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BRITISH CAVE RESEARCH ASSOCIATION

Volume 2 Number 3 October 1975

Studying worm casts in Ingleborough Cavern

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CONTENTS

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OBSERVATIONS ON THE FAUNA AND FLORA OF INGLEBOROUGH CAVERN, YORKSHIRE

by T.G. Piearce

Summary

The progressive increase in shade and relative humidity across the threshold of Ingleborough Cavern is reflected in the composition of the flora in this zone. The fauna of the cave proper enjoys a relatively constant environment in which food is scarce. The few animal species present (four of which are here recorded in the cave for the first time) are mainly detritus feeders, including the earthworms *Allolobophora chlorotica* (Savigny) and *A. rosea* (Savigny), which are rarely seen at the soil surface outside caves and which produce casts underground. Deep within the permanently dark zone of Ingleborough Cavern these species work the superficial layers of sediment deposits, which are covered with their casts in many places. Analysis of the deposits and experimental investigation of the reactions of *A. chlorotica* to light and substrate has suggested several possible reasons for this peculiar behaviour.

Introduction

Ford (1975) in a comprehensive guide, outlined the underground course, principal geological formations and history of exploration of Ingleborough Cavern, concluding with a note on its fauna and flora. Hazelton (1972) and Dixon (1974) provided summaries of Cave Research records, while Gidman (1962) gave valuable information on the distribution, abundance and activity of organisms within the cave, and at its threshold, in an unpublished report (reproduced in this issue of the Transactions) which included several new records. Gidman's observation of unusual evidence of earthworm activity in one of the more remote sections of the cave provided the stimulus for more recent studies by the present author, the results of which are presented in this paper.

From the point of view of the experimental biologist the relatively constant physical conditions underground, small number of species present, and total absence of green plants except in the entrance zone, provide valuable opportunities to analyse relationships between living organisms and their environment. The cave may be regarded as a "natural laboratory" where the number of variables is minimal. The transition from epigean to hypogean conditions is gradual in the case of Ingleborough Cavern, and Gidman's work nicely illustrates the relationship between flora and physical factors in the extensive threshold zone.

The Threshold Flora

The cave entrance, set at the bottom of a limestone cliff, lies at the end of an impressive archway 15m wide, 6m high and 14m deep. As the entrance is approached the roof of the archway becomes progressively lower, the amount of shade increases, and the air becomes still and noticeably more humid. A small stream drains from the entrance even in the driest weather and falls 15m to Clapham Beck, a larger stream which issues from nearby Clapham Beck Head Cave.

Gidman took light readings at 1.5m intervals from the point of overhang to the limit of recordable light within the cave. A photographic exposure meter was held 30 cm from a matt white board placed at floor level, orientated vertically and facing daylight. His results are depicted graphically in Fig. 1. The threshold was divided into regions of relatively high light intensity (13.7 – 9.2m from the entrance), moderate shade (9.2 – 4.6m away) and deep shade (4.6 – 0m away). Measurements of relative humidity were made at four stations using a wet and dry bulb hygrometer. The results obtained (Table 1) represent 'spot' readings made on one day, as do the light measurements. Although no significance can be attached to their absolute values, since levels of humidity and light will of course vary throughout the day, and with the weather and season, their relative values clearly demonstrate a progressive change towards the level found within the cave.

Table 1. Physical conditions and flora of four stations at the threshold of Ingleborough Cavern in the autumn of 1961 (adapted from Gidman, 1962).

Station	1	2	3	4
Distance from entrance (m)	13.7	9.2	4.5	0
Light intensity (lux)	34,400	8,600	2,150	280
Relative humidity (%)	76	84	88	90
Number of species of				
angiosperms	9	2	0	0
pteridophytes	2	1	1	4
bryophytes	4	9	7	5
algae	0	0	1	4
lichens	2	0	1	1

It is to be expected that increasing shade and relative humidity will have a marked effect on the vegetation. Table 1 gives some information on the changes observed. At the edge of the overhang and outside, the flora was typical of open deciduous woodland, angiosperms being dominant and including

