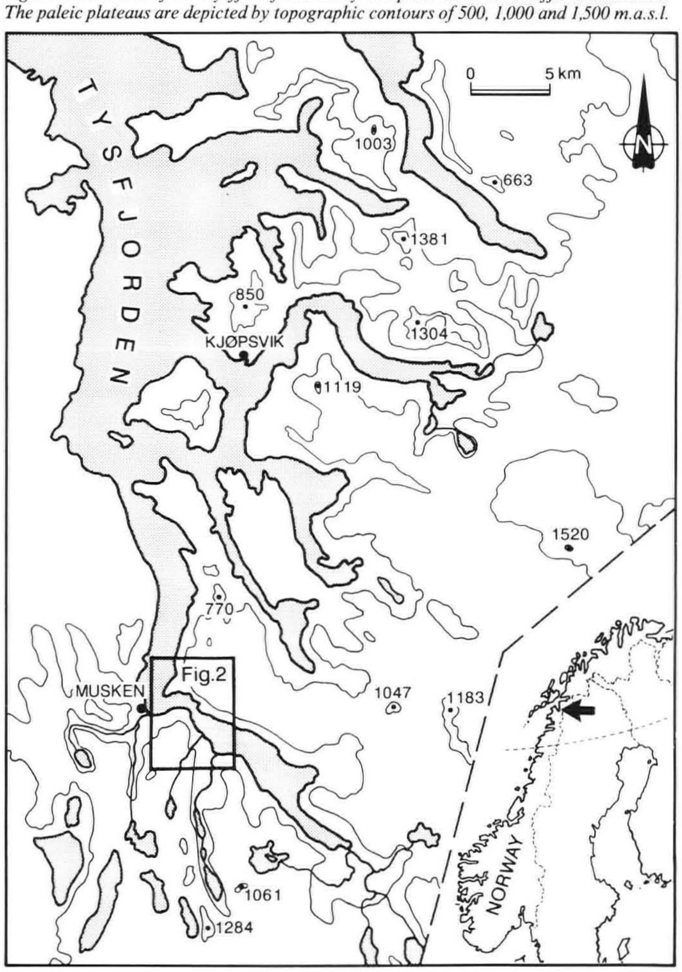
GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

Hellemofjord forms the southern branch of the Tysfjord fiord-valley complex in Nordland, Norway, Figure 1. These fjords are incised into an extensive massif of crystalline basement windows surrounded by metasediments. The resistant massifs form extensive paleic plateaus, one of them is the "Gipfelrand" at about 1000+ m a.s.l., yet another plateau is found at around 700 m a.s.l. For closer explanation of the "paleic" or "old", pre-glacial surface of Norway, see Gjessing (1967) and references therein. Hellemofjord cuts deeply into the 700 m plateau. Including the depth of the fiord (-455 m), the total relief adds up to some 1200 m. The fiord cuts through a synclinal structure which outcrops as nearly vertical strata of mica schist, gneiss and marbles, forming the typically "Norwegian" stripe karst setting (Horn 1937), (Figure 2).

The combination of vertically continuous carbonate bands (from the lakes on the plateau to down below sea level) and large scale fracturing along vertical (EW) and subhorizontal sets, provide optimal conditions for deep karstification. Although this situation is preferential for creating underground drainage, it does not necessarily support explorable caves. Vertical drops depend on the location of corresponding vertical fractures. If the density of such vertical fractures is low, the passages may locally become forced along the other, subhorizontal fracture set, forming shallow, perched sumps. This effect was noted by Heap (1969) on the Noroldahk plateau (i.e. the Noroldahk-Raigi cave), and it is also evident in the upstream section of Råggejavri-Raigi. For instance, if an upper entrance did not happen to exist by chance in a distal position of the present stream, RJR would never have been found unless the upstream sumps could have been dived.

The RJR marble band is of variable stratigraphic thickness, 20-30 m at most. This can be seen in some of the largest chambers, where the wallrock is exposed. The RJR marble is the westernmost of at least three prominent, parallel bands. The thickest, middle band has not yet yielded caves, but the eastern band contains an underground system (Nieidavaggi sink cave, Beck 1971). The three bands can be seen to continue on the north side of the fiord. They are paralleled by similar cave distributions.

Figure 1. Location of the Tysfjord fiord-valley complex. Dark shade: fjords and lakes. The paleic plateaus are depicted by topographic contours of 500, 1,000 and 1,500 m.a.s.l.



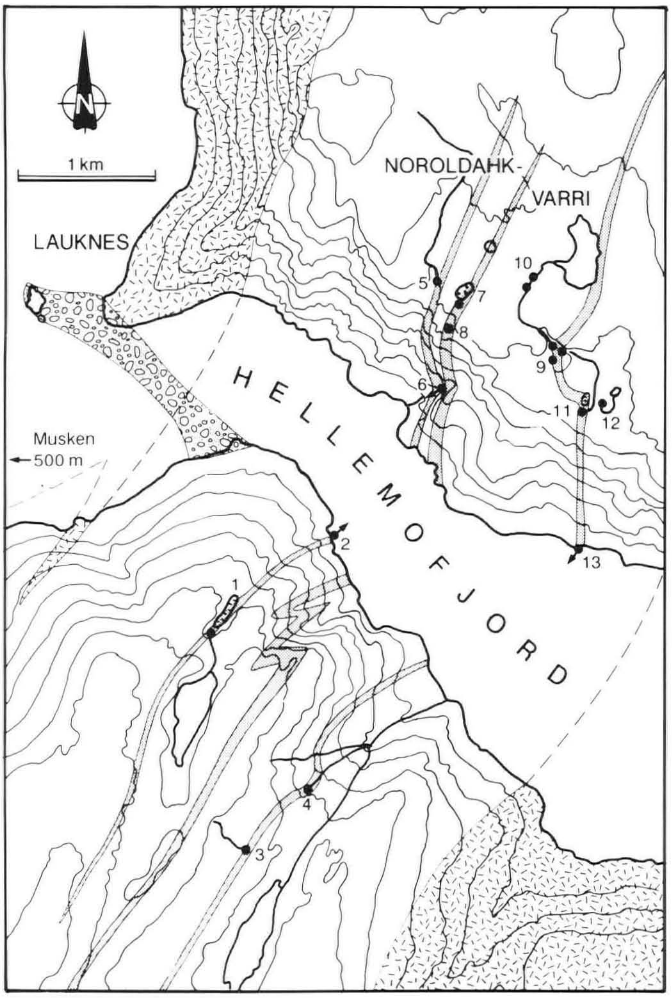


Figure 2. The Hellemofjord stripe karst. Contour intervals 100 m. Note the narrow marble bands within the metasediment syncline, the granite contacts and the Preboreal end moraine. 1: RJR upper entrances and Bumperhullet (Heap 1970). 2: Submarine spring and Vouleb RJR. 3 and 4: Nieidavaggi sink and resurgence. 5: Lauknesfjellgrotta sink. 6: Raigejokka Resurgence. 7: Main Doline, streamsink and choked shafts of Lauknesfjell marble. 8: Small caves in the distal part of Lauknesfjell marble outcrop. 9: Østhullet and associated caves. 10: Small stream canyon caves. 11: Noroldahk-Raigi sink. 12: Grågrotta sink shaft. 13: Submarine spring, probably from Noroldahk-Raigi.

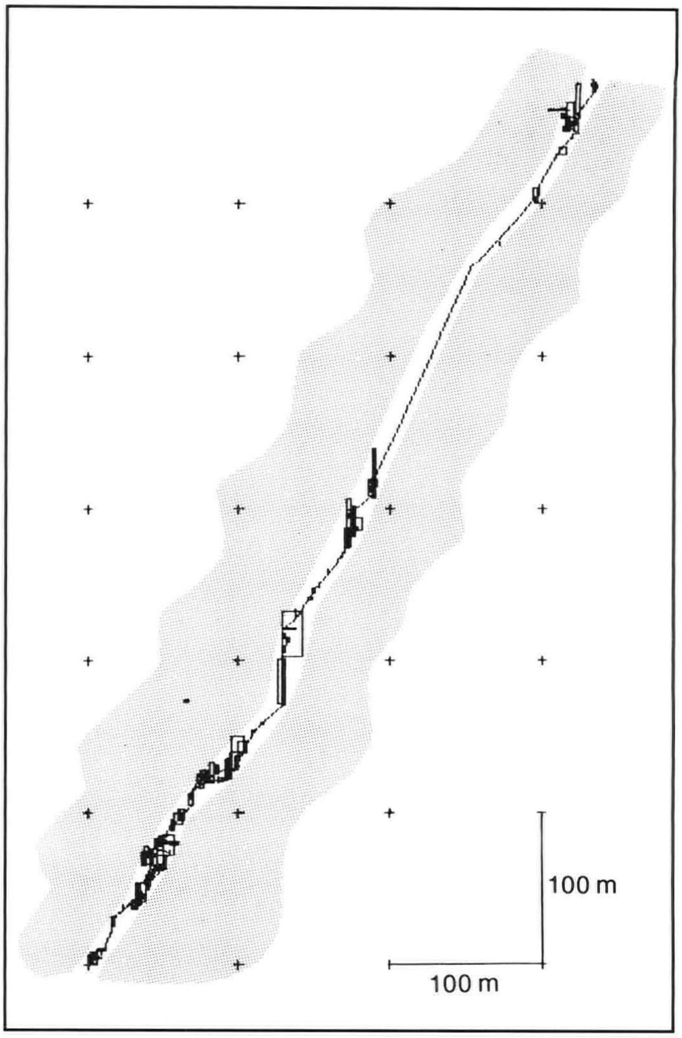


Figure 3. The nature of the intensive karstification often seen in stripe karst, as demonstrated by projecting the RJR line survey along the strike. Looking 230 degrees south-east. Shade areas: non-karstic wallrocks. In particular, the big chambers have consumed almost all of the surrounding karst rock.

The supposed RJR continuation may be the marble band that hosts Lauknesfjellgrotta (Beck 1971) and the Raigejokka resurgence cave (Heap 1970). The middle marble band (Lauknesfjell marble) is the most prominent and is visible at a long distance. It outcrops with a thickness up to about 100 m. This marble supports a large doline (about 100 m diameter, the largest in the area) with an underfit streamsink, several grikes and small choked shafts, but no substantial caves (except for JRP-cave, see below). The large doline and Lauknesfjellgrotta sinks are controlled by the same EW fracture lineament. The easternmost marble band hosts several prominent caves (Heap 1969, Beck 1971).

In all, except for a few other marble bands of negligible size, the Hellemofjord karst is controlled by three major, steeply dipping carbonate horizons. The central, apparently thickest outcrop do not seem to yield significant caves, whilst the two marginal bands support cave systems which are immense when compared to the size of the host outcrops. This effect is demonstrated in Figure 3, where RJR is projected along the strike of the marble band.

Only a few hundred meters west of the cave area, the metasediments are replaced by resistant basement rocks (the Tysfjord granites of Foslie 1942). The almost vertical contact has apparently made a significant barrier to glacial erosion, as the fiord displays a major constriction at this site, (Figure 2). Such topographic constrictions commonly affect glacier movements within fjords, particularly under deglaciations, when the ice mass is dynamically unstable. A major end moraine was deposited in the constriction between Lauknes and Segelnes (Figure 2), which has been ascribed to the Preboreal (D-event, 9,400 -9,700 B.P., Andersen 1975, Andersen *et al* 1981). The constriction would have provided a kind of "baselevel" for ice movements, as the compressed fiord glacier might have supported an englacial watertable which in turn would control the phreatic zone within the karstic siderocks. This would be the case for several of the past glacial cycles. In even more distant times, we may imagine the granite contact to form a much more stable baselevel for the incipient fjord. Within the possibilities dictated by the fracture density, either or both of these two types of baselevel may be responsible for the paleo-resurgence levels and rejuvenation features that we find inside the caves. The detailed timing of these stages would be subject to discussions of valley entrenchment and conduit wall retreat rates as outlined elsewhere (Lauritzen 1990).

THE CAVE SURVEY

Adaptions from the KCC map

The streamway in the bottom of Store Skrå was not resurveyed, as our route came in through the high level traverse down a short shaft (Main Slide) directly above Ulvegangen (Wolf Walk). We have therefore adapted survey details of Store Skrå from the original KCC map, which we consider as quite accurate.

Storstupet was not resurveyed thoroughly. The distance from our rope belay (above the winch balcony) to the bottom of the pitch was measured with a topofil device as 152 m. Average azimuth and inclination were estimated from the KCC survey. We admit that this is a rather unsatisfactory approach, as we do not know the basis of the KCC map at this place. Storstupet is a very misty and inconvenient place to survey, and we gather that the original surveyors also encountered visibility problems here (Heap 1971). The conditions may be more favorable during winter when the thermal winds become reversed, and when we should expect the discharge and spray from the waterfall to be at a minimum.

Survey standard

Nylon-coated steel tapes were used with the traditional Sunto compass and clinometer. Distance was read to the nearest centimeter and angles to the nearest degree. Survey stations were placed on protruding features of solid rock or large boulders. Occasionally, and always at the beginning of promising leads, the survey stations were either marked with cairns (wet places), or marked with carbide soot (encircled spot with station number). Neither of these marks are very durable; our experience is that modest soot marks may last up to some 5 years if the place is reasonably dry. However, we hope that we, by our approach, may have attained a compromise between upsetting other visitors and providing confident links for extensions during the next few years.

The surveys (Figures 4 and 5) should reach the standard of BCRA grade 5C (Ellis 1976). There are only a few closed loops to test the internal accuracy of the survey measurements. Standard deviations of azimuth and inclination readings were less than one degree in these loops. The new 1:50,000 scale topographic maps (M 711 series, Sheet 2230 IV, Hellemobotn) would place the cave entrance at approximately 580 m a.s.l. Adapting this map as the "ground truth", it compares quite favorably with the surveyed depth to sea level (582 m), suggesting a maximum misfit of less than a few per cent. Please note that one link, Storstupet, is not yet satisfactorily surveyed, see discussion above. The "C" standard was satisfied because cross-sections were recorded at every survey station, supported by measurements of the distances to floor, ceiling, right and left wall. This procedure is not much more time-consuming than estimating the same distances, but it greatly extends the usefulness of the survey.

A total of 172 survey legs were made. The distribution of survey leg lengths is shown in Figure 6, the modal leg length is 4 - 7 m. This is quite common for cave surveys of this type and ensure that reasonable detail is maintained in the line survey. The total surveyed length is 1915 m. The total surveyed depth is 580 m. We estimate that the remaining known but unsurveyed passages would easily add up to more than 100 m, taking the cave into the 2 km class. The through-trip elevation difference is 579 m, although the depth is apt to change with by a few per cent when better survey legs for Storstupet become available.

Aneroid altimeter measurements

In order to support the surveyed levels with independent measurements, relative elevations were estimated using an aneroid Paulin Altimeter with -350 - +720 m nominal range, readable to 0.5 m. The reliability of a pressure device underground may be subject to debate, but we have nevertheless performed a few readings that may be compared to the surveyed depths. However, surface checks have proven quite useful when repeated readings are made at short intervals under stable weather conditions. The results are shown in Table I.

Altimeter and survey readings compare quite favourably when both readings are taken either on the surface or underground. However, in the case of the elevation between Upper Entrance and the Winch Balcony, the difference is some 10 % which we may ascribe to a pressure anomaly between the cave and the surface. This is clearly demonstrated by the strong thermal wind that was drawn into the upper entrance. Based on the measurements in Table I, we feel quite confident that the Fjord Entrance is situated 80 m a.s.l rather than 100 m as suggested by the original survey.

Location	Altimeter	Survey
Upper Entrance-Winch Balcony	94 m	105 m
Storstupet, Rope belay-bottom	145 m	142 m
Sealevel - Fiord Entrance	77 m	80 m

Table I Comparison of relative aneroid altimeter readings and survey

Promising leads in the cave

Several bits and pieces were for various reasons not included in the survey:

1) The streamway part of Store Skrå may benefit from a new survey performed either during drought summer or winter conditions. Upstream pushes of the streamway may also become feasible in winter.

2) A promising lead (The French Opening) goes north-east from the top of Main Slide, the first rope pitch in the high-level route above Ulvegangen. These passages may lead across the top of Storstupet, and most probably extend the pitch upwards with several tens of meters. We gather that this route has been used by French groups in the past.

3) The main stream at the base of Storstupet disappears into a tight shaft which is passable at low water stages, preferably in winter.

4) The series of large avens distally of Storstupet have evidently acted as earlier knickpoints in the stream recession. They may connect to the nearby Bumperhullet drainage system (Heap 1970).

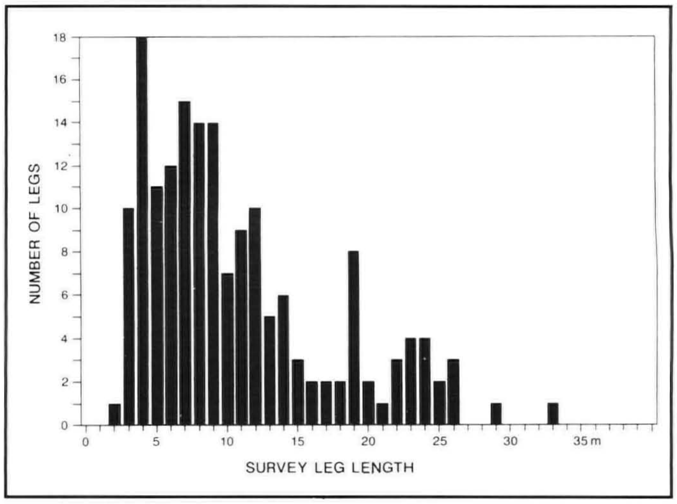


Figure 6. Frequency distribution of survey legs (n = 171) in the RJR survey, omitting Storstupet. The model survey leg length is 4-7 m, the average length is 11 m.

Several attempts have been made to climb these avens; for instance, we know of attempts by the Norwegian Bodø group that have penetrated some 30 m up into the avens. As expected, some of the avens seem to have horizontal connections at higher levels. Further penetration may require bolting and perhaps maypoling supported by camping at the site. We also consider the avens close to the top of Litlestupet as important targets for further attacks.

5) The NE wall of Litlestupet has a prominent recession above a ledge covered with rubble. To the extent we were able to observe the back wall of the recession (from the rope balcony), we could not see any openings. However, most NE leads in the cave are quite low passages developed along subhorizontal fractures, unless they have been widened by vadose undercutting and collapse. Therefore, it is not unlikely that such a lead might have been overlooked.

6) Between the Drinking Pool and Keystone Chamber, a high level route was surveyed on top of large blocks. The survey and exploration was terminated without reaching a definite end. The last survey station is marked "S22".

7) The top of Litlestupet and Galleriet correspond in altitude to the Raigejokka resurgence cave on the north side of the fiord. It is therefore likely that an old spring level might also be reached on the RJR side from the surface footpath along the 250 m a.s.l. contour. However, the steep cliffs and insignificant size of the known fjord entrance orifice suggest that this would be far from easy.

We would appreciate it if future visitors would take up these and maybe other leads and document their findings with the survey standards described above. We will then be able to link these extensions to our existing computer model of the cave.

Location of fixed survey stations

In the bottom of Clay Pot, above Wolf Walk, a good, fixed station is the rawlbolt rope belay (Station S1) for the last drop down to Wolf Walk.

Top of the 12 m pitch in Galleriet. When standing up to prepare the descent, the survey station (B09) is found at waist height on the left-hand (W) wall.

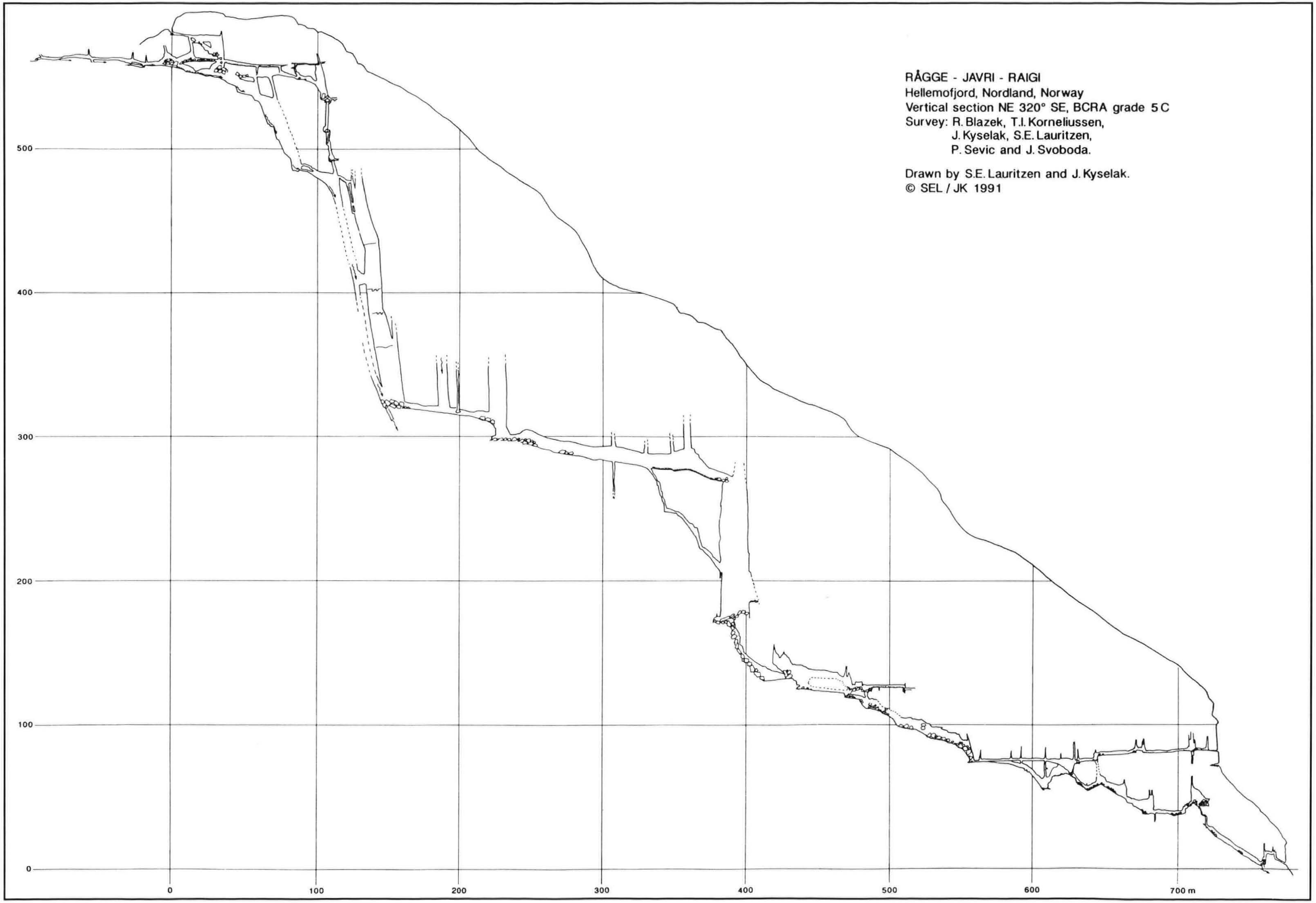
The last station at the top of Litlestupet (B19) is situated on the right hand (W) side of the passage, just before Galleriet opens out into the top of the pitch. Several survey stations further back in the passage are marked with circular soot marks (2-3 cm diameter).