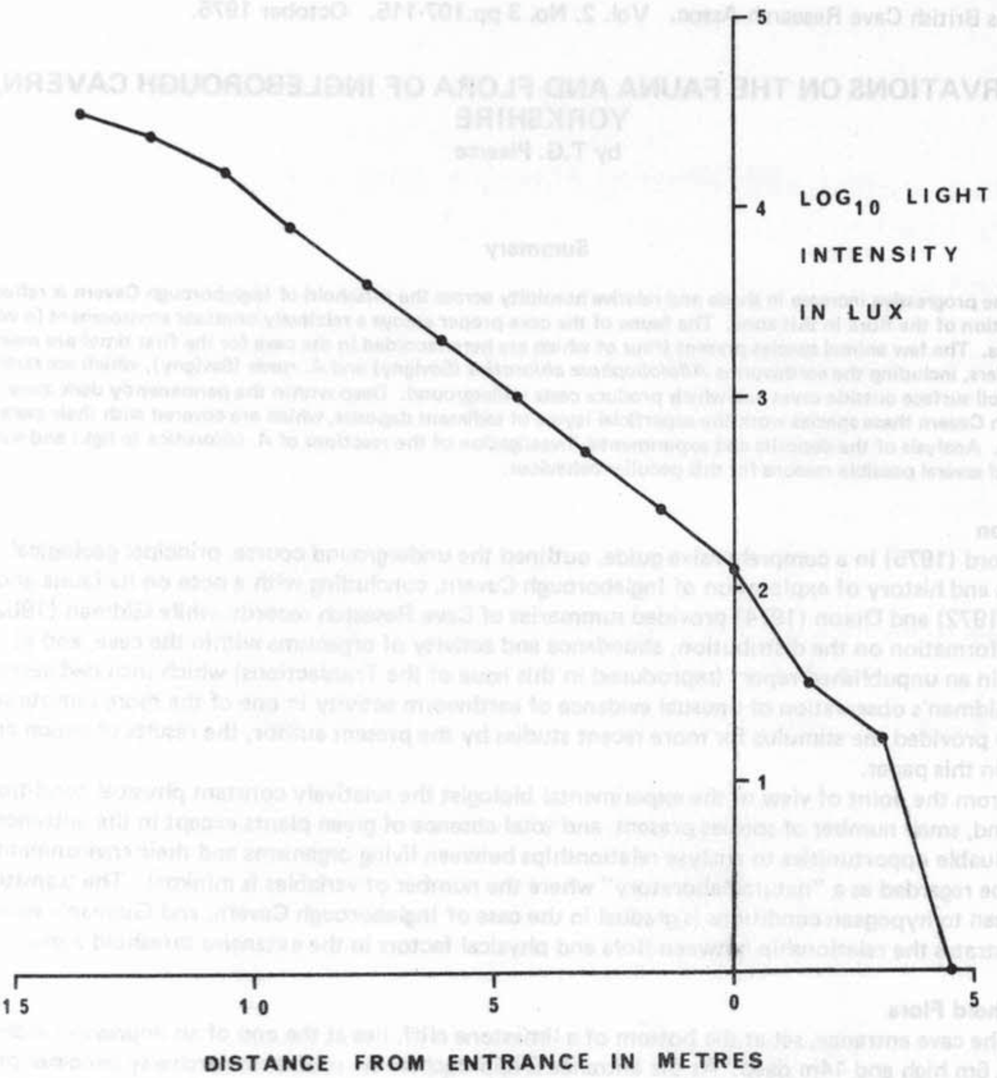

Fig. 1. Change in light intensity across the threshold of Ingleborough Cavern (adapted from Gidman, 1962).

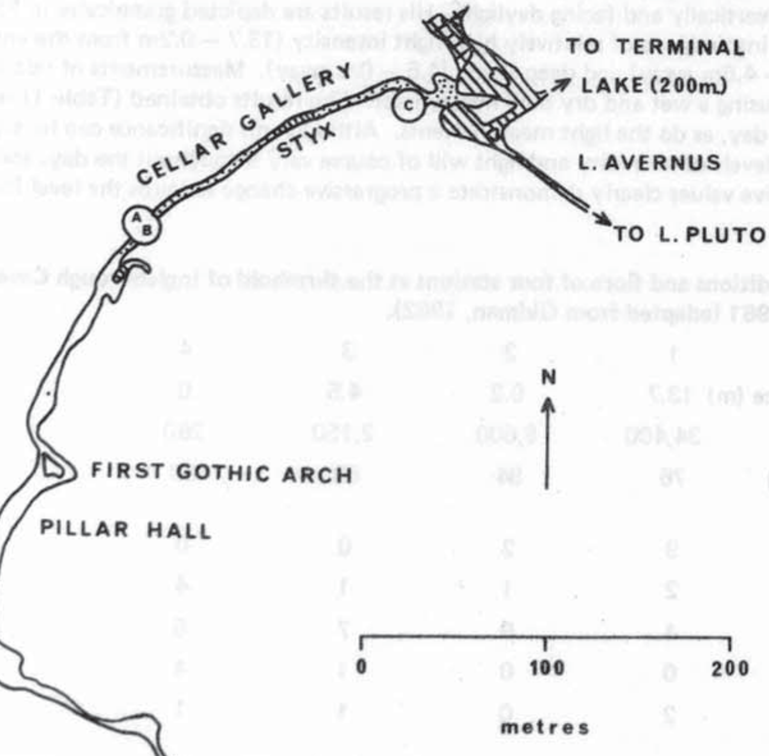

Fig. 2. Plan of part of Ingleborough Cavern, based on a plan by M. Meredith, showing location of sampling sites in Cellar Gallery (silt banks A, B) and at the Second Gothic Arch (sandy floor, C). The wormcast cover is complete at A, sparse at B, moderate with intermingled arthropod casts at C. Hatched areas partially filled with water, cross-hatched completely filled, stippled areas floored with sand or silt.

shade-tolerant 'hedgerow' species such as the Stinging Nettle, *Urtica dioica* L. and Cuckoo-pint, *Arum maculatum* L. Mosses were dominant in the well-lit zone, the thalloid liverwort *Conocephalum conicum* (L.) Dum. dominant in the middle zone, where it formed large masses on rocks by the stream course. Several species of bryophyte were growing on tufa. The shade-tolerant blue-green alga *Anacystis montana* (Lightf.) Dr. & Daily was found on the roof of this and the next most shaded zone. Angiosperms were completely absent from this final zone and *C. conicum* remained the dominant plant species right up to the entrance, showing a marked reduction in size of the thallus lobes with decreasing light intensity. The mosses in this region were noticeably different in growth form, the cushion-forming species being much less compact than elsewhere.

The Cave Fauna

The cave itself (Fig.2) is a long, winding gallery connecting a series of large chambers. The first 400m comprises the show cave which attracts thousands of tourists each year and is regularly illuminated during the summer months. Most parts of the cave have standing or flowing water and the humidity is constantly high.

Whirling hygrometer and temperature measurements were made throughout the cave and outside between 4.45 p.m. and 5.45 p.m. on 29 June 1975, after two weeks of dry weather. Although at this time of year the relative humidity of the air within the cave might be expected to approach a minimum, at no point, from 3m inside the entrance to Cellar Gallery, near the Styx, 490m inside, was it less than 98%. Three metres outside, however, the relative humidity was down to 55%, while 30m away, alongside the show cave hut, it was only 45%. The air temperature varied by less than a third of a degree within the cave, with a mean of 9.2°C compared with 13.6°C for the threshold station and 15.8°C 30m from the entrance. The air temperature in Cellar Gallery in February 1975 was 9.1°C, exactly the same as in July, suggesting that this far underground even large-scale changes in temperature with season have little effect.

The majority of animal species previously recorded for the cave have diets which include detritus. The same is true, with one exception, of those recorded here for the first time, (Table 2). The suspension-feeding larva of the caddis fly *Wormaldia* sp., a single adult specimen of which one was found in Pillar Hall, may have lived in one of the pools or streams within the cave, but it is quite possible that it lived outside, the winged adult having flown in after emergence.

Probably the most conspicuous animals in the caverns, the freshwater shrimps, *Gammarus pulex* L., are abundant in the streams and many of the pools. Many of these animals are pink or pale orange in colour, lacking the blue-grey pigment normally present. Gidman found pigmented forms, paler than usual, in the low water-filled bedding cave beyond the Second Gothic Arch. At the opposite end of the cave, just inside the entrance, the population seems to consist mainly of pigmented individuals.

It has been reported that in the show cave these animals burrow down into the silt in response to illumination (Shevelan, pers. comm.), many more being visible at the start of a day of guided tours than at the end. Gidman found a similar response to light. Ginet (1960) reported that the pigmented forms can survive much longer than the albinos at high light intensities. The burrowing behaviour may also offer some protection against the animals' being washed out of the cave by winter floods. During a visit in February 1975, after several days of heavy rain, 20 specimens were collected from the swollen beck, 20m from the cave entrance. Half of these were unpigmented. Only pigmented individuals have been found at this point along the stream on subsequent visits, suggesting that the albino specimens had been washed out by flood water. The animals collected in February were kept together for six months in a shaded place at a constant temperature of 11°C with an abundant supply of food in the form of deciduous tree litter. There was no apparent change in coloration of either form, suggesting that the lack of pigmentation is genetically fixed, and not a physiological response to the cave environment.