The high level lead above Keystone Chamber is marked with station "S22". It is easily visible on the vertical wall just above the continuation of the passage.

Gour Passage drops into a rift chamber. At roof level, small leads may be found northeastward. The nearest station (S48) is located on the pointed corner only 1/2 m downstream of the lowest rock-mill pot, i.e. the "Gours" of the KCC survey (Heap 1970).

EXPLORATIONS ON THE NORTHERN PLATEAU

As mentioned, caves of the northern plateau, Noroldahkvarri, were previously explored and mapped by Heap (1969,1970) and by



RÅGGE - JAVRI - RAIGI
Hellemofjord, Nordland, Norway
Vertical section NE 320° SE, BCRA grade 5 C
Survey: R. Blazek, T.I. Korneliussen,
J. Kyselak, S.E. Lauritzen,
P. Sevic and J. Svoboda.
Drawn by S.E. Lauritzen and J. Kyselak.
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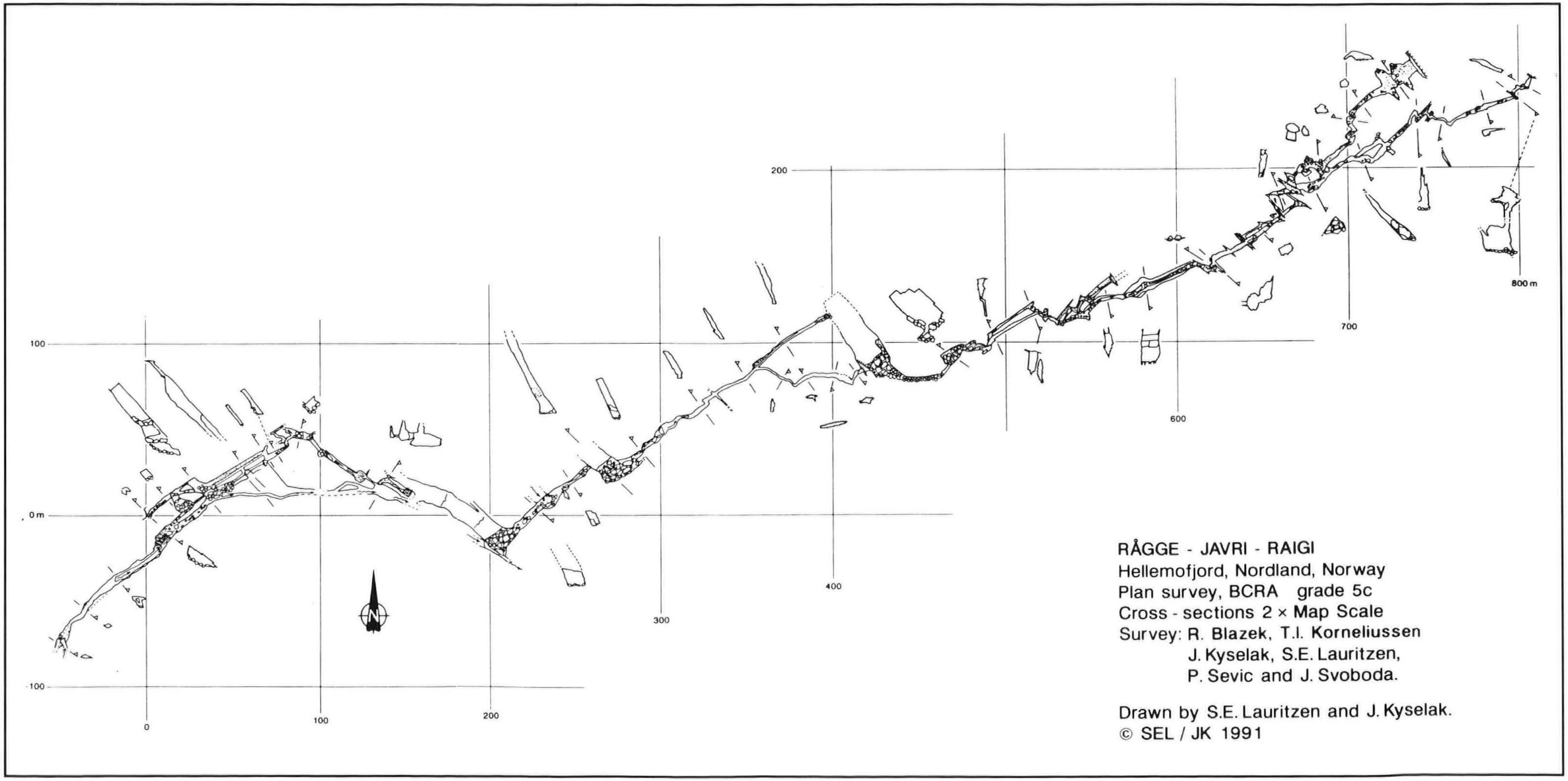
500
400
300
200
100
0
0
100
200
300
400
500
600
700 m

Figure 4 (above). Vertical section through RJR. The plane of projection is parallel with the strike of the host marble, NW 320° SE. The grid system refers to sea level as vertical datum, and the northward distance uses the upper entrance as origin. Grid interval: 100 m. Please note that the vertical grid lines shown are 100 m apart in this plane of projection; they are therefore not identical to those on the plan projection.

Figure 5. (below). Plan projection of RJR. All cross-sections (2X map scale) are shown looking downstream. The grid system has (0,0) in the upper main entrance, east is positive. Grid interval: 100 m.



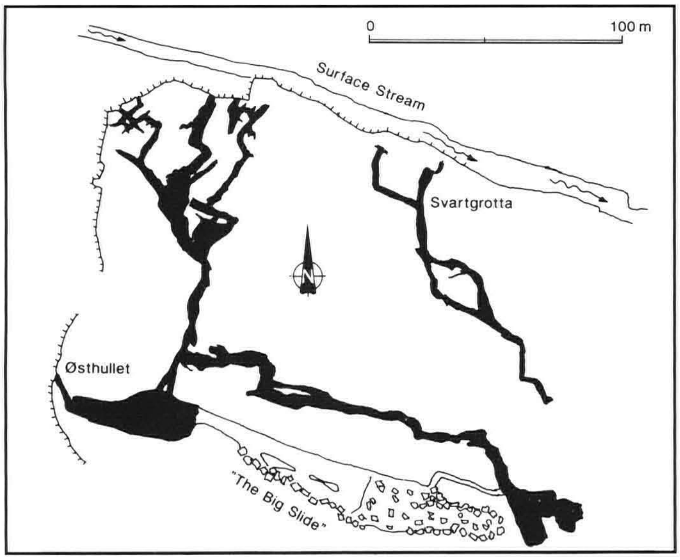


Figure 7. Plan of Østhullet, with extensions below "Giants Causeway". Original survey from Beck (1971), The Big Slide extensions drawn by J. Kyselak.

Beck (1971). We have inspected most of the known caves and provide modest additions.

Østhullet, extension of the Giants Causeway. A continuation of the main chamber, named the "Giants Causeway" by Beck (1971), was explored beyond the major boulder choke at the bottom of the chamber and the continuation found to run parallel with the main streamway passage (The Great Inclined Plane), and join into it at the terminus. The Big Slide extension adds nothing to the total depth of the system, but another 120 m to the length, now totalling some 900 m. The extension is shown in Figure 6.

The Lauknesfjell marble outcrop. As mentioned, the major marble outcrop, named the Lauknesfjell marble, supports some grikes and an underfit streamsink into the largest doline of the area. This small streamsink could not be penetrated. No other entrances could be seen within the doline, but a substantial snowpatch occupying the NE side halted complete inspection. On the distal ridge of the doline, several promising, choked shafts or widened grikes were located. Half a day was spent digging out one of these chokes. We penetrated some 2 m down; it still continues, but tools for moving large blocks are needed.

JRP-cave. Small cave entrances were found at the distal side of the marble outcrop, close to the fiord wall, but were choked with debris after a few meters. However, one of them could be explored for some 35 m at a relatively steep slope down to a boulder choke (Kyselak 1991). (See Figure 8).

Small canyon wall caves. The river draining from lake 735 into the Noroldahk-Raigi sink follows a minor marble band just downstream of the lake outlet. A series of small, shattered caves are located in the western canyon wall.

IMPACT OF VISITORS.

Due to the depth record and throughtrip possibilities, RJR has attracted numerous visitors from abroad during the past 20 years. Norwegian groups have also been active visitors, and we are of course aware that we, as scientists, also leave annoying signs of sampling and excavation behind us. The area has also become much more accessible, recently manifested by the hydroelectric power lines crossing the fiord just above the Noroldahk-Raigi waterfall sink. Wilderness, apparently, is the loosing part.

The impact of travel is quite visible in RJR, where distinct footpaths may be seen in several places. Occasionally, the limestone is abraded and often smeared with clay. Rusty rawlbolts may be seen in numbers above and around the major drops. Such worn belays and handholds would contribute to making the cave less safe with time. We found the lower route down to the Fiord Cave by tracing pieces of toilet paper and topofil string, hence the name "Bogroll Squeeze". Very few of these travel marks could be seen during a previous visit by one of us (SEL) in 1982, although Holbye (1977) reported that old telephone wire could be found inside the cave. We have finally removed this historically necessary wire of agony from the outside dump and brought it down by helicopter with our own garbage. Judging from the state of other caves in the area, RJR seem to have attracted almost all caving activity in the region. In our judgement, the Noroldahk caves were practically untouched in comparison with RJR. It is therefore evident, that the perhaps most famous of all Norwegian caves is in the process of sacrificing pristinity for the temporary benefit of its virgin neighbors.

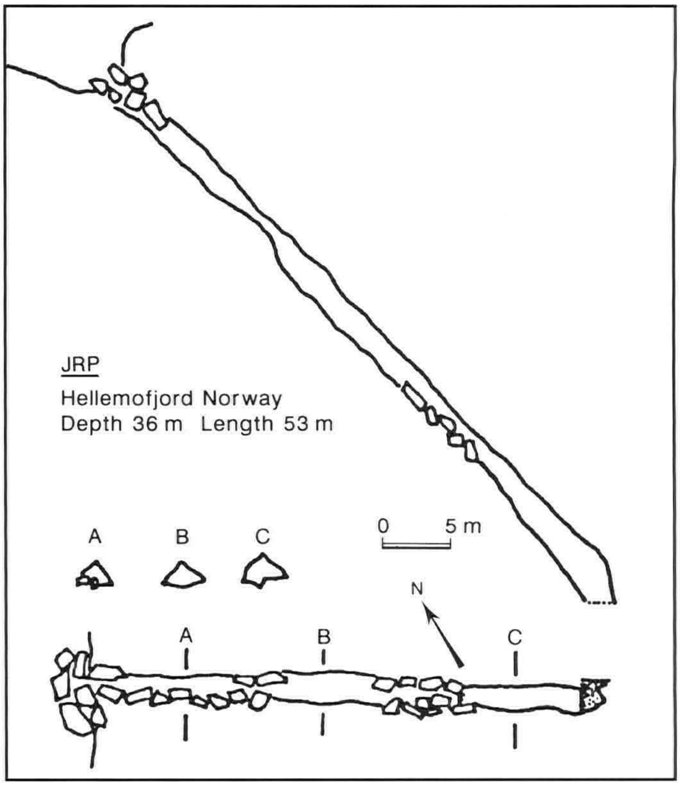


Figure 8. JRP-cave. From Kyselak 1991.

According to the value classification and management categories we have applied to Norwegian karst sites (Lauritzen 1988, 1991), RJR is a typical "sporting cave" and should also be devoted to this kind of use in the future. It is, however, an interesting site where we may test a cave's travelling capacity, i.e. how many visitors such a system may take before impact becomes visible. We would therefore appreciate receiving more accurate estimates of the total number of individual through-trips that have been made. Moreover, a few sensitive features are of scientific interest in the cave: insect remains and sediment banks. Both are rare and very vulnerable to trampling, and we hope they will remain as references for the future. For instance, we have just in time, "saved" a section of the Clay Pot deposit for paleomagnetic measurement. This site is a part of the much travelled Upper Traverse route down to Storstupet.

Another unique value of RJR is the strong thermal wind through the entrances. This phenomenon is unlikely to be affected much by future use of RJR, provided that no changes are made to entrances or constrictions inside the cave.

ACKNOWLEDGEMENTS

Field work was financially supported by the Norwegian Science Foundation (NAVF), the Norwegian Oil Directorate, the Directorate of Nature Management and by Fridtjof Nansen and affiliated funds for the advancement of Science and the Humanities. Expedition members were, in addition to the authors: Petr Sevcik, Jitka Sevcikova, Radek Blazek, Jan Svoboda and Tor Inge Korneliussen. We also enjoyed support from members of the Czech "Trias" caving club who joined us for a shorter time. Our efficient sampling and surveying programme would never have been possible without excellent rigging done by Iain Schrøder and his Norwegian "adventure travel" group of no less than 18 persons! Survey parties were: Upstream parts and Ice Climb to Fiord Cave (P. Sevcik and R. Blazek). Drinking Pool - Ice Climb and Clay Pot - Upper Traverse (S.E. Lauritzen and T.I. Korneliussen). Remaining parts were done by J. Kyselak and J. Svoboda. The expedition was organized after the "Kon-Tiki Raft" model: an international team working together within a lateral rather than pyramidal organization. All members contributed equally to the present result. This has proven successful before (i.e. Lauritzen *et al* 1986). Although food preparation was a circulating duty, we all became faint amateurs when encountered to the delicious, spicy meals of Jitka Sevcikova. The people in Musken provided tolerance and helpfulness, and the council of Tysfjord municipality permitted the use of helicopter on the state-owned land. Needless to say, we are also indebted to the original explorers for their surveys and the ideas they have initiated. We owe them all our sincere thanks. This is contribution No. 24 of the Karst research Project in Norway.

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Appendix: Nomenclature of RJR.

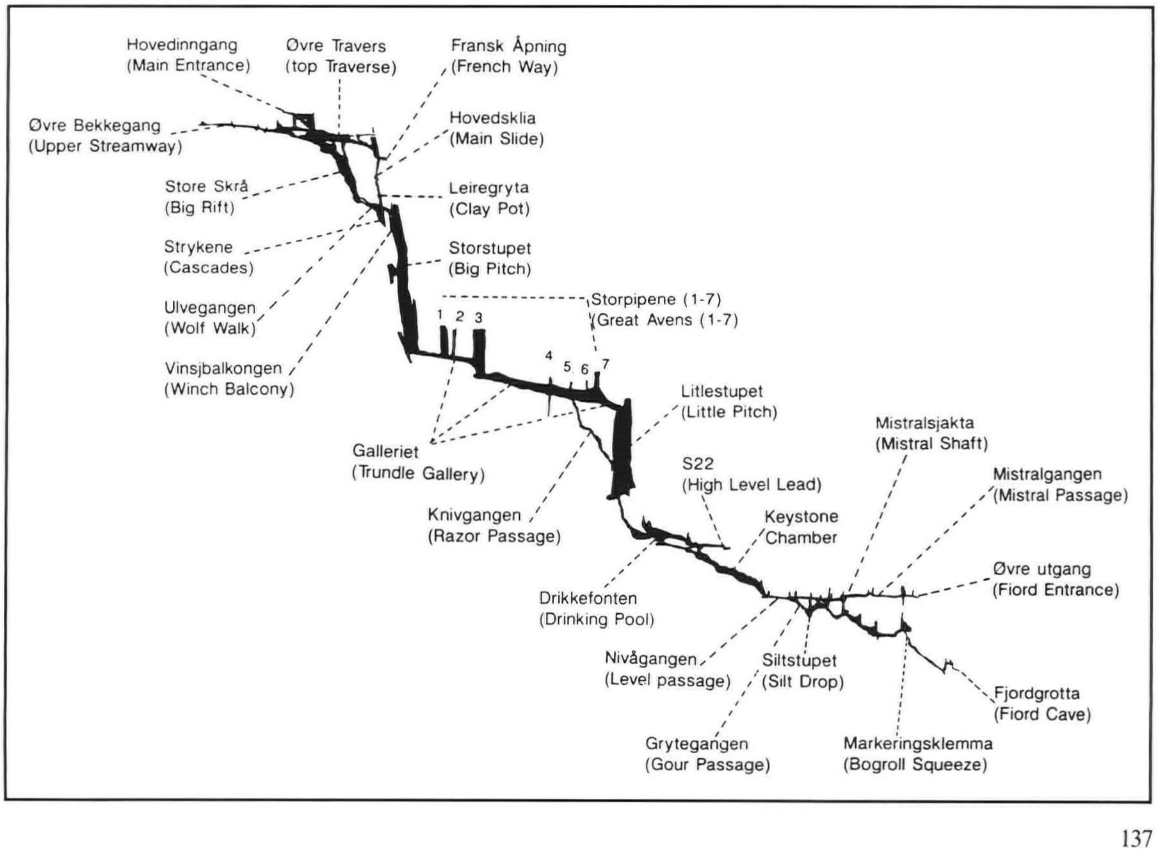
Beyond any doubt, the original explorers possess the sovereign right to name the features which they document on their surveys. On the other hand, later explorers (i.e. Holbye 1977) have advocated the need for translating English names into the language of the host country. This attitude was already customized by Heap (1969), who adapted the Lappish naming of the cave itself. The lake is named Rågge-Javri, meaning "the lake in the (shallow) pit". Raigi means cave, hence the cave's name would read something like "Pit-Tarn-Cave". This is not a unique name, as there are several tens of "Rågge-Javri" tarns and lakes in northern Norway, many of them with caves connected to them. But RJR is indeed *the Rågge-Javri cave,* and of course, nobody would ever dare to challenge this name elsewhere!

In the following, we present our attempts to make appropriate translations of the original KCC English names and vice versa, with one exception: "The Hall of The Mountain King". This name, "Dovregubbens Hall" in Norwegian is taken from the Peer Gynt suite by the Norwegian composer Edvard Grieg, and has unfortunately been thoroughly abused ever since by the tourist and film industries. Second, "Dovre" refers to a mountain massif in *South Norway.* Third, the term refers to "Trolls", which are not inherent in Lappish tradition; we may rather encounter the "Stallo" (devil) in names like Stallo-Råggi (Devil's pit). For all these reasons, "Hall of the Mountain King" does not sound too good to most contemporary Norwegian cavers. Holbye (1977) expressed similar views and suggested the understatement: Litlestupet (Little Pitch!) for the site. This has been in use ever since, and we take the liberty of adapting the name as permanent. Other names, like "Keystone Chamber", sounds good to us, and we have decided to entirely use the English form. Being aware that naming is a sensitive issue, subject to taste and therefore endless debate, we nevertheless hope that our suggestions in Table II and Figure 9 may be used as a consistent nomenclature for the future.

English name	Norwegian Standard	Lappish form
Main Entrance	Hovedinngangen	Canadag
Upper Streamway	Øvre Bekkegang	—
Big Rift	Store Skrå	StuorGållo
Top Traverse	Øvre Travers	—
The French Opening	Fransk Åpning	—
Main Slide	Hovedsklia	—
Clay Pot	Leiregryta	—
Wolf Walk	Ulvegangen	—
Cascades	Strykene	—
Winch Balcony	Vinsjbalkongen	—
Big Pitch	Storstupet	Stuorgahcdag
Great Avens (1-7)	Storpipene (1-7)	Riephena
Trundle Gallery	Galleriet	—
Razor Passage	Knivgangen	Salsag
Hall of M. King	Litlestupet	Hagno
Balcony	Balkongen	Latnja
Drinking Pool	Drikkefonten	—
Keystone Chamber	Keystone Chamber	—
High Level Lead	S22	—
Gour passage	Grytegangen	—
Silt Drop	Siltstupet	—
Ice Hall	Ishallen	—
Ice Climb	Isblokka	—
Mistral Passage	Mistralgangen	
Mistral Shaft	Mistralsjakta	—
Bogroll Squeeze	Markeringsklemma	—
Fiord Entrance	Øvre Utgang	Ålgus
Fiord Cave	Fjordgrotta	Vuoleb RJR

Table II Nomenclature in RJR (Lappish names adapted from Holbye, 1977).