Unpigmented *G.pulex* are certainly more conspicuous than pigmented individuals in the light, and might fall easy prey to predators which hunt by sight. Trout have been seen by cave divers in the underground section of Clapham Beck. A brown trout caught in Terminal Lake in 1974 was initially very pale in colour but become darker when kept in the light (Checkley, pers. comm.). It is possible that sufficient food is available within the cave to support a resident fish population; however, the light-coloured frog discovered living deep inside (Jarman, pers. comm.) was probably a stray immigrant which, being cold-blooded and so having a low energy consumption, was able to survive prolonged starvation.

Another animal which may have been an immigrant was the adult caddis fly, *Wormaldia* sp. found in Pillar Hall (Table 2). However, it is quite possible that the detritus-feeding larva of this specimen lived in one of the cave pools or streams.

Table 2. New fauna records for Ingleborough Cavern

Date	Location	Group	Species	Collected	Determined
1962	Fine silt, cellar Gallery, 440m from entrance	Lumbricidae OLIGOCHAETA	*Allolobophora rosea* (Savigny)	C. Gidman	C. Gidman assisted by A. Brindle
13.4.74	-do-		*A.rosea f.typica*	T.G. Piearce	T.G. Piearce
13.7.74	Fine silt, Cellar Gallery 500m from entrance		*Dendrobaena rubida* (Savigny) *f.subrubicunda* (Eisen)	T.G. Piearce	T.G. Piearce

1962	Sandy floor, Gothic Arch, 275m from entrance.	Carabidae COLEOPTERA INSECTA	*Trechus micros* (Herbst)	C. Gidman	C. Gidman assisted by A. Brindle
22.2.75	Crevice in wall, Pillar Hall, 160m from entrance.	Philopotamidae TRICHOPTERA INSECTA	*Wormaldia* sp.	T.G. Pিearce	P.W.H. Flint

An invertebrate predator and undoubted resident is the small carabid beetle *Trechus micros* (Herbst). This species was collected from the Gothic Arch by Gidman and from the Second Gothic Arch by the present author, in both cases from the sandy floor. The Collembola which are abundant on the floor and walls in several parts of the cave, feeding on detritus and microorganisms, may provide a large part of this beetle's diet.

At the far end of Cellar Gallery and in the region of the Second Gothic Arch numerous small piles of cylindrical casts cover the surface of banks of sandy silt. Each cast seems to consist largely of mineral particles, suggesting that the animal that produced it feeds on the sediment itself. The size and nature of these deposits is consistent with their having been produced by the flat-backed millipede *Polymicrodon polydesmoides* (Leach), three specimens of which have been collected from this region by the author.

Gidman noted the remarkable abundance of earthworms in Cellar Gallery, and recorded two species, both of which are commonly found in caves, *Allolobophora chlorotica* (Savigny) and *A.rosea* (Savigny). A specimen of the latter species collected in 1975 was identified as the typical form (Table 2). A specimen of a third lumbricid commonly found in caves, *Dendrobaena rubida* (Savigny) *f.subrubicunda* (Eisen) was collected from the far end of Cellar Gallery in July 1974, and two more specimens were found in the low water-filled bedding plane in July 1975.

In August 1975, a single specimen corresponding in all external features to the descriptions of *A.caliginosa* (Savigny) given by Gerard (1964) and Støp-Bowitz (1969) was found, together with approximately twenty *A.chlorotica*, crawling on the surface of a bank of silt lining the wall of Cellar Gallery at the start of the Styx. Unfortunately the specimen was immature and identification cannot be positive, so that it is not included in Table 2.

There are two strikingly peculiar aspects to the behaviour of earthworms in this part of the cave. First, *Allolobophora chlorotica* and *A.rosea* can frequently be seen crawling on the surface and can even be found on the roof of Cellar Gallery, a habit very different from that outside where these two species live in the top 10cm or so of the soil and are rarely seen at the surface. Secondly, none of the species found in the cave normally produces casts on top of the soil (Edwards and Lofty, 1972) yet in many places in Cellar Gallery the sediment banks are completely covered with casts. The floor of the bedding plane to the right of the approach to the Low Section is partially covered, and so is that at the Second Gothic Arch. In an attempt to identify the reasons for this unusual behaviour sediments have been analysed, and the response of the animals to light and substrate has been investigated experimentally.