Figure 9. Places and names in Råggejavri-Raigi



CAVE SCIENCE Vol. 18, No. 3, December 1991
Transactions of the British Cave Research Association

Cave Development on New Providence Island and Long Island, Bahamas

John E. MYLROIE, James L. CAREW, Neil E. SEALEY and Joan R. MYLROIE

Abstract: Survey and study of the rock of eight caves on New Providence Island, Bahamas, and six caves on Long Island, Bahamas demonstrate that the caves developed during a past interglacial sea level high stand. The cave morphologies are consistent with formation under flank margin model conditions. These dissolution features developed under the flank of subaerial ridges at the distal margin of a discharging fresh or brackish water lens where superposition of the vadose/phreatic mixing zone and the marine/fresh water mixing zone occurs. On each island there is a cave that shows evidence of development and subsequent subaerial exposure followed by further dissolution. The features of these two caves may provide evidence for sea level fluctuations during a single interglacial sea level high stand, or less likely, overprinting by a second interglacial high stand. Other evidence of multiple sea level high stands is found in another cave on New Providence Island, which has developed from one eolianite upward through an overlying paleosol into a second eolianite.

Based on an isostatic subsidence rate for The Bahamas of 1-2 m per 100,000 years, and sea level curves for the late Pleistocene, the time available for development of the caves was limited to the sea level high stands associated with oxygen isotope stage 5 that occurred between 85,000 and 140,000 years ago. Salt Pond Cave on Long Island contains a chamber with a volume in excess of 14,000 m^3. Given the limited time (no more than 30,000 years) during which sea level was high enough for dissolution of that chamber to occur in a freshwater lens, the rate of rock dissolution during formation of that chamber must have been no less than 0.5 m^3 per year. Large chambers formed in short time periods within a small freshwater lens call into question quantitative mixing-zone dissolution models such as those described for the Yucatan Peninsula of Mexico.

The caves of The Bahamas contain a wealth of information regarding the development of the islands during the last several hundred thousand years. The islands and their caves represent a record of climatic change and sea level fluctuations that occurred during the Pleistocene Epoch, when ice sheets repeatedly advanced across the latitude portions of continents and then retreated. The total range of sea level change during the Pleistocene is thought to have been about 130 metres (425 feet), from a 6 m higher to almost 125 m lower than today (Carew and Mylroie, 1987a).

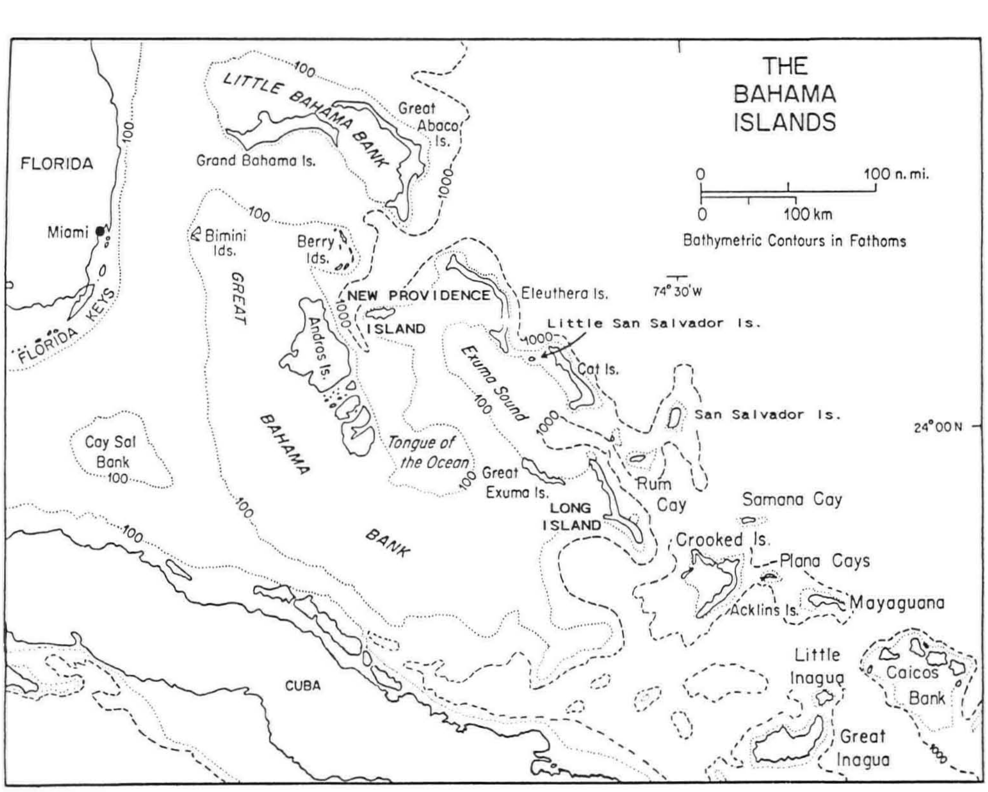
The Bahamas have long been famous for their Blue Holes, which are water-filled shafts that extend below modern sea level and often lead into caves that extend for significant horizontal distances (R. Palmer, 1985). In contrast, the caves that extend above modern sea levels are not as well known. The early study of caves in The Bahamas usually concerned their archaeologial or paleontological potential (Granberry, 1980; et. al., 1990). Other early cave reports were from zoologists that studied bat populations (Koopman, et. al., 1957; Budge, 1975; 1985). Comprehensive and systmatic examination of Bahamian caves did not begin until the late 1970s. Since then work carried out on San Salvador Island (Mylroie, 1983; 1988; Carew, *et al.*, 1982; Mylroie and Carew, 1988; 1990; Vogel, *et al.*, 1990) and Cat Island (R. Palmer *et al.*, 1986) has documented a great variety of caves. Preliminary work has also been done on Eleuthera and Great Inagua Islands (Mylroie, 1988, and on South Andros Island (Carew and Mylroie, 1989).

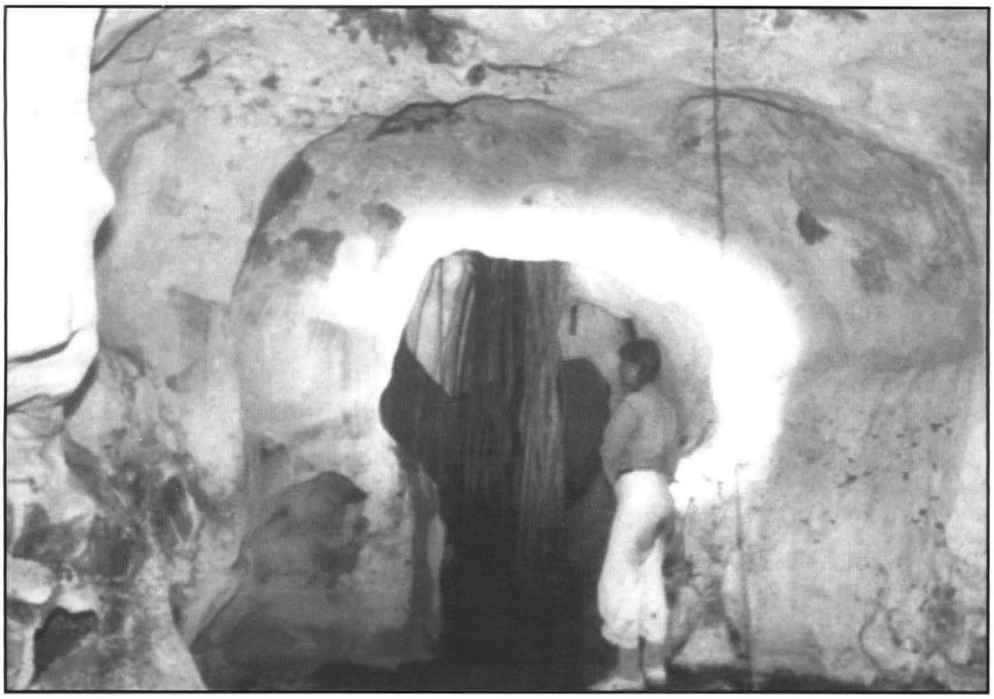
GEOLOGIC AND HYDROLOGIC SETTING

The Bahamas islands are an archipelago that stretches 1,000 km from near the Florida peninsula on the northwest to Hispaniola on the southeast (Figure 1). They are low-lying carbonate islands with eolian (dune) ridges that extend up to 60 m above sea level. The islands are tectonically stable and appear to be isostatically subsiding at the rate of no more than a few metres per hundred thousand years (Carew and Mylroie, 1985). Therefore, any caves that occur above sea level in The Bahamas must have been produced when sea level was higher than it is today. Clear evidence of such past higher sea levels can be seen throughout The Bahamas in the form of fossil coral reefs that occur as high as four metres above modern sea level (Curran and White, 1989).

In any essentially homogeneous body of rock like that of the Bahama Islands, the freshwater lens floats on underlying denser

Figure 1. Map of The Bahamas, showing locations of the islands discussed in the text.





Cave passage in Harry Oakes Cave, New Providence Island. The cave walls show the large-scale cusps typical of flank margin cave development, which in some cases becomes a series of globular chambers arranged like beads on a string. Tree roots are present in foreground and background.

sea water that permeates the carbonate islands. The model for the ideal behaviour of these water masses is the Ghyben-Herzberg model. In reality, variations in rock permeability and other factors result in the distortion of that ideal lens shape (Vacher and Bengtsson, 1989). None-the-less the Ghyben-Herzberg model serves as a useful first approximation of the relationship between the freshwater and the underlying marine groundwater in an island.

During past higher stands of sea level, the fresh groundwater lens in each island was higher than it is today. Beneath the surface of these past freshwater lenses, within the limestone rock of the islands, caves were produced by dissolution. Each time sea level fell, the caves became abandoned and dry. Under today's climatic conditions the earth is warm and sea level is relatively high, but not quite as high as at some times in the past. We can therefore enter dry caves today in The Bahamas. In contrast, the Blue Holes of The Bahamas lead into caves that formed when sea level was lower than today, and they are flooded at modern sea level position. The Blue Holes of The Bahamas represent the cumulative dissolution that has occurred during many sea level fluctuations. So the complexity of cave passages found in Blue Holes is the result of overprinting of repeated marine, freshwater, and subaerial conditions during the Pleistocene. Conversely, the currently dry caves of The Bahamas formed during the relatively short time periods of the Late Pleistocene when sea level was higher than at present. Bahamian caves that formed above modern sea level elevation in the Middle to Early Pleistocene have, by today, sunk below modern sea level because of isostatic subsidence of the platforms. Compensating for isostatic subsidence, analysis of the published sea level curves for the last 500,000 years indicates that sea level was high enough to produce the observed subaerial caves for a maximum of about 30,000 years of that time period (Mylroie and Carew, 1990). In addition, during such past sea level high stands, only the eolian ridges and a few beach and shoal deposits stood above sea level. During sea level high stands island size in The Bahamas was dramatically reduced compared to today's islands, and as a consequence, freshwater lens volumes and discharges were comparably reduced (Mylroie and Carew, 1990, Figure 4), The end result is that the dry Bahamian caves represent development in a very short period within small freshwater leases with minimal overprinting by later events. Any model that attempts to explain development of these caves must operate under severe constraints of time and space.

Even though the marine groundwater and the freshwater lens may both be saturated with $CaCO_3$, where they mix, the resultant combined chemistry will permit more $CaCO_3$ to be dissolved (Plummer, 1975; A. Palmer *et al.*, 1977). The potency of this dissolution mechanism has been demonstrated in The Bahamas (Smart *et al.*, 1988). Therefore, it is evident that caves should develop preferentially at the bottom of the freshwater lens, in what is referred to as the mixing zone or halocline. Even if the lens is brackish, dissolution still occurs in the mixing zone. Small caves may also form at the top of the freshwater lens (or watertable) where vadose water percolating down from the surface reaches and mixes with the freshwater lens (Mylroie and Carew, 1988).

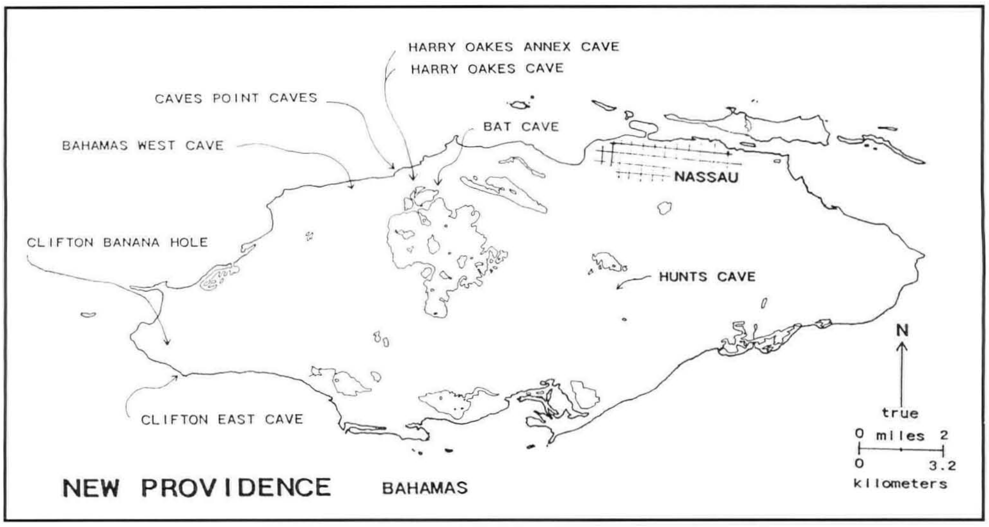
Sanford and Konikow (1989), based on studies from the Yucatan Peninsula in Mexico, have produced a quantitative model that explains dissolution at the margin of the freshwater lens as a result of concentration of discharge. Their calculations for dissolution in small islands, based on Bermuda as the example, imply that large caves cannot occur. The Yucatan model is driven by large freshwater discharges associated with a continental landmass. Such high discharges are not available in islands like those of The Bahamas, and at past higher sea levels, the islands would have been even smaller with concurrently smaller lens size and discharge. Research conducted on Andros Island has demonstrated that pervasive dissolution does occur in the mixing zone of a large island (Smart, *et al.*, 1988). Current numerical models of mixed-water dissolution appear inadequate to explain the development of large caves in small islands.

At the distal margin of the lens, near the shoreline of an island, the top and bottom of the lens are close together. There, the vadose/phreatic mixing zone and the marine/fresh water mixing zone are superimposed. It is in this setting, at the distal margin of past freshwater lenses, that the largest subaerial caves of The Bahamas are currently found. The superposition of the two favourable dissolution environments at the margin of the freshwater lens has been proposed as the reason that large dissolution caves can form in these islands under the given constraints of time, space, and discharge (Mylroie and Carew, 1990).

At times in the past, when sea level was higher than it is now, the only emergent portions of the Bahama Islands were the higher portions of the eolian ridges and related deposits. The caves of The Bahamas developed just under the flank of these ridges, at the margins of the discharging freshwater lenses. These caves have been termed "flank margin caves" (Mylroie, 1988).

Flank margin caves have a limited variety of morphologies. They consist of oval or linear chambers that are oriented parallel to the trend of, and just under the flank of, the ridge in which they have formed. Small radiating tubes extend from these large chambers into the ridge interior where they end abruptly or pinch out. Many cave passages loop back into one another or the main chamber, and isolated bedrock pillars and thin wall-partitions are common. A more complete discussion of the freshwater lens, cave development, and the flank margin model can be found in Mylroie (1988), Mylroie and Carew (1988), Mylroie and Carew (1990), and Vogel *et al.* (1990).

The flank margin model was developed to explain the numerous caves found on San Salvador Island, Bahamas, and a small number of caves observed during short visits to other Bahamian islands. Research reported in this paper was conducted on New Providence Island and Long Island, Bahamas, in 1988 and 1990 to determine whether caves located in those two islands had the morphologies and occurred in settings predicted by the flank margin model.



Map of New Providence Island, Bahamas, showing locations of caves from the island mentioned in the text, lakes, and the capital city of Nassau.

CAVE DESCRIPTIONS

The caves were surveyed using a Suunto compass and inclinometer, with fibron fibreglass tape graduated in metres and centimetres. Cave survey data was reduced and plotted each evening. Loop closure errors were less than 1%. Cave elevations were determined from Bahamas Lands and Surveys topographic sheets of the islands. Because of the thick vegetation, it was not possible to tie the cave surveys to benchmarks. Therefore cave elevations given in the following descriptions should not be considered accurate to better than one metre.

NEW PROVIDENCE

Figure 2 shows the locations of the caves of New Providence Island that are described in this report. Because of the high degree of commercial and residential land development around the Bahamian capital of Nassau, New Providence has many roads and road cuts which make the geology and the cave sites extremely accessible compared to other Bahamian islands. While there are probably more caves on the island, we believe we have located and surveyed the majority of the accessible large caves.

Caves Point Caves

Two of the best known caves in all of the Bahamas are found at Caves Point on the north shore of New Providence. The caves are easily seen from the road, and the area around the entrances is a small park. There are two main caves. Erosion of the hillside in which they developed has removed their outer (northern) chamber wall and exposed their interiors. It is possible that they once shared a common passage or chambers that are now eroded away. The entrance chambers have a floor about 3 metres above sea level.

Caves Point East Cave — This cave is basically a large single chamber (Figure 3). The east-west oriented entrance is 21 m wide and averages 3 m high. The chamber extends 16 m to the south. It has a bedrock floor that rises to the rear of the cave, and the ceiling is breached by two dissolution pits. The cave has a more simple plan than most Bahamas caves, because it lacks a series of complex tubes and passages radiating from the main chamber.

Caves Point West Cave — This cave is similar to its eastern neighbour, except that the large, broad entrance chamber has passages off the back that lead to a large inner chamber (Figure 4). It is conceivable that such an inner chamber also lies behind the East Cave. This cave is a simple cave with two large chambers that overlap and are connected by a few opening that are several metres in diameter. The east-west oriented entrance is 23 m wide and the entrance chamber is an average of 3 m high. The entrance is the breached wall of a room that extends to the south about 9 m. To the west are several small chambers. The floor of the entrance chamber slopes upward to the south. Three holes in the floor of the chamber, and two holes at the back of the chamber lead down to a second, inner chamber that lies under and to the south of the entrance chamber. This room, that extends to the south, is 22 m long and 12 m wide, and the ceiling averages 5 m high. There is a low wide chamber developed further to the west from the inner chamber. The floor of the passages floods during high tide. All chambers have smooth, phreatic dissolution surfaces. A series of steps cut into the stone lead from the northernmost part of the inner chamber southward and up to the top of a collapse-block in the centre of the room.

Figure 3

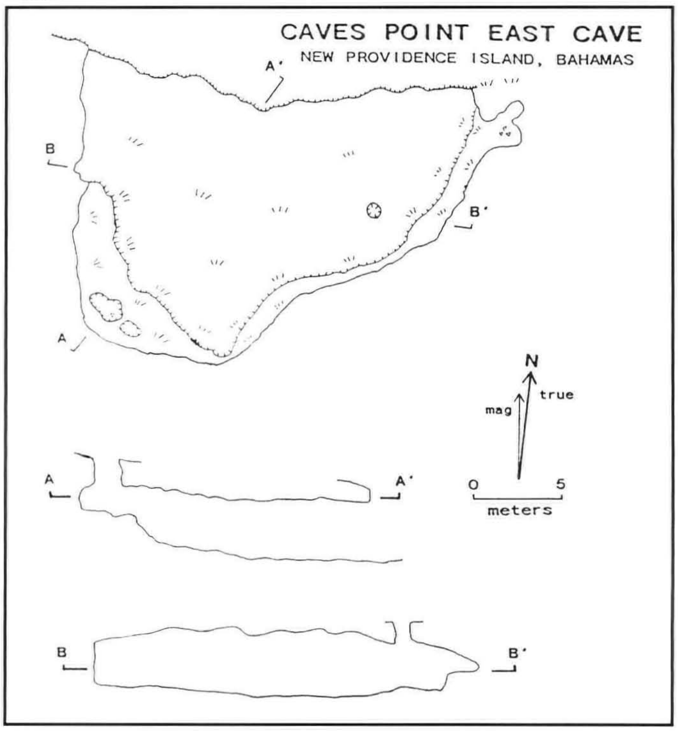
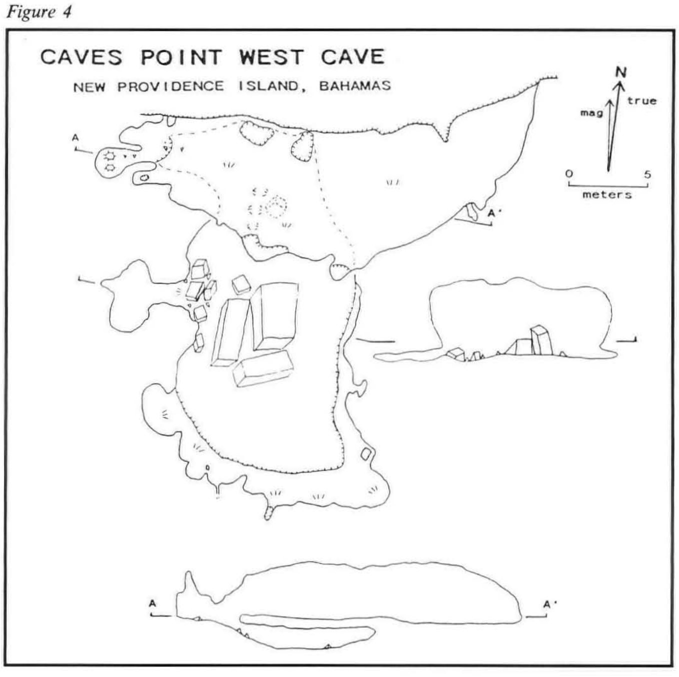


Figure 4



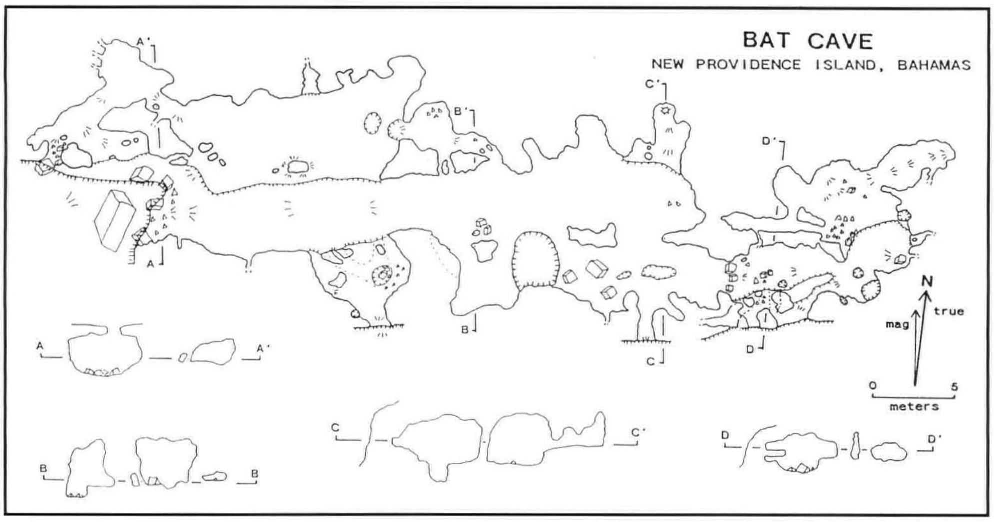


Figure 5

The large open entrance to the Caves Point Caves make them appear, at first glance, to be sea caves that formed during a past higher sea level. This is especially true for East Cave. However, close examination reveals flowstone and dissolved rock surfaces that are characteristics of phreatic cave development followed by a drop of the water level (during a sea level fall) and the deposition of secondary subaerial calcite (flowstone). The features of the inner chamber of West Cave could only have formed by chemical dissolution. Both caves lack the many small tubes and interconnections found in most flank caves, but the overall form fits the flank margin model.

Bat Cave

Bat Cave is located west of Lake Cunningham but east of Blake Road on the southern flank of the ridge just north of John F. Kennedy drive. The cave trends east-west, parallel to the south slope of the ridge, for 57 metres (Figure 5). The cave has at least 10 entrances, and a number of other small daylight holes. It is tucked just under the flank of the ridge, and all the entrances are located where erosional retreat of the slop has breached the underlying cave passages. The cave floor is approximately 3 m above sea level. The cave is essentially one long passage with small rooms and loops that add complexity.

From the eastern 3 m deep pit entrances, a series of low (1 to 1.5 m high) chambers heads north and east for 10 m. To the west, the cave is of walking height and subdivides toward the south into two passages closely spaced one above the other. The passages pass a series of low entrances to the south. Continuing west, the passages unite and enlarge to over 3 m high and 10 m wide. Small rooms and passages leave the main passage at the floor and ceiling levels, but they either end abruptly or rejoin the main trend. There is a large entrance hole in the ceiling of the main passage, and a walking height passage continues to the large west entrance amid a pile of breakdown blocks. A complex of small tubes trends northwest from the breakdown before ending or opening into the western entrance area. Bat Cave is a classic flank margin cave, with looping and dead-end side passages, maze-like characteristics, a large central chamber extended parallel to the eolian ridge margin, and many thin wall partitions and bedrock pillars.

Harry Oakes Cave

This cave was used by Harry Oakes, a famous personality in Nassau in the 20s and 30s, as a place to hold social events. The central chamber of the cave has a depression that was made into a swimming pool, and walkways can still be seen leading through the cave. Along the walls there are carved niches that held lanterns.

Harry Oakes Cave is located south and downslope of the old Harry Oakes mansion which is situated on the ridge above Caves Point and east of Blake Road. The cave is on the south flank of the ridge, and the cave floor about 3 m above sea level. The cave trends east-west for 47 m (Figure 6). Its large central chamber is breached along the south margin, and this forms the main entrance to the cave. Other smaller entrances are found to the east and west, where retreat of the hillslope has not breached the cave as fully. From the broad main entrance a large chamber extends 15 m to the north and 20 m east-west. The ceiling of this chamber is breached by one large and many small pits and collapses. About 10 m to the west, a series of small passages and rooms leads to a tiny entrance. The bulk of the cave lies eastward, where the entrance chamber leads through a broad arch to a room that is 12 m by 10 m. To the south, the room leads over a collapse to another large entrance. To the north, the cave trend curves as a large passage to the northeast, then south to still another entrance. A warren of small rooms and passages to the east leads to yet another small entrance area. There are a number of small holes that penetrate up to the surface above. The cave exhibits the

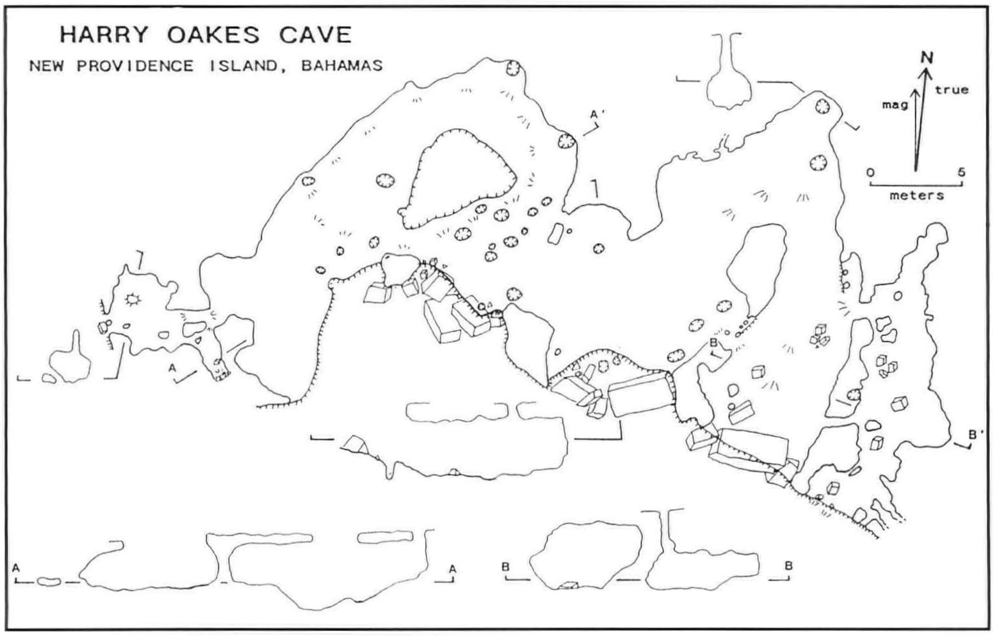


Figure 6

Small tubes and pockets dissolved into the wall of a passage in Harry Oakes Cave, New Providence Island. This type of dissolutional fretwork is common on the margins of cave chambers and passages in the Bahamas.

classic characteristics of a flank margin cave, but it is in an advanced stage of degradation by surface erosion. The wall of the main chamber has a horizontal notch or groove at an elevation of about +5 m. The notch appears natural, and may represent a past level of the water table, halocline, or soil infill.

The western end of the cave opens to an area of large collapse, and the cave probably originally continued farther west to Harry Oakes Annex Cave, before collapse severed the system. The roof over the existing portion of the cave is within and perforated, and within a short amount of time (geologically), the Harry Oakes Cave main chamber will collapse, leaving only isolated fragments of the cave.

Harry Oakes Annex Cave

About 100 m west of Harry Oakes Cave, along the strike of the south flank of the ridge and at the same elevation (+3 m) is Harry Oakes Annex Cave. The western-most entrance of Harry Oakes Cave leads into a large salient in the flank of the hill that is filled with collapse debris. On the far (west) side of this feature is the eastern entrance to Harry Oakes Annex Cave. This cave is 20 m in east-west dimension, and extends only 10 m northward into the hill (Figure 7). There are two adjacent entrances at the western end of the cave. The cave passages average 3 m high and 4 m wide and enlarge into rooms in the middle and at the west end of the cave. Bats roost in the central region of the cave. The ceiling of the cave at the west end has a number of extremely symmetrical cylindrical holes that are about 0.5m in diameter and 0.5 to 0.75 m high. The ceiling is at about +5 m elevation. Most cave ceiling pockets or holes in The Bahamas are bell shaped, but these have a flat top with perpendicular walls.

Harry Oakes Annex Cave is an isolated fragment of what was once a very large cave that extended east into Harry Oakes Cave. The morphology of this remaining fragment is consistent with that of a side passage off a large central chamber of a flank margin cave.

Bahamas West Cave

Bahamas West Cave is located about 1 kilometre west of Caves Point in the Gambier area. It is on the south side of an east-west eolianite ridge that runs along the north coast of New Providence Island. The cave extends northward under the hill from the south flank of the eolianite ridge. It has an original natural entrance at the southeast end of the cave, and several new entrances to the west that were produced by recent excavation for land development. The cave floor is about 3 m above sea level. All the entrances lead into the central main chamber of the cave, which is 15 m wide and extends 20 m northward into the ridge (Figure 8). The ceiling is generally 2 to 3 m high. A few small holes in the ceiling open from this chamber to the surface above. To the west there are a few small rooms. To the east and north are a series of small rooms with a multitude of small unenterable passages that lead off from them. One major passage leads northwest from the central chamber. It passes under a 6 m high dome in the ceiling and into a series of low crawls and small chambers which soon end. This northwest portion of the cave has a few bat colonies.

An interesting aspect of this cave is that dissolution has extended upward from the eolianite into an overlying paleosol that consists of angular rock fragments in a red matrix (a breccia). Examination of the surface outcrop above the cave shows that a younger eolianite has been deposited over that peleosol. The paleosol is essentially a limestone unit, and smooth, curved dissolution surfaces pass from the wall rock of the cave through

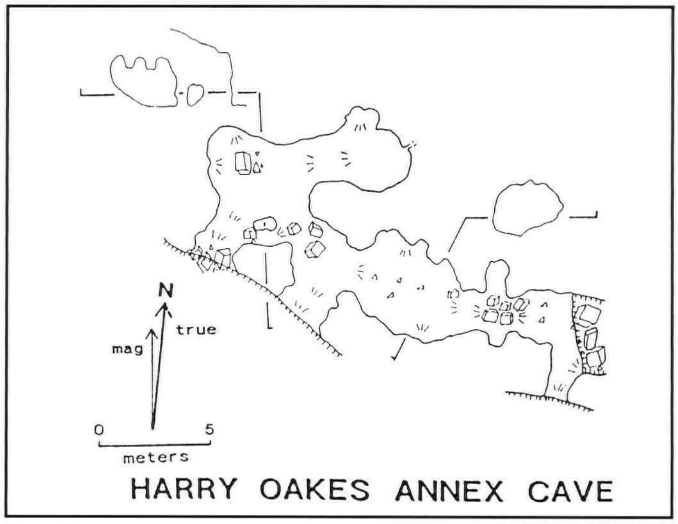
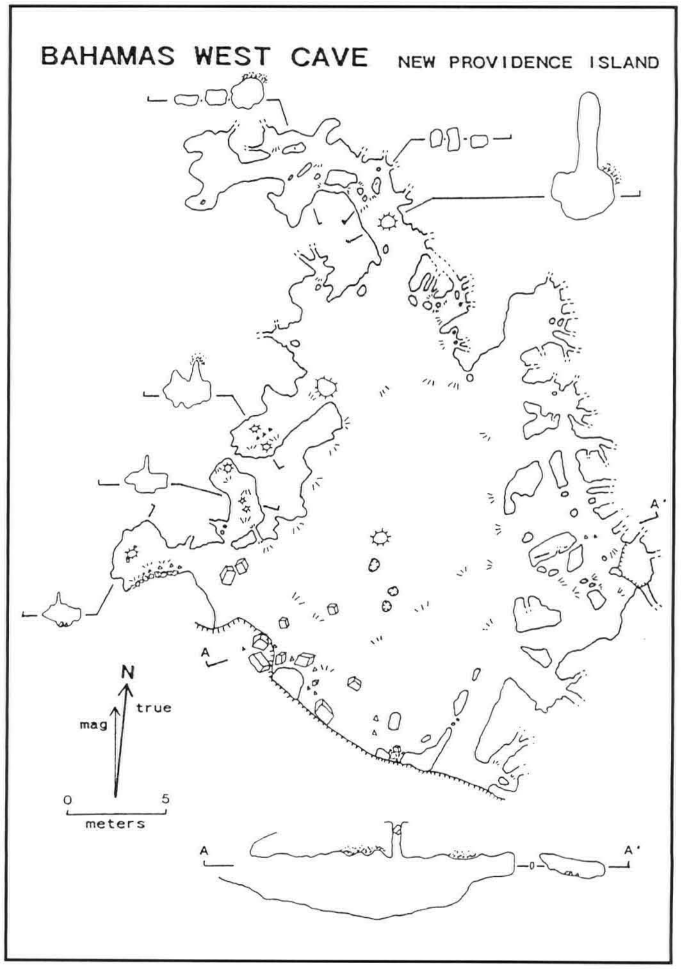
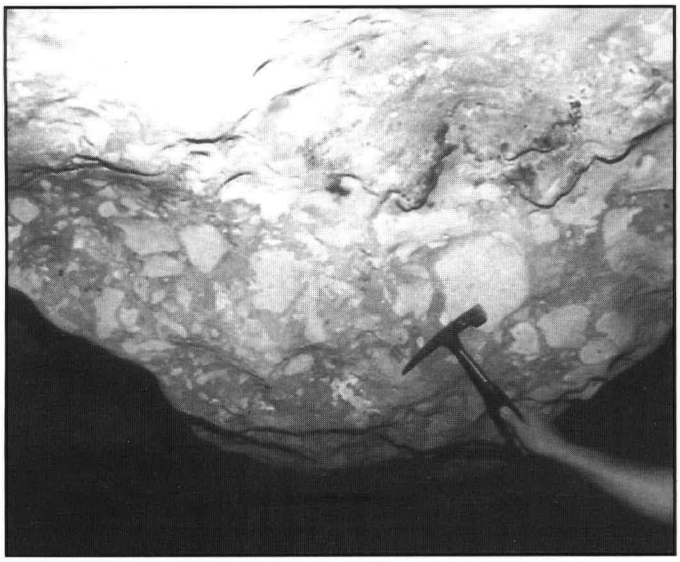


Figure 7

Figure 8. Map of Bahamas West Cave, New Providence Island. Patterned areas shown on cross sections represent paleosol outcrop with dissolutional surfaces.





Breccia facies, possessing the characteristics of a paleosol, in the ceiling of Bahamas West Cave, New Providence Island. Note the dissolution surfaces in the paleosol, and the smooth surface transition from matrix to clasts to surrounding eolianite.

Figure 9

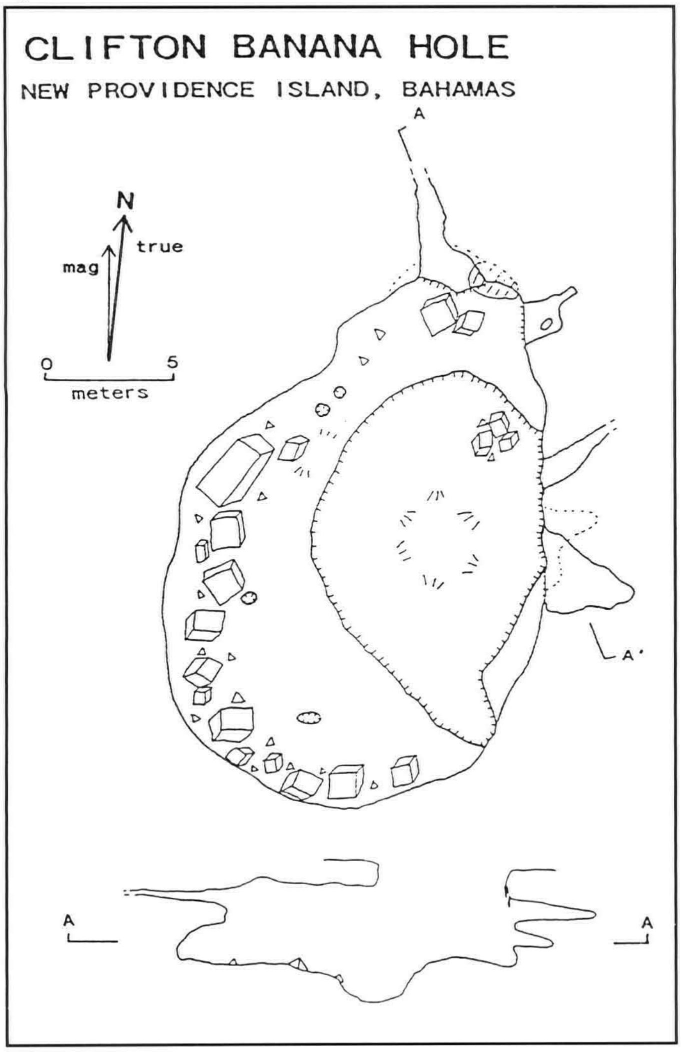
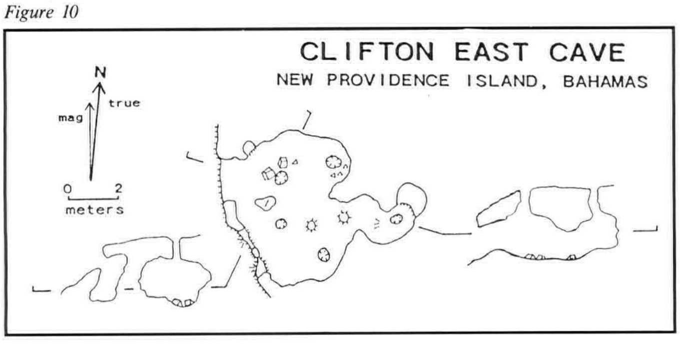


Figure 10



matric and clasts of the paleosol as a continuous and uninterrupted surface. In a few places within the cave, the paleosol has been penetrated and dissolution has reached into the younger eolianite. Therefore the cave must be more recent than the younger overlying eolianite

Clifton Banana Hole

Clifton Banana Hole is adjacent to the west side of the road that runs south from Lyford Cay to Clifton, about halfway between the two communities. Although surrounded by bush, the large entrance pit has an iron railing which can be seen from the road. The cave is a large dissolution chamber that can be entered where the ceiling has collapsed (Figure 9). The entrance pit is 13 m north-south and 9 m east-west. It can be entered by a free-climb at the northeast side. After a climb of 4 m down, one enters a large chamber that is 20 m north-south and 14 m east-west. The remaining bedrock roof is only about a metre thick. In addition to the main pit entrance, the ceiling is breached by a number of small holes. The floor has a large amount of collapse debris and breakdown which slumps downward to a depression on the east side of the room. A few small passages lead off to the east at several levels, but they soon become low or end. To the north is a small basin which looks artificially excavated and which contained a pool of water. At ceiling level, above this pool, is a long low crawl that extends north for at least 5 m. The east wall of the chamber has stalactites and flowstone that are now drying and crumbling. These deposits indicate that the cave once had a complete roof and the propoer intgernal atmospheric conditions for the deposition of subaerial calcite.

Although it is exceptionally large, this cave is similar to many in The Bahamas that are called "banana holes". The banana holes of The Bahamas do not fit the setting of flank marging caves as they are not restricted to the flanks of eolianite ridges. Like Clifton Banana Hole, they are often found in low plateaux. They initially develop by dissolution below the water table, but later undergo extensive modification by vadose water and collapse when sea level and the freshwater lens fall in elevation. The origin of banana holes is problematic, and is the topic of current research (Smart and Whitaker, 1989; Mylroie, 1990).

Clifton East Cave

Clifton East Cave is located about 0.75 km east of the Clifton pier on the east flank of a small north-south trending eolianite ridge that lies along the southwest coast of New Providence. The cave entrances are about 3 m above sea level, and have been opened by erosional retreat of the slope of the ridge. The entrances lead into a small main chamber that extends 7 m north-south, and penetrates into the eolianite ridge about 5 m (Figure 10). The chamber is 2 to 3 m high and has a number of tubes that rise upward and breach to the surface. From the back of the main chamber a short passage leads east for 4 m. Clifton East Cave falls within the range of morphologies exhibited by flank margin caves, but it is the smallest version found on New Providence.

Hunts Cave

Hunts Cave is a well known cave that is marked on Sheet 2 of the 1:25,000 New Providence topographic map. The cave, which shelters a large bat colony, is located just south of Harold Pond and Fire Trail Road, and slightly west of a quarry on the southern end of a small northwest-southeast trending eolianite ridge. The entrance to the cave is at the end of a 15 m long trail that follows a low trough from a dirt side road to the entrance. The trough appears to be a collapsed cave passage, and low entrances and half-chambers can be seen along its length. From the entrance, the 5 m wide, 1.5 to 2 m high cave passage trends northward for 20 m to a major junction of passages (Figure 11). At the junction there are a number of large flowstone deposits that form part of the walls and ceiling and show evidence of phreatic dissolution, as was reported by Garrett and Gould (1984).

To the east of the main passage-junction a passage leads 7 m to an oval room that is 4 m in diameter and has a high arched ceiling. To the west, a passage leads 6 m to a room that is 11 m long and 3 m wide. Northward from the junction another passage continues a few metres to a 5 m diameter chamber with a 2 m deep pit in the floor. Small tubes penetrate the east wall of the chamber, and low passages penetrate to the west, northwest, and north. The low western passage enters the 11 m by 3 m room previously described. The northern and very low northwestern passages rejoin after 10 m. The northern passage, after a few metres, enters an area of pits and domes that extend 5 m up and 2 m down. Several small chambers open off this vertical complex at a variety

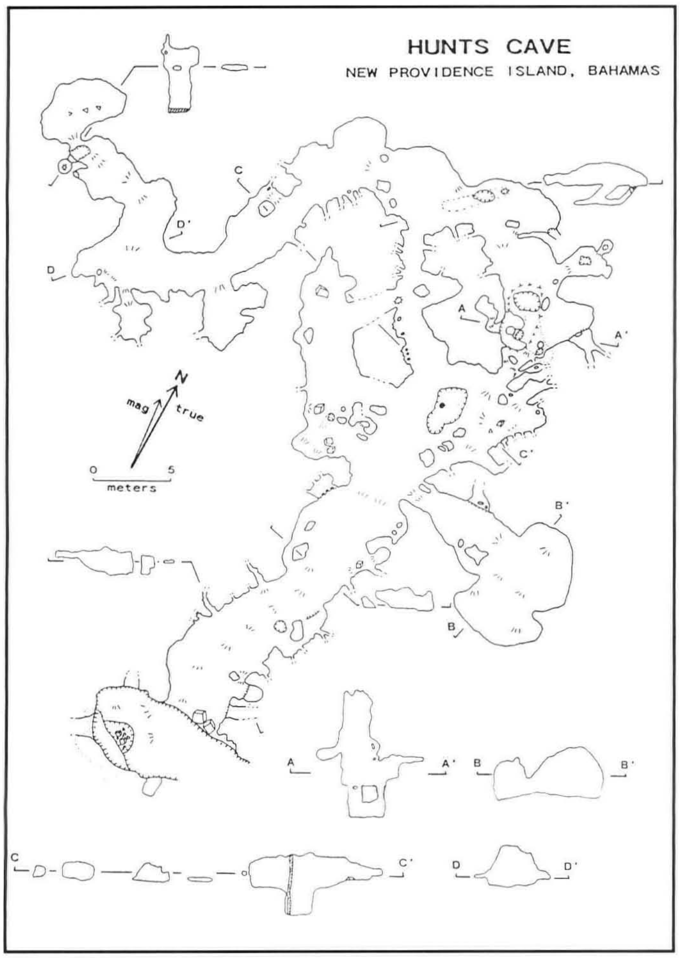


Figure 11

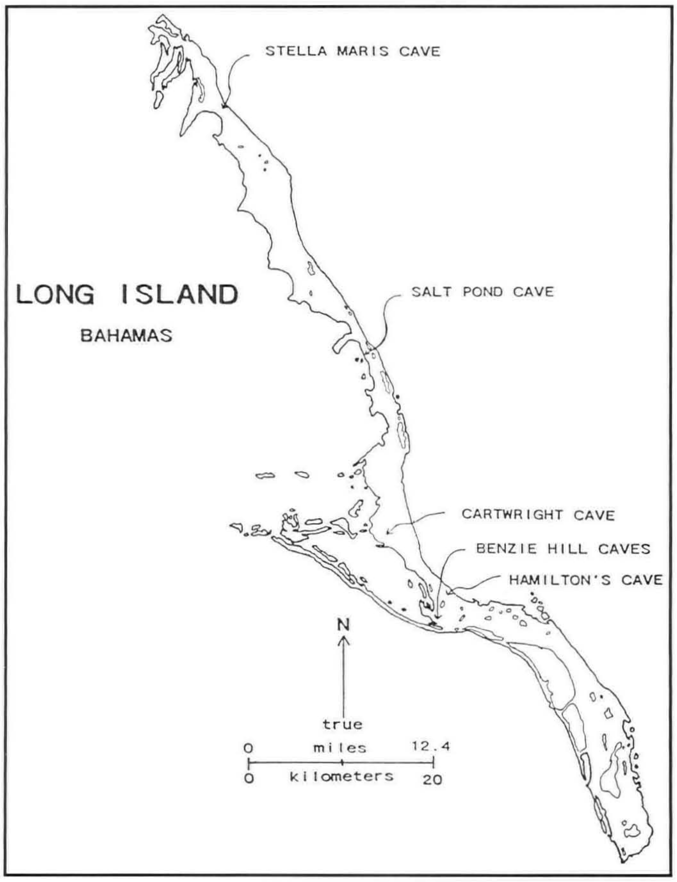
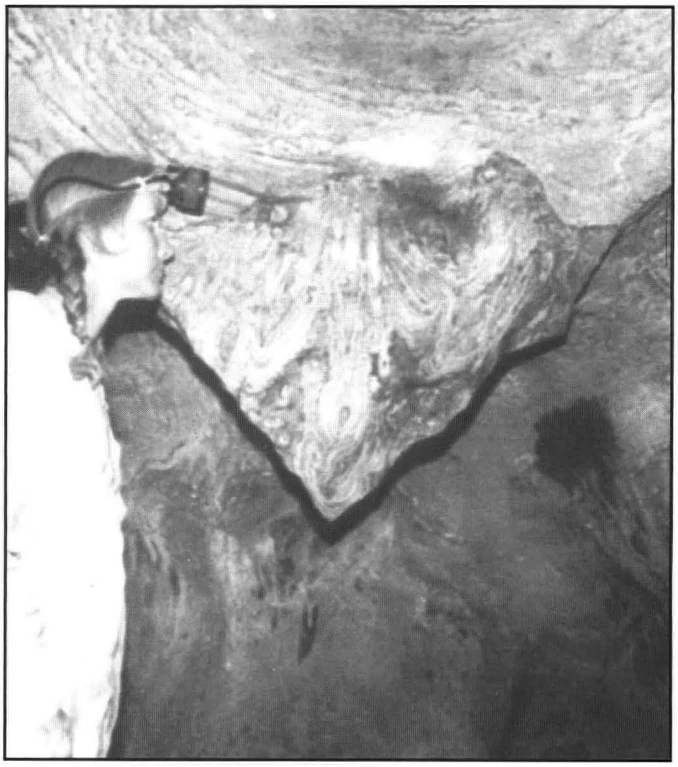


Figure 12. Map of Long Island, Bahamas, showing locations of caves from the island mentioned in the text.

of levels. The main trend continues north and northwest to where small chambers on the northern wall have pits that lead downward to a lower level that we have not entered because of the small passage size between the levels. At the junction of the northwestern and northern passages, a hole in the floor leads to a small room. From this junction the cave trends 35 m west, south, and west again as a low tube that is 2 to 4 m wide and 1 m to 2 m high. A few small chambers lead south from this passage. The passage ends in a low room just after passing a dome-pit to the south that leads 3 m down to water. Throughout the cave, the passage walls possess many small tubes that extend laterally from the main trend of the cave. The overall plant of the cave fits that of a flank margin cave. The central area of the cave is a collection of linked passages that approximate a large central chamber.

Other Caves

1. Luden's Cave is a small cave in Gladstone Ridge with 25 m of total passage that has been surveyed by the Bahamas Archaeological Team. The cave is short but of phreatic origin. About 100 m east of Luden's Cave is a very small dissolution pocket just big enough for one person to squeeze into.
2. Near the Fox Hill Blue Holes, on the east side of Nassau, there are some crevices and overhangs where subsidence has produced some small caves that are not true dissolution caves. Instead, they are similar to caves like Rat Bat Cave on South Andros Island, which was produced by progradation of collapse upward from a deep-seated dissolution void (Carew and Mylroie, 1989).
3. Adjacent to the quarry just east of Hunts Cave are a large number of incompletely investigated dissolution pits and small caves.
4. Just west of the pier at Clifton are a series of open fissures that lead underground. One fissure enters the cliffs on the coast and heads inland; another descends from the plateau above. These caves seem to be developed along tension cracks produced by block-gliding of the cliff face seaward. Their location at Clifton is probably the result of the narrowness of the shallow shelf at this locality. This situation is similar to that which has produced the large fracture systems that parallel the eastern shelf margin of South Andros Island (Carew and Mylroie, 1989).



Dissolutionally truncated subaerial calcite (flowstone) in Hunts Cave, New Providence Island. Truncated flowstone is seen as a pendant in the centre of the photograph, and in the upper right hand corner. The smooth dissolutional surface of the phreatic ceiling pocket at the top centre of the photograph continues across the dissolved flowstone pendant.

LONG ISLAND

Figure 12 shows the locations of the caves of Long Island that are described in this article. Long Island has many more caves than we could visit, let alone survey, in the time available. A select few were surveyed to provide an overview of the tremendous speleological potential of this island.

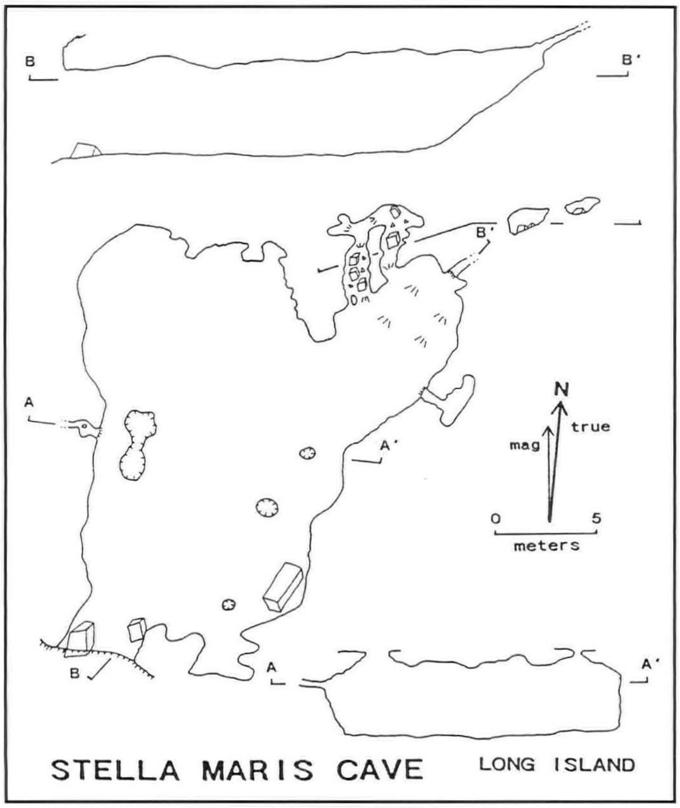


Figure 13

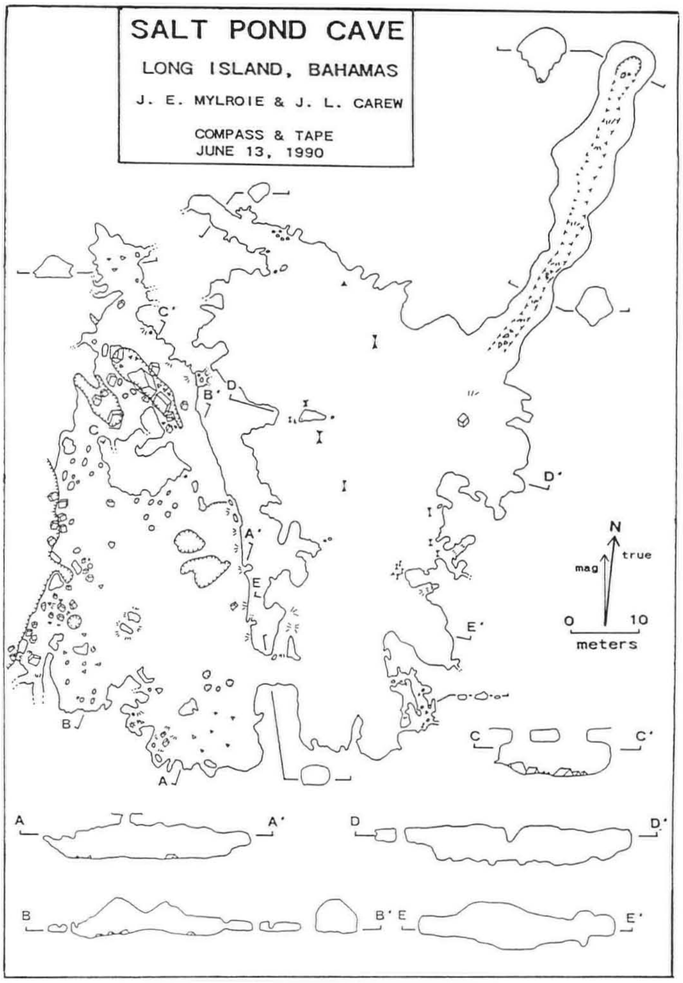


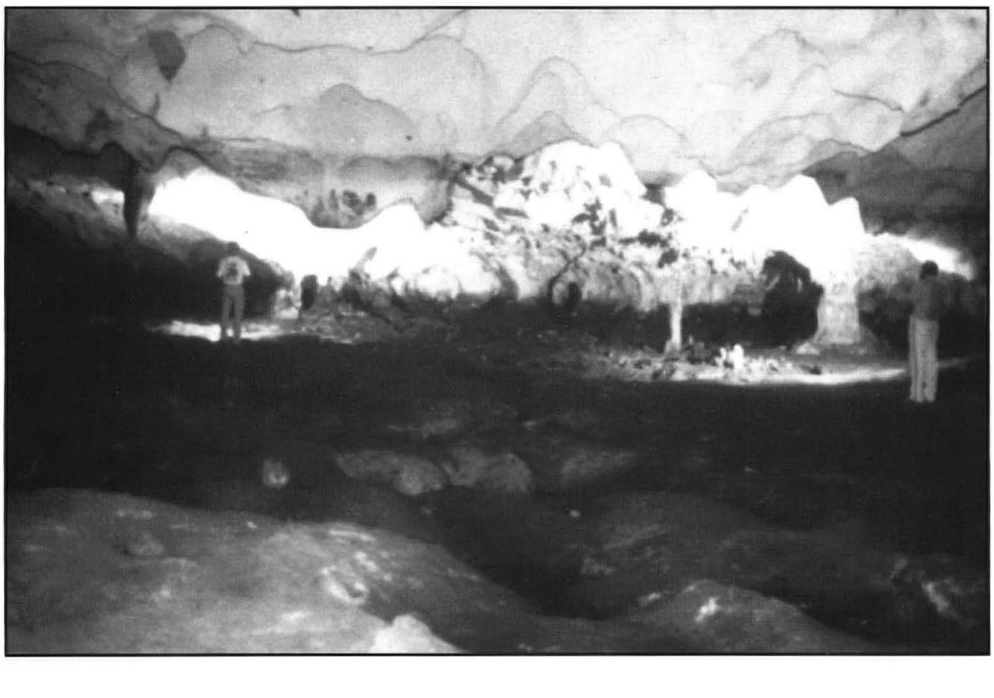
Figure 14

Stella Maris Cave

Stella Maris Cave is located in Stella Maris on the southwest side of an eolianite ridge that trends northwest-southeast on the eastern side of the island. The cave is used by the Stella Maris Inn as a night club. The cave is entered where the hillslope has eroded back and breached into the cave located in the flank of the ridge. The cave floor is about 4 m above sea level. The entrance is 4 m wide and leads into a large chamber that is 18 m wide and extends 25 m to the north (Figure 13). The ceiling is 4 to 5 m high, and there is one large skylight and several small tubes that reach to the surface of the hillside above. To the northeast, the main chamber ascends a bedrock slope and pinches out at a small tube. To the northwest of that slope, a series of tubes and and rooms that are 1 to 2 m high and a few metres wide form a loop. Near the ceiling, a few small tubes extend only a few metres into the east and west walls. The cave is a typical flank margin cave. The cave ceiling is soot-stained from the use of kerosene lighting, and from use of a barbecue pit. A model of a galleon, and other decorations for the hotel's bar are present in the cave.

Salt Pond Cave

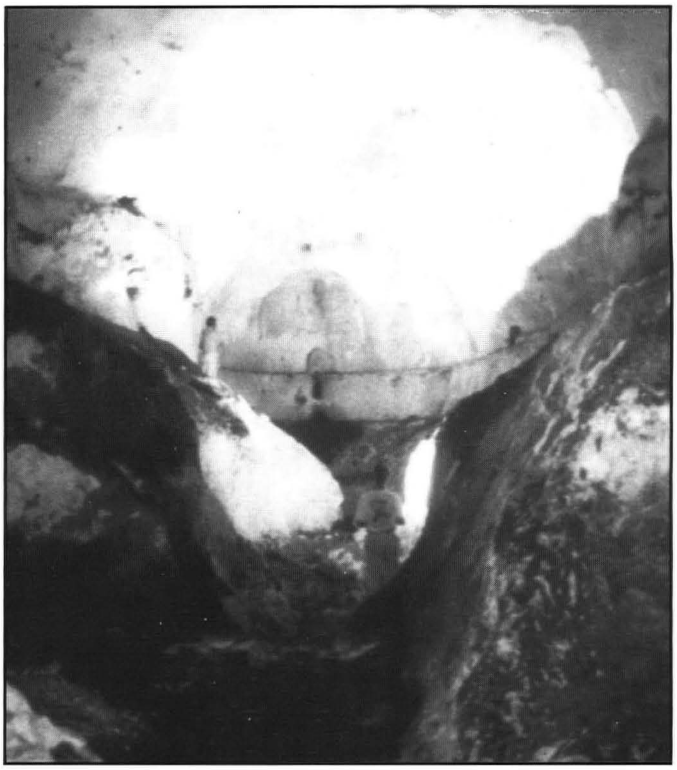
Salt Pond Cave is located on the northern outskirts of the settlement of Salt Pond on the west coast of Long Island. Just inland from the west coast, a series of pits enter the cave from above. The cave can also be entered from the west where its chambers have been intersected by erosional retreat of the hillside. The cave floor is 2 m above sea level. The cave comprises two very large and complex chambers that are separated by a thin bedrock partition (Figure 14). Short dead-end tunnels extend from these chambers. The main entrance to the cave is an opening that is 28 m wide and 1 to 2 m high, interrupted by collapse material and remnant bedrock pillars. This main entrance leads into a large chamber that is 40 m wide and penetrates 30 m to the east. The



A portion of the large inner chamber of Salt Pond Cave, Long Island. Phreatic dissolutional surfaces of the ceiling, walls and floor are evident. Total chamber volume is in excess of 14,000m³.

ceiling has two large skylights, and a number of small holes that extend to the surface. The southern wall of this chamber degrades into a series of alcoves, bedrock pillars, and tiny tubes. To the southwest, near the entrance, the passages are small and were incompletely explored. The eastern wall of this outer chamber is smooth, with only a few alcoves, except for the 3 m diameter tunnel that leads eastward to the large inner chamber. To the north, the outer chamber is low and very complex, with a maze of alcoves, bedrock pillars, and short tubes that lead into an adjacent northern chamber that is 15 m in diameter. This northern chamber has two large elongate skylights with a natural bridge between them that spans across the centre of the chamber. A tunnel 3 to 5 m wide and about 2 m high extends north from this chamber for 12 m before it ends.

A short 6m tunnel connects the southeastern portion of the outer main chamber to the southwestern portion of the inner main chamber. The outer chamber is dimly lit by daylight from the many entrances, but the inner chamber is totally dark. The inner chamber extends 70 m north-south, is 50 m wide, and is generally 3 to 4 m high. With a volume in excess of 14,000 m^3, this chamber is one of the largest in The Bahamas. This chamber would be considered an appreciably-sized void in most of the world's karst areas. The south wall of this chamber contains some small alcoves, but where the chamber wall swings around and becomes the east wall there is a small complex of passages. The east wall contains many alcoves and short tubes, and an occasional cluster of stalagmites and columns, most of which are desiccated. From the northeastern corner of the chamber a large oval tube 5 m wide and 7 m high extends north-northeastward for 52 m, then ends abruptly at a solid rock wall. This passage has beautiful dissolution sculpturing and a series of distinctive wall notches at approximately +5 and +6 m elevation which are horizontal and cut across the primary structure of the wall rock. Like the notch seen in Harry Oakes Cave on New Providence Island, these notches may relate to past water table levels, halocline positions, or the level to which cave earth and bat guano extended before it was removed. A bat colony roosts in the tunnel. The north and west walls of the inner chamber contain alcoves and exhibit broad dissolutional surfaces. A tube that is 2 to 3 m high and 3 to 4 m wide extends 18 m northwest from the northwest corner of the chamber, then ends abruptly. The cave has been mined of its guano and earthfill, and contains minimal breakdown and secondary calcite deposits. For these reasons, the original bedrock configuration of the cave is well displayed. Salt Pond Cave is a very good example of a flank margin cave, but on a grand scale.



Major side passage in Salt Pond Cave, Long Island. See persons in centre foreground and left centre background for scale. Note wall notches, and abrupt termination of the passage in a blank bedrock wall.

Cartwright Cave

Cartwright Cave is located in an eolian ridge to the east of Lower Deadman's Cay, about 1 km from the main road. The ridge containing the cave is pock-marked with a tremendous number of pits and shafts which were not investigated. Cartwright Cave has five entrances that are spread out along its 47 m length (Figure 15). The long axis of the cave is oriented east-west. The cave lies just under an east-west trending hillslope. The eastern-most entrance is a low arch that descends downhill into an oval chamber 6 m in diameter. The floor and ceiling follow the foreset beds of the eolianite and are spaced about 2 m apart. At the west end of this room two low passages, one above the other, lead 2 m into the second chamber, which has a flat dirt floor. This chamber is 7 m in diameter with a ceiling 4 m high. A bedrock slope to the north ascends up dipping foreset beds to a pit entrance that extends up to the surface. From the west end of this second room, a climb-up of 3 m, a crawl traverse of 3 m, followed by a 3 m climb-down leads into the third chamber. This is a 6 m wide and 4 m high elongate hall that extends 15 m to the west. A hole to the surface is tucked under the north wall of the room, which has a dirt floor with occasional blocks of loose rock. A few small alcoves trend southwest from this room, but the way on is northwest through a low arch into a 6 m diameter chamber with a hole to the surface. To the northwest out of this room two low crawls that are superimposed on one another unite after 3 m and a single crawl leads for 2 m via a very small passage to the last entrance at the western end of the cave. Foreset beds that dip 25 degrees from the north-northeast to the south-southwest appear to have controlled the passage cross sections. The cave is dry, and its floor is about 3 m above sea level. Instead of the more common single chamber configuration, this cave comprises a series of interconnected chambers developed parallel to the flank of the eolianite ridge and parallel to the strike of the dipping foreset beds. This configuration of chambers has been compared to beads on a string (Vogel *et al.*, 1990).

Benzie Hill Caves

The Benzie Hill Caves are located on the west side of Benzie Hill, near the east coast southeast of Hamilton's. There are two short caves here, both of which are found under the flank of the eolianite ridge that is Benzie Hill.

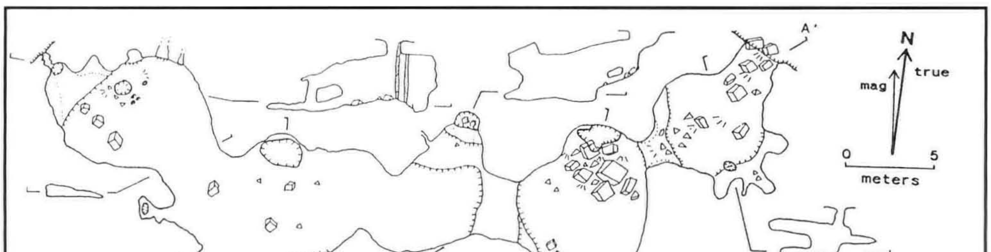
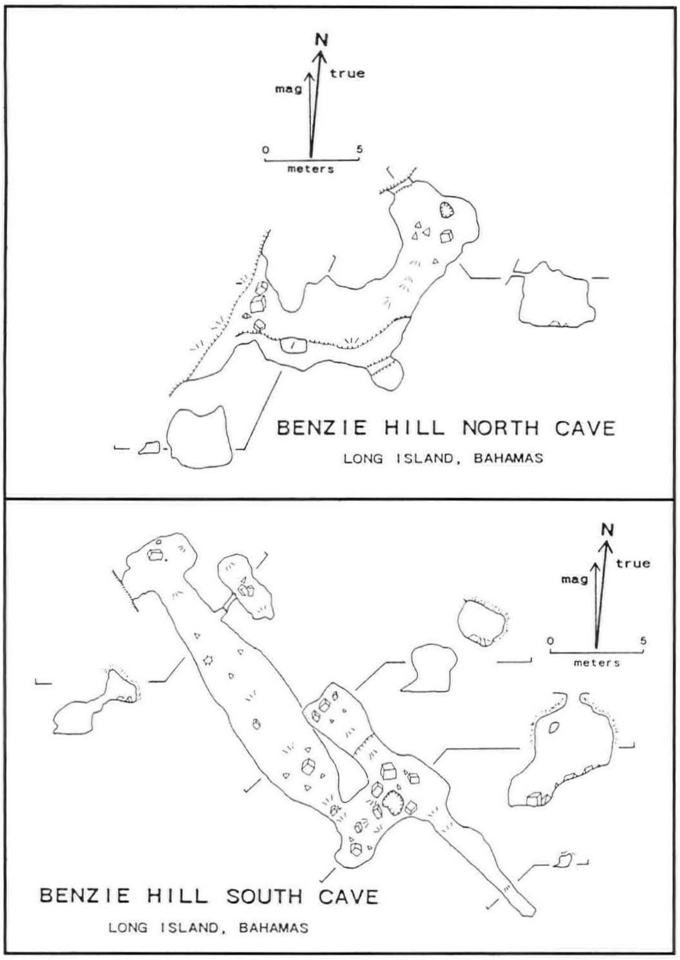


Figure 15



Figures 16 and 17. Map of Benzie Hill South Cave, Long Island. Patterned areas shown on cross sections represent breccia.

Benzie Hill North Cave — This dry and dusty cave has an entrance in a north-south trending cliff face. The floor of the cave is about 4 m above sea level, a higher than normal elevation for flank margin cave development in The Bahamas. The entrance is 8 m wide and 2 m high, but quickly narrows to 3 m wide with a cut-around to the south before expanding into the first chamber of the cave (Figure 16). The first chamber is 3 m high and 5 m in diameter. A dead-end alcove trends southeast, but the main trend is up a slope to the north into the terminal room. This terminal room is 4 m in diameter and 2 m high with a small skylight to the surface. At ceiling level a horizontal crack leads out to the cliff face to the northwest. The morphology of this cave is characteristic of the flank margin type, on a small scale.

Benzie Hill South Cave — This cave, which teems with insect life and which some sheep use to escape the heat, is elongate parallel to the northwest-southeast trending hillside. The entrance, at about 3 m above sea level, is 1.5 m wide and 1.5 m high. It leads northeast 2 m into a low room, which slopes down to the southeast into a 2 m high corridor that is 15 m long and up to 4 m wide (Figure 17). Near the entrance, on the northeast wall of the corridor, a tight passage provides access to a short section of upper level passage that is parallel to the lower passage but sealed at both ends by collapse. The northeast wall and the ceiling of the upper chamber consist of a breccia facies. The lower corridor ends to the southeast at a narrowing where a passage trends up a slope to the northeast into a high chamber with a skylight to the surface 5 m overhead. The floor of the chamber slopes up to the northeast, where a T-junction is reached. To the northwest a section of upper level passage trends northwestward toward the previously described truncated fragment of upper chamber off the main corridor. The ceiling and northeastern wall of this passage are also composed of breccia, as are the upper walls of the skylight room. To the southeast, a small passage with breccis facies in the ceiling continues 8 m before pinching out. While the cave is only a short section of passage, it is very complex. The breccia facies in this cave consists of angular to subangular rock fragments of eolianite embedded in a reddish to white matrix. The breccia is cemented and has a mechanical strength equivalent to the wall rock around it. Benzie Hill South Cave appears to be an elongate version of a typical flank margin cave.

Hamilton's Cave

Hamilton's Cave, which provides shelter for many bats, is located to the northeast of the main road midway between the Hamilton's and Scrub Hill settlements. A track leads 0.75 km across a flat area then rises up and to the southwest onto a low eolianite ridge. A large collapse sinkhole contains the entrances to the western and eastern branches of the cave (Figure 18). The western part of the cave trends 130 m west then southwestward to two other entrances. The ceiling ranges from 2 to 4 m high, and passage widths range from 8 to 28 m. The floor is dirt and rock rubble, and large desiccated flowstone columns are abundant. The passages are large and impressive. To the east of the collapse sinkhole, the cave trends south and then east for over 250 m. This is one of the longest continuous cave passages in The Bahamas, and to our knowledge only Hatchet Bay Cave on Eleuthera is comparable. These southeastern passages are quite large, often 25 m wide and 5 m high. Well-developed phreatic dissolution features are abundant. Numerous side passages either loop back to the main passage, or end abruptly. Flowstone is abundant in specific areas but it is old and desiccated. Skylights are extremely common in the long hall that trends south from the entrance sinkhole. About 100 m into the cave from the sink entrance, a large pit enters from the surface, but the next 150 m of cave is developed back into the eolianite ridge until finally another entrance complex is reached at the extreme southeastern end of the cave.

The cave has been mined for its guano and earthfill, so the passages have their original dimensions in most areas. Some cave chambers show a wall notch or groove about +5 m, similar to what was seen in Harry Oakes Cave and Salt Pond Cave. In 1988 this cave was sketch mapped by A. N. Jimenez and colleagues, of Cuba. Time did not allow a full survey by the authors, but we did add additional information to Jimenez's map, a copy of which was

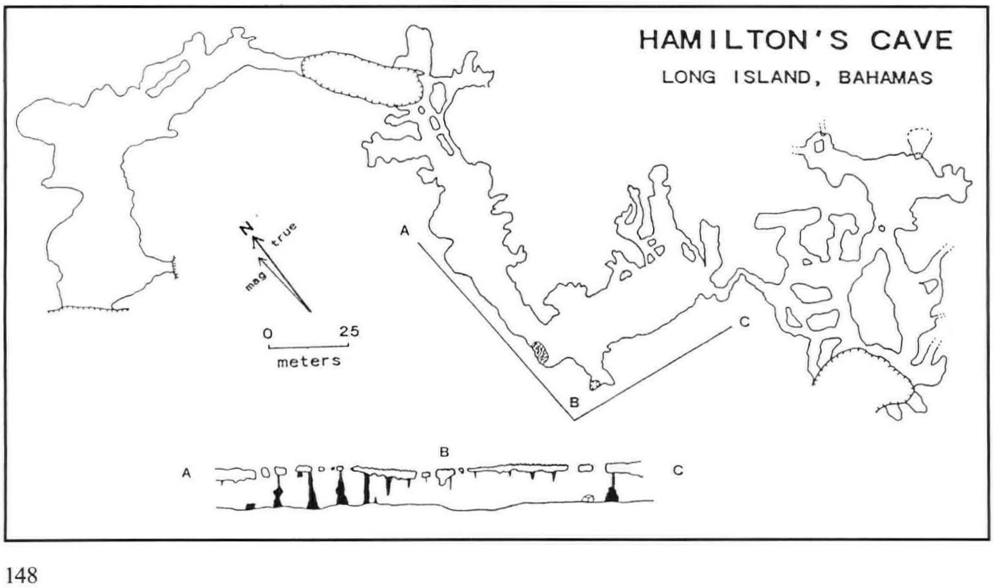
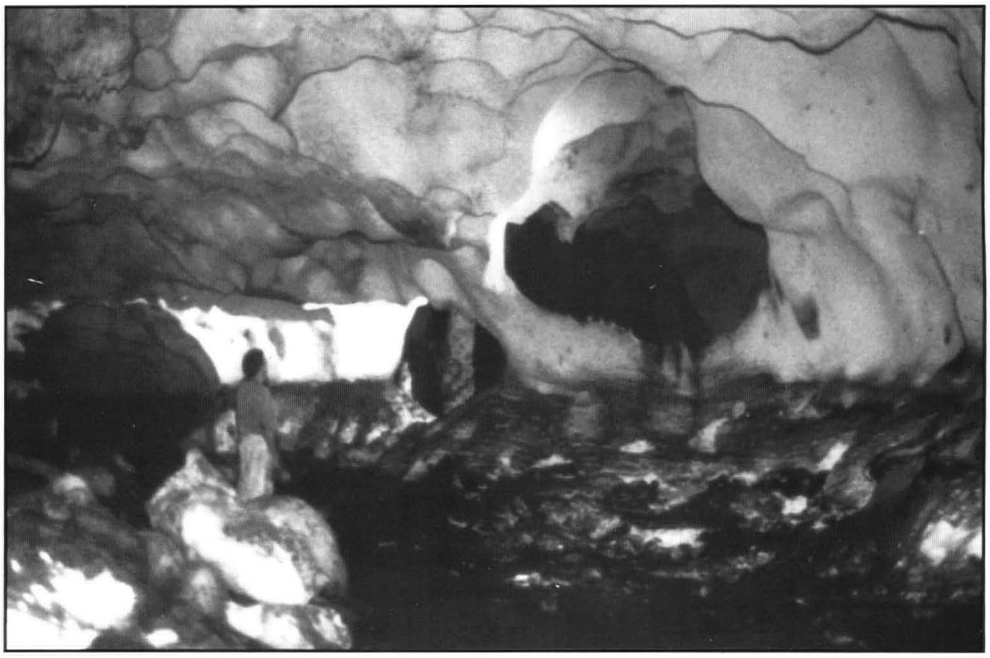


Figure 18

Large chamber in Hamilton's Cave, Long Island, Bahamas, with another large chamber beyond the natural bridge. The cave-earth fill has been removed for fertiliser, the former level of the fill is evident at shoulder height of the person in the left centre of the photograph.



supplied by the landowner. The cave is clearly one of the largest in The Bahamas, and like Salt Pond Cave, exhibits the large chambers, bedrock pillars, and dead-end passages typical of flank margin cave development. Unlike Salt Pond Cave, Hamilton's is extended along the strike of the eolianite ridge, as a series of connected chambers. This elongate morphology is found throughout The Bahamas at a variety of scales. Hamilton's Cave should be surveyed in detail, and correlated with surface topography. Without a complete and accurate map, a more detailed description of the passages is not possible.

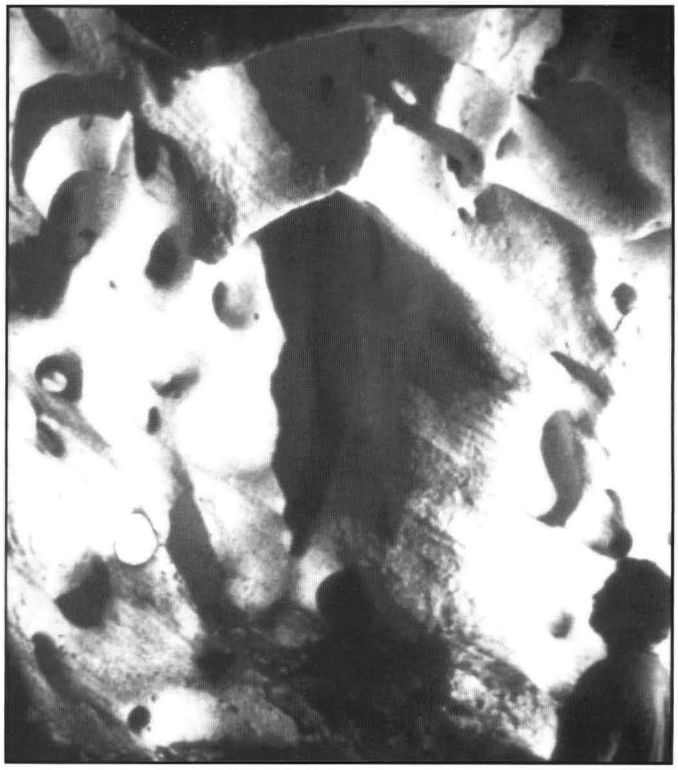
Other Caves

During the expedition, we obtained information about many other caves on Long Island, but we were only able to visit a small fraction of them. In some places, large cave entrances were visible from the main road.

1. In the Mangrove Bush-McKenzie-Cartwright Settlement area, large cave entrances could be seen east of the road in the settlements. In many cases houses are built in front of the entrances, or on the hillside above the entrances. At Pettys Settlement a number of openings, some large, could be seen just east of the main road. Where the hill abuts the road, pits and shafts could be seen while driving by at modest speed.
2. A large cave on the east coast was visited but not mapped. It is reched by a dirt road that goes from Hamilton's over the high ridge. The cave entrance faces east, and the cave consists of a truncated main chamber, much like the Caves Point Caves on New Providence. The entrance is at least 20 m wide and 6 m high, and extends west about 20 m into the hill before breaking up into a series of smaller passages. Large desiccated columns, stalagmites and stalactites are abundant.
3. The local population was extremely helpful in assisting us in finding caves, and we received accounts of many more large caves than we were able to investigate. Finally, during take-off of our flight when leaving Long Island from the Deadman's Cay airport, a very large cave entrance was noted just beyond the eastern end of the runway. The entrance appeared to be 10 to 15 m across and 5 m high.

DISCUSSION AND CONCLUSIONS

The survey of caves on New Providence Island has been extensive, and enough of the caves have been studied there to allow the general pattern of cave development to be understood. While more caves may exist on New Providence, the sample presented here is believed to be representative of cave development on the island. The New Providence caves fit the flank margin model for cave development, except where mass movement of rock is suspected, such as at Clifton pier or Fox Hill. In contrast, on Long Island only a few of what are many caves have been adequately surveyed. While all the caves studied to date fit the flank margin model, there is not yet enough data available to conclusively characterize cave development on Long Island. Some of the caves on Long Island are very large, and are among the largest in The Bahamas. This study has shown that the Long Island and New Providence Island caves have a consistent location and morphology over a variety of scales, and that they formed rapidly during the sea level high stand(s) associated with oxygen isotope stage 5 from 140,000 to 85,000 years ago.



Dissolution pockets in eolian foreset beds in a passage in Hamilton's Cave, Long Island.

A perplexing question concerning Bahamian caves is why maximum cave size should be so different among the Bahamian Islands. For example, the average and maximum cave sizes on New Providence are similar to those observed on San Salvador Island (Mylroie, 1988), and South Andros Island (Carew and Mylroie, 1989). In contrast, the caves on Long Island are generally larger, and the largest caves are similar to other large caves known in The Bahamas, such as Hatchet Bay Cave and Tenbay Cave on Eleuthera (Mylroie, 1988). One many note that both Long Island and Eleuthera are long thin islands that strike northwest, and contain large caves; whereas New Providence and San Salvador are small ovoid islands, and contain relatively smaller caves. In actuality, the role of island shape and orientation is probably irrelevant, because it is the shape of the emergent portions of the Pleistocene ridges of these islands during times of past higher sea level that is the critical factor in controlling freshwater lens shape, volume, and geochemistry. Paleoclimatic factors such as evapotranspiration and precipitation also play a role in cave development (Vacher and Mylroie, in press); however, it is unlikely that such closely spaced islands experienced significantly different climates when the caves developed. In the end, we have no adequate explanation for the markedly different sizes of the caves developed on various Bahamian islands.

The location and morphologies of the caves on New Providence Island and Long Island fit the pattern predicted by the flank margin model (Mylroie and Carew, 1990). The caves tend to be large single chambers that extend from the flank of a ridge back into the ridge, or a linear arrangement of chambers that are oriented parallel to the ridge trend and lie under the flank of the ridge. Complexes of small tubes, bedrock pillars, looping passages, and dead-end passages are common. The walls show classic sculptured surfaces produced by dissolution under water.

Hunts Cave on New Providence Island and Benzie Hill South Cave on Long Island show evidence of multiple dissolution events. The dissolved flowstone from Hunts Cave suggests the following history: 1 — the cave formed in a freshwater lens, 2 — it was subsequently drained as a result of a fall of sea level, 3 — the flowstone was deposited in the air-filled cave, 4 — sea level rose again and the cave was re-flooded by the freshwater lens within which the flowstone was subjected to dissolution, 5 — sea level fell once more and with it the watertable also fell, and one can now enter the dry cave.

The breccia in Benzie Hill South Cave also provides evidence of multiple sea level events. The breccia is similar in all respects to infill material found in karst features on San Salvador Island (Mylroie, 1988), and is interpreted to be a mixture of slumped soil, weathered surface rock fragments, and cave wall collapse material that infilled pre-existing dissolution cavities of the main cave. Smooth curved phreatic dissolution surfaces extend from the eolianite through the breccia. The original cave was formed phreatically, then exposed to subaerial conditions when sea level fell. During the subaerial phase, surface processes breached the cave and the breccia facies was introduced. Then on a subsequent high sea level the cave was re-invaded by a freshwater lens and further dissolution of the original limestone and the infilling breccia occurred. This cave exhibits a two-cycle flooding history similar to Hunts Cave on New Providence Island.

Cave outcrops such as those just discussed provide important evidence concerning events in the caves that are related to global climatic and sea level changes. The data available do not allow us to determine if these two dissolution events were minor fluctuations during a single major sea level high stand, or the result of two major sea level high stands widely separated in time. The second interpretation requires that the caves formed on an initial high sea level event and had not isostatically subsided before the second high sea level event produced more dissolution. Given subsidence rates of 1 to 2 m per 100,000 years, and the generally accepted elevation (+2 m) of the oxygen isotope stage 7 high sea level event 220,000 years ago of (Harmon, *et al.*, 1983), it is unlikely that Hunts Cave and Benzie Hill South Cave initially formed during or before stage 7, with subsequent modification during the high stand of stage 5. It is more likely that they formed during the proposed first high stand associated with substage 5e (140,000 years ago), and were later modified during the second, major high stand (125,000 years ago) associated with the substage 5e event (Johnson, 1991). It is also possible that the caves formed initially during substage 5e and were modified during the substage 5a high sea level event (85,000 years ago), which has been reported to have reached at least modern sea level elevation (Vacher and Hearty, 1989).

Another example of multiple sea level events recorded by a cave can be found at Bahamas West Cave. In the Bahamas, eolianites form only when the platform is partially flooded by marine water during a sea level high stand. Paleosols largely form when the platform is emergent during sea level low stands (Carew and Mylroie, 1985; 1989; 1991). Bahamas West Cave shows development in two eolianites and an intervening paleosol. The initial eolianite formed during platform flooding and carbonate sediment production during one sea level high stand. The paleosol largely formed during a following sea level low stand, and the overlying eolianite was deposited on a subsequent sea level high stand. Bahamas West Cave did not develop until after this second eolianite was deposited. If this second eolianite was produced during the transgressive phase of the second sea level high stand, then the Bahamas West Cave data can be explained in two sea level events: the first associated with deposition of the lower eolianite, and a second during which the upper eolianite was deposited and subsequently the freshwater lens migrated up into the younger eolianite package as the second transgression reached its maximum elevation. On the contrary, if the second eolianite formed during regression from the second sea level high stand, then a third sea level high stand would be necessary to raise a cave-forming freshwater lens into both eolianites. All of these events must have occurred before the sea level low stand preceding the current sea level high stand. Bahamas West Cave is an example of how cave data can help unravel sea level history, even in the absence of absolute ages.

One of the major implications of the existence of these fossil flank margin caves is that similar caves should be forming in the distal ends of the modern freshwater lenses of the Bahama islands. For about 5,000 years the modern high stand of sea level has been high enough to hold the freshwater lens in the vicinity of current sea level, and flank margin caves should be forming in coastal areas. This development should be occurring not only in Pleistocene eolianites, but also in eolianites produced during the Holocene transgression (Carew and Mylroie, 1985). No investigation has yet been undertaken to determine whether flank margin caves are currently forming in The Bahamas.

As sea level has risen and fallen many times during the Pleistocene, in The Bahamas the preferred sites of cave development have also moved up and down (Mylroie and Carew, 1988). The extremely complex caves found by Scuba divers in Blue Holes represent the accumulated cave production and overprinting produced by many stands of sea level over many hundreds of thousands of years. In contrast, the dry caves of the Bahamas, such as those described in this report, must have formed very quickly, as sea level has been higher than at present only as short discrete events widely separated in time that cumulatively amount to no more than a few tens of thousands of years. Some of the caves on Long Island are immense, and they indicate that the mixing of fresh and salt water must be a powerful geochemical tool to have produced large voids in such a limited amount of time. The age of the rocks exposed in The Bahamas is less than 500,000 years (Garrett and Gould, 1984; Carew and Mylroie, 1987b; Stowers *et al.* 1989;), therefore that is the upper limit for the age of caves found in these rocks. In actuality, the age of the rock is irrelevant, because the development of caves that are now subaerial is limited to the time when sea level was at a high stand that was above current sea level. The high sea level stands that could have produced the caves is limited to those of the past few hundred thousand years, as isostatic subsidence of The Bahamas would have brought older caves below modern sea level. The oxygen isotope stage 7 sea level high stand was not high enough to have produced the conditions necessary for the formation of these caves, and any caves produced during earlier sea level high stands would by now have subsided below modern sea level. The sea level high stands associated with oxygen isotope stage 5 are therefore the only ones that could have provided the conditions necessary for the production of Bahamian flank margin caves. This interpretation is also supported by U/Th dates from speleothems. While the data on speleothems collected at or above modern sea level is scanty (Carew and Mylroie, 1987), no dates older than 70,000 years have been reported. This restriction on age means that the rock of the 14,000 m^3 inner chamber of Salt Pond Cave must have been removed in no more than 30,000 years, an excavation rate of not less than 0.5 m^3 per year. In addition, Vogel, *et al.* (1990) reported that cave dissolution occurs faster than many diagenetic processes, as cave wall rock containing up to 40% metastable primary aragonite still exists in some San Salvador caves.

One final interesting aspect of flank margin caves is that they scale from small chambers up to immense caves without loss of their general morphology or position with respect to the land surface. Clifton East Cave, on New Providence Island has a central chamber that is 6 m across, while Salt Pond Cave on Long Island has one that is 70 m across. That is a difference of more than one order of magnitude, yet their morphologies are nearly identical. Even larger are the chambers of Hamilton's Cave on Long Island that extend along the flank of the eolian ridge for over 300 m. This scaling is not unique to these islands, as similar scaling from very small to moderately large can also be seen among San Salvador Island caves (Mylroie, 1988; Mylroie and Carew, 1990). The general morphology of flank margin caves is similar to that of other caves formed under different mixed-water conditions (Mylroie, in press), such as in the Guadalupe caves of New Mexico. This pattern of globular chambers, maze-like passage connections, thin wall partitions, and dead-end passages are called spongework or ramiform caves (A. Palmer, 1991). The Guadalupe caves, like Bahamian caves, scale across at least one order of magnitude while retaining their ramiform pattern. The Bahamian caves present a particular challenge because it is difficult to demonstrate how they could form so consistently under such limited constraints of time, space, and water discharge.

ACKNOWLEDGEMENTS

The investigators thank The Bahamas authorities for permission to do this work. Dr. Donald T. Gerace, Executive Director of the Bahamian Field Station, was instrumental in obtaining government permission for the project. The support of Maurice C. L. Isaacs BSc., DVM, Director of Agriculture, was essential and is much appreciated. Our thanks are also extended to Maurice Minnis, Agriculture representative on Long Island, for his support and encouragement. The support of the Bahamas National Trust and the Natural Science Division of The College of the Bahamas is also appreciated. Mr. Oris Russell and Mr. John Newman provided logistical support and cave location information for the work on Long Island. John Winter also provided cave location information. Cave surveys were by the authors, with assistance from O. S. Russell, M. & A. Cartwright, R. T. Lopez, A. N. Jimenez, J. C. Corella, N. V. Rayes and A M. Cardosa. Support from the College of Charleston and Mississippi State University was essential. Trevor Ford and an anonymous reviewer provided helpful suggestions that improved the manuscript. The people of The Bahamas were most gracious and helpful. They guided us to caves, assisted our surveys, and generally made us feel welcome. Our heartfelt thanks to all.

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CAVE SCIENCE Vol 18, No. 3, December 1991
Transactions of the British Cave Research Association

Xu Xiake, a Chinese Traveller of the Seventeenth Century, and His Contribution to Karst Studies

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Abstract: From 1637 to 1640, Xu Hongzu, under the assumed name of Xu Xiake, travelled in the largest and most spectacular karst region in the world: the karst of China. His book, entitled Xu Xiake Youji (The Diary of the Travels of Xu Xiake), is the first comprehensive Chinese book to describe karst landforms systematically. This paper discusses Xu Xiake's contribution to karst studies based mainly on the original classical Chinese text in Xu Xiake Youji. Xu Xiake's contribution to karst studies includes explanations of karst process, classification and description of individual karst landforms, and analysis of the regional characteristics of karst landscapes. His contribution not only created an initial classification of karst in China but also was a pioneering work on karst in the world at that time.

For more than thirty years he perambulated the most obscure and wildest parts of the empire, exposed to all kinds of difficulties and sufferings, ... His notes, ... read more like those of a 20th-century field surveyor than of a 17th-century scholar. He had a wonderful power of analyzing topographical detail, and made systematic use of special terms which enlarged the ordinary nomenclature, such as staircase (thi), basin (phing), etc. Everything was noted carefully in feet or Li (1 Li= 0.5 Kilometer)., without vague stock phrases (Needham, 1959, p. 524).

This is the commentary of Joseph Needham, a world-renowned scholar in the history of Chinese science, on Xu Xiake (A.D. 1587-1641, Fig. 1, copied from Xu, 1642, plate 1), a Chinese traveller and explorer of the seventeenth century.

Xu Xiake is an assumed name of Xu Hongzu, who was born in Jiangyin County, Jiangsu Province, China, on January 5, 1587. Xu Xiake was very interested in reading geographical, historical, and travel books and, as he grew up, he decided to become a traveller to explore the secrets of nature. From 1607, when he was twenty years old, to 1640, Xu Xiake spent more than thirty years travelling around China. The areas in which he travelled included Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Hubei, Hunan, Guangdong, Guangxi, Guizhou, Yunnan, Shandong, Hebei, Henan, Shanxi, and Shaanxi, a total of sixteen provinces. Among them, Hunan, Guangxi, Guizhou, and Yunnan provinces, in the southern part of the country, constitute the major karst area in China. As Marjorie M. Sweeting states,

The total limestone area in the provinces of Yunnan, Kweichow and Kwangsi (Keichow and Kwangsi are old spellings of Guizhou and Guangxi) is about 600,000 km2 and it is therefore the largest karst region of the world (Sweeting, 1972, p.289).

She also points out:

Conditions for the development of karst are unique in southern China, more so than in the classic areas of European karst in Yugoslavia. First, there are large areas and great thicknesses of pure limestones, uninterrupted by any significant intercalations of other rocks; secondly, a warm and wet climate — over a long period, uninterrupted by intense cold phases; and thirdly, the area has been subjected to much neo-tectonism because of its situation close to the Himalayan and South-east Asian uplifts, where thousands of feet of uplift have taken place in the later phases of the Tertiary and in the Quaternary period . . . The karst in southern China could become the basis for a world model of karst (Sweeting, 1978, pp. 199-200, 204).

Many kinds of karst landforms, such as karst towers, cone karst, dolines, dry valleys, blind valleys, natural bridges, poljes, uvalas, karren, swallow holes, karst plains, and caves, are well developed in this region. It is lauded by Sweeting as "the most spectacular and interesting area of tower karst in the world" (Sweeting, 1972, p. 288). The unique conditions for the development of karst in China enabled Xu Xiake to make a major contribution to early karst studies.

Xu Xiake travelled in Hunan, Guangxi, Guizhou and Yunnan provinces from 1637 to 1640 during the last travels of his life (Fig. 2, compiled based on the map, Hou, 1962, between pp. 64-65). In the spring of 1637, Xu Xiake reached Chaling in Hunan province from Jiangsu province and then approached Heng Mountain. Starting from Hengyang, he made a circular tour in the southern part of Hunan province, including Dao County, which Xu Xiake thought was the eastern boundary of the Fenglin (tower karst) in the Chinese karst landscape. After this circular tour, Xu entered Guangxi province where he travelled nearly one thousand miles and explored more than one hundred caves as well as the most spectacular karst region of Guilin and Yangsuo. In the spring of 1638, by way of Nandan, Xu Xiake went north and arrived in Guizhou province, where he stayed about one-and-a-half months. In the summer of the same year, he reached Yunnan province by way of Puan. Xu Xiake thoroughly explored the eastern part of this province, visiting, among other places, Luoping. Xu Xiake thought the distribution of Fenglin in the Chinese karst extended eastward from Luoping to Dao County, Hunan province. In the spring of 1639, Xu arrived in Lijing, the northern point of his travel in Yunnan province. The last place he travelled in his whole life was Jizu Mountain in Yunnan province, to which he returned in the autumn of 1639 for about four months. At that time he became sick and travelled homeward for about 150 days. In the summer of 1640, Xu Xiake arrived in his hometown in Jiangsu province, in the southeastern part of China, and he died in 1641 (Ting, 1921, pp. 329-330, and Xu, preface, pp. 1, 6-7).

For more than thirty years, Xu Xiake travelled almost entirely by himself and on foot. During his travels he met with every kind of difficulty and danger. He was robbed twice and he ran out of food three times. However, especially in the later part of his travels, wherever he went, he always made very careful observations and analyses of geographic phenomena, such as landforms, vegetation, weather, mineral outcrops, and hydrology. He also made some simple quantitative measurements and collected field samples. The most important aspect was that almost everyday during his travels, Xu Xiake made detailed notes about his investigation in the form of a diary, Xu Xiake Youji (The Diary of the Travels of Xu Xiake), which was published in 1642.

Xu Xiake Youji was written in stages before 1641 and the first copy, handwritten by Ji Huiming (Fig. 3, from Xu, 1642, plate 3), appeared in 1642. The original manuscript is archived in the

Figure 1. Portrait of Xu Xiake

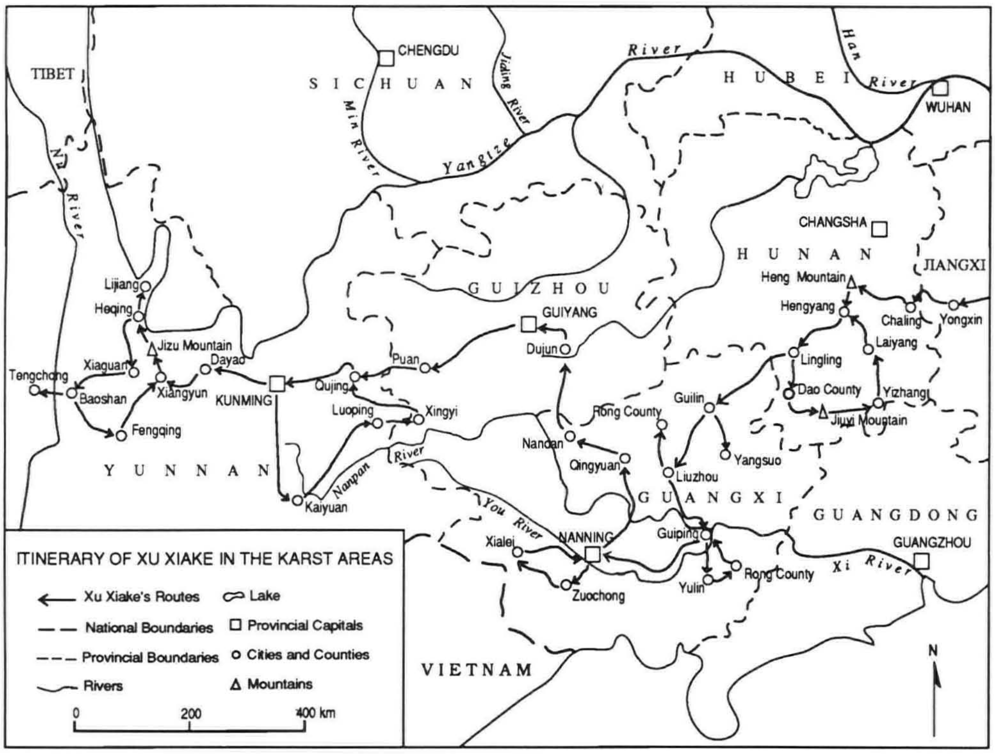


Figure 2.

National Library of China in Beijing and is entitled Xu Xiake Xi Youji (The Diary of the Travels to the West of Xu Xiake). There is a total of five ce (volumes) in the original manuscript. Since the seventeenth century, Xu Xiake Youji has been published several additional times, the first printed copy being published by Xu Zhen in 1776. Because of war and other disruptions in Chinese history, the early copies of Xu Xiake Youji are not complete and some parts of them were lost. The best edition presently is that of 1980 which was published in Chinese by Shanghai Guji Chubanshe (Shanghai Press on Ancient Books). This edition was compiled on the basis mainly of the original manuscript made by Ji Huiming and the first printed copy published by Xu Zhen. In addition, some other early manuscripts and printed copies of Xu Xiake Youji were consulted in compilation. (Xu, preface, pp. 18-24) The Library of Congress and the library of Brigham Young University in the United States have reprints of the 1980 edition, which was reprinted by the same press in 1982.

The contents of Xu Xiake Youji are concerned with many aspects of geography and geology. However, the most important part of the book is the description and explanation of karst landforms. In total, Xu Xiake Youji includes the diaries for 1,463 days and is about 690,000 Chinese characters long. The diaries from the karst area are 976 days and about 560,000 Chinese characters long. Karst terrain accounts for more than half the days of the diaries and more than 2/3 of the length of the whole book (Research Group in the History of Geoscience, Institute of the History of Science, Chinese Academy of Sciences, 1984, p. 59). Therefore, Xu Xiake Youji is the first comprehensive Chinese book to describe karst landforms systematically. In general, Xu Xiake's contribution to research in karst includes explanations of karst processes, classifications and descriptions of individual karst landforms, and analysis of the regional characteristics of karst.

EXPLANATION OF KARST PROCESSES

Many processes operate in the formation of karst landforms. Three of them, the dissolution and precipitation of carbonate minerals by natural water, the mechanical erosion brought about by flowing water, and collapse, play particularly important roles. Although it was impossible for Xu Xiake to analyze karst processes systematically and quantitatively, he described all three of the above processes in his writing.

When Xu Xiake explored Laojun Cave at Zhenxianyan in Rong County, Guangxi province, he noticed the stalactites in the cave. In his diary, he described their shape and explained their formation as follows, "a big column hangs from the roof of the cave . . . This is the result of solution and precipitation of rock." (Xu, p. 377. All references to this work are the author's translation from the original classical Chinese.)

Based on careful observation, Xu Xiake realized that mechanical erosion by flowing water influences the formation of some karst landforms. He gave a description of a cave in Guangxi, *There is a cave in the southern side of Foziling Mountain. ... The entrance of the cave is facing south. A stream was flowing into the cave. The shape of the stream bed looks like a trough . . . When I explored the cave, the stream was dry. Therefore, I entered the cave through the stream bed . . . The entrance of the cave is so small that only one person can pass through . . . During the flood period, the cave is full of water and the water back floods upward from the lower reaches. It is apparent that both the cave and stream bed are formed by erosion by the flowing water (Xu, pp 547-548).*

Another example is seen in his description of dolines, *There are many depressions in the top of a hill. The shape of each depression looks like an upset Fu (A Fu is a kind of cauldron used in ancient China). There are holes in the bottom of the depressions. Most of the holes are formed into wells. The depth of the wells is varied. It can be seen that these wells under the depressions are formed by water flowing through the holes (Xu, p. 182).*

Xu Xiake had clear ideas about the role of collapse in the formation of karst landforms. He explained the formation of some negative karst landforms in his diary of Guangxi.
There are many depressions in this area. All of them are formed by collapse. The shapes of these depressions are varied. Some of them are long and they look like gorges. Some of them are round and look like wells. There are many stones in the bottoms of the depressions. Rivers are flowing on the bottom. Underground about 2 to 3 Zhang (1 Zhang is equal to about 10.9 feet) deep, streams are flowing. Rocks with many gaps occur above the underground stream. When the rocks fall down, new depressions are formed (Xu, p. 405).

DESCRIPTION OF KARST LANDFORMS

One of Xu Xiake's contributions to research on karst is that he carefully described the characteristics of many individual karst landforms. Mainly based on the shapes and sizes of the karst landforms, he classified them and made systematic use of special terms. Some of the terms he invented himself. A few special terms used or invented by Xu Xiake, such as Shichi or Stone teeth (Spitzkarren: since many terms in Xu Xiake Youji do not correspond exactly to western terminology, translations of these terms are approximate), Tianshengqiao (natural bridge) and Fuliu (disappearing river) are still used in research on karst landforms in China at present. Some of his descriptions of karst landforms have been examined by modern Chinese geomorphologists and the results show that his descriptions are surprisingly accurate. Some modern special terms in karst studies in China, such as Fenglin or Peak Forest, originated from Xu Xiake's descriptions. In addition, Xu Xiake also explained the formation of cave deposits and variations in the strength of wind in caves. These explanations are quite reasonable in light of subsequent studies.

Surface karst landforms

Shichi or **Stone Teeth** (Spitzkarren): Xu Xiake described Shichi in his diary of Quizhou. "Shichi are developed on the north ridge. In shape Shichi look like saws. They are so sharp and crowded that there is not enough room to stand." (Xu, p. 621)

Yuanjing or **Dry Wells** and **Panwa** or **Stone Depressions** (Dolines): As Xu Xiake described, "The smaller ones are Yuanjing and the larger ones are Panwa." (Xu, p. 695) In shape a Yuanjing "looks like an upset Fu. There are holes in the bottoms of Yuanjing. Most of the holes are formed into wells. The depth of the wells is varied." (Xu, p. 182) "When a Yuanjing is full of water, a lake can be formed." (Xu, p. 751) A Panwa "is a large closed depression with rocky sides and of a circular plan. It is very deep." (Xu, p. 459)

Wu or **Depressed Place** (Polje or Uvala): In Xu Xiake's description, "A Wu is a large closed depression surrounded by cliffs on four sides with a flat floor on the bottom." (Xu, p. 458) "There is a Wu from the south to the north. The floor of the Wu is very flat. It is an agricultural land and water is flowing from the cliffs." (Xu, p. 629). Xu Xiake's description of the Wu is very close to the modern term Polje. According to Jennings' (1985) book, Poljes are "large closed depressions with flat floors across which streams flow. The flat floors often provide the only agricultural land around." (Jennings, 1985, p. 124) In addition, Xu Xiake also noticed that there are some large closed depressions with uneven floors, although he also described this kind of depression using the term Wu.

Tianshengqiao (Natural Bridge): When Xu Xiake visited the Long Cave in Luocongyan, he found a Tianshengqiao and described it in this way, "The cave is in the northwest corner of the hill. The entrance is facing the north. A river runs through the cave. The pieces of rocks are piled up at the top of the cave from the east to the west. Tianshengqiao is formed." (Xu, pp 438-439) Here, Xu Xiake not only described the characteristics of Tianshengqiao but also implied that the river is a factor which influences the formation of Tianshengqiao.

Kujian (Dry Valleys): Xu Xiake described the following scene: "Five Li after I left the upper reaches of the Yu River, I passed by a stone bridge which cross a Kujian." (Xu, p. 872) The Kujian (river bed) "is very deep and without any water." (Xu, p. 872)

This description of Kujian is very similar to the western definition of dry valleys — "Dry valleys are those without, or with only a temporary , watercourse." (Sweeting, 1972, p.115). The meaning of Kujian in Chinese is also similar to that of Dry Valleys in English.

Fuliu (Disappeared River) In karst areas rivers often flow into caves or their water sinks and disappears into the karst rocks perhaps reappearing at a rising in another place. Xu Xiake used "Fuliu" (Xu, p. 562) to refer to this kind of water flow. The meaning of Fuliu in Chinese is "concealed water flow" and it is so appropriate that it is still used in modern karst research in China. Xu Xiake described a Fuliu between the northern and southern cliffs of the Fuoziling Mountain in his diary of Guangxi.

The water from the western Wu is flowing to the south and enters a cave in the bottom of the mountain. The entrance of the cave is large and facing the north. A deep pool is formed in the cave. The water of the pool is clear and is too deep to be measured. The pool is surrounded by stone walls without any gap. I heard that there is a cave under the water in the south side of the pool and the water is flowing into this cave from the north. When the cave is full of water, water could flow out from the southern cliff of the mountain (Xu, p. 547).

Xu Xiake also described other surface karst landforms in detail although he did not use special terms for them. One of these landforms is the Fenglin, or Peak Forest. Fenglin is a fundamental term used in karst landform research by Chinese geographers and geologists. As Song Linhua states,

Fenglin consists of separate hills, each culminating in a single summit. They may vary in shape and size, and may occur either in isolation or in closely spaced ranks. The diagnostic feature of Fenglin is that each hill is separated from its neighbors by a more or less level surface from which all the hills in the group appear to rise (Song, 1986, p. 50).

The definition of Fenglin is close to that of tower karst in English. As Sweeting describes it, tower karst or turmkarst "consists essentially of steep-sided hills usually occurring in groups, each hill or group of hills often being surrounded by a river or alluvial plain." (Sweeting, 1972, p. 281) In Xu Xiake's description, characteristic Fenglin consists of "isolated steep-sided hills occurring in groups." (Xu, p. 697) In some Fenglin or Peak Forest areas, "at the bottom of the hills, water gathers. The depth of the water is from about half a Chi (1 Chi is equal to about 1.09 foot) to one Chi. The hills stand out from the water and are so beautiful that they look like green lotuses growing up from the water." (Xu, p. 288) Xu Xiake's description of the characteristics of Fenglin or Peak Forest is so accurate and vivid that the special term "Fenglin" or "Peak Forest" used in karst studies in China at present originates from his description. Other surface karst landforms which Xu Xiake described without special terms are blind valleys and water swallets, for example, "after 1 Li, the running river from the west reaches a cliff and suddenly flows into the rocks through a hole." (Xu, p. 1024)

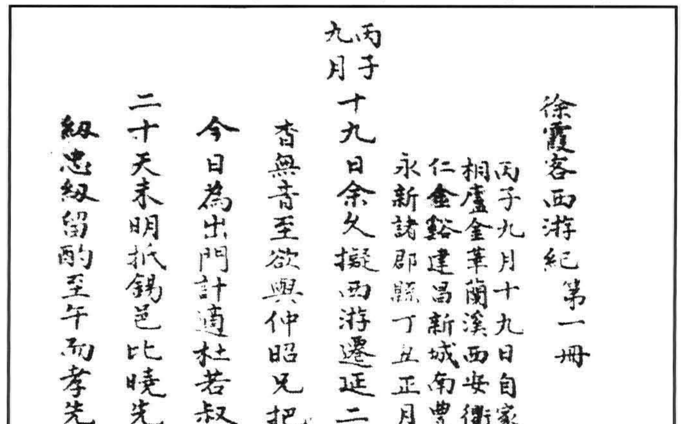
Caves

Explorations and descriptions of karst caves are a very important part of Xu Xiake Youji. For example, in Guangxi province alone, Xu Xiake explored more than one hundred and sixty named caves and tens of caves without names (Chu and Hong, 1986, p. 175). Many of these caves had never previously been explored. When he explored these caves, Xu Xiake measured their size, depth and other dimensions by pacing or by visual estimation. He also collected some samples of cave deposits. His descriptions of the caves included the distribution, structure and relationships of the caves; the shape, size, and the direction of cave passages; direction, height, size, shape, and hydrology of cave entrances; the shape, size and colour of cave deposits; the overall water flow in caves; and explanations of the formation of deposits and variation of the strength of wind in caves.

From Xu Xiake's description of Mayie Cave in the west of Chaling in Hunan Province, it can be seen how detailed were his descriptions of caves.

A stream from west to east is flowing into a river in the front of the cliff. Along the stream, I came to a pile of stones in the west of the cliff. The stream is flowing into rocks in the bottom of the cliff. Above this point, there is a cave. This is Mayie Cave (Xu, p. 184).

Figure 3. Original manuscript of Xu Xiake Youji handwritten by Ji Huiming.



徐霞客西游紀第一冊
友弟季夢良會明甫較錄
丙子九月十九日自家起身由錫邑姑蘇崑山青浦至浙江杭州歷餘杭臨安
桐廬金華蘭溪西安衢州常山諸郡縣由是入江西歷玉山廣信鉛山弋陽安
仁金谿建昌新城南豐宜黃樂安永豐吉水吉安
永新諸郡縣丁丑正月初十日至芀子樹下止　吉安訪張侯後裔
丙子九月十九日余久擬西游遷延二載老病將至必難再遲欲候黃石齋先生一晤而石翁
杳無音至欲與仲昭兄把袂而別而仲兄又不南來昨晚趨晤仲昭兄於土瀆庄
今日為出門計適杜若叔至飲至子夜乘醉放舟同行者為靜聞師
二十天未明抵錫邑比曉先令人知會王孝先自往看王受時已他出即過看王忠
紉忠紉留酌至午而孝先至已而受時亦歸余已醉復同孝先酌於受時處孝先

Here, Xu Xiake described the location of the cave and a water swallet which is under the cave.

The entrance of the cave is facing the south and the size of the entrance is only like a Dou (Dou is a container. Its dimension is about 2 feet) . . . At first, we both put our feet in it, and went down by steps in the light of torch. After making several turns, we reached the bottom of the cave. Here the passage is a little bigger than the cave entrance. We could lean our bodies and straighten out our heads . . . There are rock gaps without entrance in the east and west. There is a hole in the north and it is only about 1 Chi high and wide. The bottom of this hole is very dry and flat . . . We climbed into it like snakes. The hole is so small that even if we kept our stomachs closest to the rock our backs still touched the roof of the hole. This is the first pass of this cave . . . The size of the second pass was similar to the first. We entered the second pass . . . The passage here becomes so high that we could not see the roof. The upper part of the passage is arched and the lower part is narrow (Xu, pp 184-185).

Here Xu Xiake described the direction and size of the entrance; and the shape, size, direction and variation of the cave passage. From this paragraph it can be inferred that Xu Xiake used a compass during his travels. He clearly knew the directions in the cave, although there is no direct record of compass use in his book. Following the preceding section, Xu Xiake described a dry underground stream bed.

The bottom of the stream bed is covered by sand and stones. It is dry . . . Under a layer of stone, the stream bed extended to the south. The distance between the rock and bed is only about 1 Chi. This must be the way the stream had flowed into the cave beforehand (Xu, p. 185).

Cave deposits are an important focus of cave studies. Based on the shapes and sizes of cave deposits, Xu Xiake divided them into three classes: Shisun (stone bamboo shoots), Shizhu (stone columns), and Shishu (stone trees). In addition, he also described some special deposits although he did not use specific terms to refer to them. For example,

I collected ten strips of deposits. They all were about six to seven Cun (1 Cun is equal to about 0.11 foot) long. Their shapes looked like tubes with white outward appearance . . . I also collected a white deposit like lotus flower with the dimension about 3 Chi. The thin petals of this stone flower hung down to the cave floor. Its root looked like a string and was connected to the cave floor. The size of the point of the connection between the roof and floor was only like a fist and it was very easy to cut it down (Xu, p. 551).

Explaining the formation of the deposits, Xu Xiake explained that "This is result of solution and precipitation of rock." (Xu, p. 377). He also explained the variation of strength of wind in caves. In his diary of Guilin, he explained that "I entered a pass in the cave. Here the wind was so strong and cold that it blew out my lamp. The reason for this is that the passage here is narrow so that the wind becomes stronger when it passes through the narrow passage after it is blowing into the cave from the entrance." (Xu, p. 294)

Many of Xu Xiake's descriptions of karst landforms are surprisingly accurate. For example, in 1953, Chinese geographers surveyed Qixingyan (Seven Star Cave) in Guilin. The result of this survey shows that, except for some branches which Xu Xiake did not find, his accounts of distribution, structure and size of the caves are basically correct (Chen, 1957, pp. 56-75). Some of Xu Xiake's descriptions are still valuable to karst research today.

REGIONAL CHARACTERISTICS OF KARST

After his several years' investigation, Xu Xiake documented the distribution of Fenglin landforms and analyzed their regional characteristics.

In his diary of Yunnan, he described the distribution of Fenglin or Peak Forest landscape as being from Luoping, Yunnan province to Dao county, Hunan province.

I could see the isolated steep-sided hills occurring in groups along the eastern boundary . . . The distribution of this kind of hill is from here (Loupin, Yunnan province) towards the northeast to Daozhou (Dao county). It covers the area for thousands of Li and is a famous travelling site in the southwest of China (Xu, p. 697).

The results of investigations by modern Chinese geographers show that his above description is basically correct except that the eastern boundary of Fenglin extends a little further than Dao county, Hunan province, into an area which Xu Xiake did not visit.

Xu Xiake also analyzed the regional characteristics of Fenglin. Based on the nature of rock and sediment, he divided the distribution of Fenglin or Peak Forest into three regions.

Many hills in the western part of Guangxi province are pure stone hills. Some hills consist of stone and soil. They are separately distributed from pure stone hills. Since most of the hills in this region are pure stone hills, many rivers in this region are flowing through caves and the water is clear. Most of hills in the southern part of Yunnan province consist of soil and stone. The ratio between soil and stone is around from 10:1 to 10:2. Therefore, there are many closed depressions in this region and the rivers are clogged with muddy water. The nature of the hills and rivers in the southern part of Guizhou province is between the above two characteristics. The hills in this region are characterized by their steepness (Xu, p. 711).

In general, the carbonate rocks in Guangxi province are purer and thicker than those in Yunnan and Guizhou provinces. Karst landforms in Guangxi province approximate those of a theoretical holokarst. In contrast, in Yunnan and Guizhou provinces both carbonate and non-carbonate rocks occur in the same areas. The total area of carbonate rocks in Guangxi, Yunnan and Guizhou provinces is about 600,000 km^2 and the total size of these three provinces is more than 780,000 km^2. Hence, non-carbonate rocks in these three provinces occupy about 180,000 km^2 and most of these are in Yunnan and Guizhou provinces. Therefore, both karst and non-karst landforms occur in these two provinces. Xu Xiake's description shows that he not only had the insight to analyze the regional variation of karst landforms but he also realized that the nature of the carbonate and other rocks had a great influence on the characteristics of landforms.

CONCLUSION

From 1637 to 1640, Xu Xiake travelled in the largest and most spectacular karst region in the world. His diaries in the karst area included a total of 976 days. The unique geographical condition of this area and his unusually long period of field investigation established a solid basis for Xu Xiake to make a major contribution to karst studies.

The first handwritten copy of Xu Xiake Youji appeared in 1642 and it is the first comprehensive Chinese book to describe karst landforms systematically. In his book, Xu Xiake explained some karst processes, classified and described many kinds of individual karst landforms, and analyzed the regional characteristics of karst in the area. His explanations of karst processes and analysis of the regional characteristics are quite reasonable. The classifications and descriptions of individual karst landforms in his book are mainly based on the shapes and sizes of karst features — factors which play an important role in the classification of karst today. The karst features which Xu Xiake described include most of the karst landforms which we recognize today. They include karren, dolines, poljes or uvalas, natural bridges, dry valleys, disappearing rivers, tower karst, blind valleys, water swallets, cave deposits, and caves themselves. His descriptions of these karst features are also basically accurate and detailed.

Like many early works on karst, Xu Xiake's work is also mainly descriptive. An important limitation of his work is that his study is in the form of a diary. Because of the limitation of this writing style, Xu Xiake's observations on karst are scattered in his book. This limitation prevented him from systematically studying karst as a whole.

However, from the view of the seventeenth century, Xu Xiake's contribution not only created an initial classification of karst in China but also was a pioneering work on karst in the world at that time. In general, other research on karst in the world did not surpass the level of Xu Xiake Youji until about one-and-a-half centuries later.

ACKNOWLEDGEMENT

I should like to extend my sincere thanks to Dr. Michael J. Day, professor in the Department of Geography, the University of Wisconsin-Milwaukee, for revising an early draft of this paper.

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CAVE SCIENCE Vol. 18, No. 3, December 1991
Transactions of the British Cave Research Association

Forum

Readers are invited to offer review articles, shorter scientific notes, comments on previously published papers and discussions of general interest for publication in the Forum section of Cave Science.

WATER STRATIFICATION IN ACTIVE PHREATIC PASSAGES

J. N. Cordingley

A common phenomenon in passages in the phreatic zone is that of water layering. This may arise for several reasons (Balcombe *et al,* 1990) but that which interests the writer is a visible one characteristic of major conduit sumps in the Yorkshire dales caving region. Here brown "peaty" water is often seen occupying the upper part of the body of water whilst nearer the floor the water may be almost transparent. The interface between the two layers is often very well defined. Observations made by the writer in sumps frequently visited confirm that these phenomena may remain stable for many weeks under conditions of low discharge. Indeed their locations in sumps and levels in passages can usually be predicted after major flood events have subsided.

Cave divers have noted this effect on many occasions in the past (Yeadon, 1976). The usual conclusion drawn was that peat-stained water in the roof of sumps indicates the presence of an inlet. In the writer's opinion this is not correct because careful searches of passages where this effect is known to occur have usually failed to reveal even the most insignificant of inlets. In fact it is now believed that drifting into an area of peat-stained water actually means that the cave diver has lost the main flow route.

In order to simplify this brief discussion it is assumed that in flood conditions Yorkshire's major conduit sumps such as Keld Head, Hurtle Pot etc. carry mainly allogenic water from stream sinks of various sizes. In drought conditions what flowing water there is will be largely derived from stores and will have a greater percolation component (Halliwell, 1980). Major conduit sumps are not generally accessible to cave divers during violent floods so no observations of layered water have been recorded under such conditions. However with the associated rapid discharge it must be assumed that any stratification phenomena which already exist will be destroyed.

The purpose of these notes is to describe a possible mechanism for the formation of the effect described above. It is hypothesised that during a flood virtually all of the water in a sump will be replaced by relatively aggressive and peat-stained allogenic water. Such water has relatively low density (for reasons yet to be determined). As the flood subsides the proportion of water from stream sinks will decline and autogenic percolation water will account for an increasing percentage of the flowing water in the sump. Such post-flood autogenic water will be slightly more dense due either to its chemical characteristics or to its relatively low temperature (at least during most months of the year). The less dense allogenic waters will tend to become trapped in high level "backwaters"' caused by irregularities in the roof profile and held in position by the denser (flowing) autogenic layer beneath.

If the mechanism proposed above is responsible for the water stratification described there are several interesting implications for students of speleogenesis. For example it might explain why joints crossing phreatic passages often give rise to large solution domes in the roof but without a correspondingly cavity in the floor. Simple explanations of phreatic passage development would have us believe that solution occurs fairly evenly all around. However, many examples of differential solution at cross joints related to different levels in the passage exist. These are common even where floor sediments are completely absent, i.e. where it cannot be argued that any barrier to solution at floor level exists. The writer believes that such lofty domes are produced by bodies of very aggressive allogenic water trapped indefinitely in the roof. These cause continued rapid corrosion here throughout periods of low discharge when one would expect relatively little solution to be occurring. This long term upward "stopping" by aggressive water in the roof is perhaps more likely to be the real cause of these large domes than mechanisms suggested previously (Pitty, 1971)

Another feature often noted by cavers in now drained phreatic passages is the presence of horizontal notches along the walls. Good examples occur in the area of the ducks near to The Valley Entrance of The Kingsdale Master Cave near Ingleton, North Yorkshire. The traditional explanation for these involves "previous water levels" in the passage. However stable water surfaces in caves are fairly ephemeral both for short term reasons (floods, droughts etc.) and in the long term (receding nick points, growth of rimstone dams, silt deposition etc.). It may well be that these notches are instead related to mixed water corrosion (Bögli, 1980) at water interfaces (of the kind described above) which occurred whilst the phreatic passage was still active. Indeed such notches have been observed by the writer whilst diving in passages which have never been drained. These notches may prove to be of value when studying speleogenesis in tectonically active areas of the world. If notches of this type exist which are not horizontal they may indicate tectonic activity subsequent to the draining of phreatic passages.

The above speculations are based on the writer being able to observe actively forming phreatic passages directly unlike most previous workers who do not appear to have appreciated the significance of water layering in passage development. It was intended to begin a long term investigation of one site where such stratification is known to form reliably, namely in the Downstream Sump of Hurtle Pot near Ingleton, North Yorkshire. Here the passage is 8m high at a point some 60m from the entrance. A vertical line transect was to have been installed supporting limestone tablets (as indicators of solutional activity) at intervals between floor and roof over a long period. Regular visits were anticipated to measure water temperatures (at intervals from roof to floor, rather than the reverse, to avoid any interference with any layering by rising exhaust bubbles). Water samples from different heights in the passage were also to have been collected for chemical analysis. Unfortunately a collapse of boulders near the entrance prevented this particular investigation from being carried out.

The writer is presently unable to devote sufficient time to the project but would be pleased to offer suggestions to any other cave divers who would like to investigate the phenomenon. It should be noted that the effect described is believed to be widespread in phreatic passages in all major British caving regions and not just in the Yorkshire Dales. It was only noticed because allogenic waters here tend to be characteristically peat-stained. Finally the writer would like to acknowledge many helpful discussions with Drs. J. S. Beck, J. Gunn and R. A. Halliwell on this and other topics in the past.

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B.C.R.A. Research Funds and Grants

THE JEFF JEFFERSON RESEARCH FUND

The British Cave Research Association has established the Jeff Jefferson Research Fund to promote research into all aspects of speleology in Britain and abroad. Initially, a total of £500 per year will be made available. The aims of the scheme are primarily:

a) To assist in the purchase of consumable items such as water-tracing dyes, sample holders or chemical reagents without which it would be impossible to carry out or complete a research project.
b) To provide funds for travel in association with fieldwork or to visit laboratories which could provide essential facilities.
c) To provide financial support for the preparation of scientific reports. This could cover, for example, the costs of photographic processing, cartographic materials or computing time.
d) To stimulate new research which the BCRA Research Committee considers could contribute significantly to emerging areas of speleology.

The award scheme will not support the salaries of the research worker(s) or assistants, attendance at conferences in Britain or abroad, nor the purchase of personal caving clothing, equipment or vehicles. The applicant(s) must be the principal investigator(s), and must be members of the BCRA in order to qualify. Grants may be made to individuals or small groups, who need not be employed in universities, polytechnics or research establishments. Information and applications for Research Awards should be made on a form available from S. A. Moore, 27 Parc Gwelfor, Dyserth, Clwyd LL18 6LN.

GHAR PARAU FOUNDATION EXPEDITION AWARDS

An award, or awards, with a maximum of around £1000 available annually, to overseas caving expeditions originating from within the United Kingdom. Grants are normally given to those expeditions with an emphasis on a scientific approach and/or exploration in remote or little known areas. Application forms are available from the GPF Secretary, David Judson, Rowlands House, Summerseat, Bury, Lancs. BL9 5NF. Closing date 1st February.

SPORTS COUNCIL GRANT-AID IN SUPPORT OF CAVING EXPEDITIONS ABROAD

Grants are given annually to all types of caving expeditions going overseas from the U.K. (including cave diving), for the purpose of furthering cave exploration, survey, photography and training. Application forms and advice sheets are obtainable from the GPF Secretary, David Judson, Rowlands House, Summerseat, Bury, Lancs. BL9 5NF and must be returned to him for both GPF and Sports Council Awards not later than 1st February each year for the succeeding period, April to March.

Expedition organisers living in Wales, Scotland or Northern Ireland, or from caving clubs based in these regions should contact their own regional Sports Council directly in the first instance (N.B. the closing date for Sports Council for Wales Awards applications is 31st December).

THE E. K. TRATMAN AWARD

An annual award, currently £25, made for the most stimulating contribution towards speleological literature published within the United Kingdom during the past 12 months. Suggestions are always welcome to members of the GPF Awards Committee, or its Secretary, David Judson, not later than 1st February each year.

BRITISH CAVE RESEARCH ASSOCIATION PUBLICATIONS

CAVE SCIENCE — published three times annually, a scientific journal comprising original research papers, reviews and discussion forum, on all aspects of speleological investigation, geology and geomorphology related to karst and caves, archaeology, biospeleology, exploration and expedition reports.
Editor: Dr. Trevor D. Ford, 21 Elizabeth Drive, Oadby, Leicester LE2 4RD. (0533-715265).

CAVES & CAVING — quarterly news magazine of current events in caving, with brief reports of latest explorations and expeditions, news of new techniques and equipment, Association personalia etc.
Editor: A. Hall, 342 The Green, Eccleston, Chorley, Lancashire PR7 5TP. (0257-452763).

CAVE STUDIES SERIES — occasional series of booklets on various speleological or karst subjects.
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No. 1 Caves & Karst of the Yorkshire Dales; by Tony Waltham & Martin Davies, 1987.

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