Analysis of Sediments

In September 1974 cores 4cm in diameter were taken at 1m intervals along a bank of fine silt in Cellar Gallery which was completely covered with casts. Subsamples were removed, representing casts, sediment to 2cm depth and sediment 10-12cm down. The moisture content of half of each subsample was determined as weight loss on drying at 100°C, and organic content as loss in weight on ignition of 450°C. The remaining half of each subsample was brought into aqueous suspension and its pH determined conductimetrically. With fine-textured soils and those of low organic content a considerable proportion of the weight lost on ignition can be due to elimination of water, and this can lead to serious over-estimation of organic matter (Gounot, 1960). Since the sediment was an organically poor (Table 3) fine silt, a second series of cores was taken in February 1975 and organic matter re-estimated by wet oxidation, using the Walkley-Black method (Jackson 1962). The moisture content of this second set of cores was also determined.

Cores were also taken at 1m intervals along a silt bank on the opposite side of the gallery which had very few casts on its surface, and in a regular array over a 2 x 4m area of the floor of the bedding plane at the Second Gothic Arch where there was an incomplete cover of casts. Both sets of cores were analysed as before, except that organic content was estimated as loss on ignition only. The results of the analyses are given in Table 3. The significance of the difference between mean values was determined by calculation of 'Student's 't' (Table 4).

Cores removed from the cast-covered site in Cellar Gallery are very uniform in colour and texture, the fine grey-brown silt becoming only slightly darker towards the surface. At the Second Gothic Arch site the differences with depth are more pronounced; a layer of fine, dark sediment forms an incomplete layer over sandy silt of a much lighter colour. At the cast-free Cellar Gallery site the sediments are more mixed than at either of the other sites, light coloured layers of sand alternating with dark layers of fine silt. Textural differences were reflected in the moisture content of samples, the finer holding more water, as can be clearly seen when the data for the cast-covered bank in Cellar Gallery and the Second Gothic Arch site are compared (Table 4). The moisture content of casts and sediment at the former site in February 1975 was not significantly different (at the 5% level of probability) from that in September of the previous year, despite the fact that the winter samples were taken after two weeks of exceptionally wet weather. It seems likely, therefore, that the moisture content of the silt in this part of the cave varies little throughout the year, except in times of flood.

Table 3. Analytical data for cave sediments.

	Date	Sample	No. replicates	Moisture (% dry wt.)		pH		Organic matter (% dry wt.) Loss on ignition		Organic matter (% dry wt.) Wet oxidation	
				Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
Cellar Gallery Bank of fine silt covered with casts	13.7.74	Casts	15	45.3	0.9	8.07	0.03	4.41	0.03	–	–
		0-2 cm	15	41.4	0.8	7.87	0.03	3.19	0.05	–	–
		10-12 cm	13*	44.6	1.0	7.87	0.03	2.48	0.05	–	–
-do-	22.2.75	Casts	15	46.9	1.4	–	–	–	–	3.88	0.07
		0-2 cm	15	43.0	0.8	–	–	–	–	2.39	0.06
		10-12 cm	13*	48.2	2.5	–	–	–	–	2.12	0.25
Cellar Gallery Coarser sediments with few casts	29.6.75	0-2 cm	8	31.9	1.4	8.011	0.05	3.333	0.28	–	–
		10-12 cm	8	26.3	3.0	7.96	0.05	2.24	0.27	–	–
Second Gothic Arch Sandy silt, casts abundant	22.9.75	Casts	24	36.5	1.4	7.99	0.02	5.44	0.36	–	–
		0-2 cm	14	15.2	2.3	7.93	0.02	1.52	0.17	–	–
		10-12 cm	14	7.7	1.1	8.00	0.03	1.29	0.25	–	–

* At the show cave end the sediment bank was < 12 cm deep.

Table 4. Significance of differences between mean moisture and organic matter contents of casts and sediment from Cellar Gallery and the Second Gothic Arch site as determined by 'Student's' 't' test.

Comparison		Moisture	Organic Matter (Loss on ignition)
Cellar Gallery	casts x sed. (0-2 cm)	$P < 0.01$	$P < 0.001$
	casts x sed. (10-12 cm)	N.S.	$P < 0.001$
	sed. (0-2 cm) x sed. (10-12 cm)	$P < 0.02$	$P < 0.001$
Second Gothic Arch	casts x sed. (0-2 cm)	$P < 0.002$	$P < 0.001$
	casts x sed. (10-12 cm)	$P < 0.001$	$P < 0.001$
	sed. (0-2 cm) x sed. (10-12 cm)	$P < 0.02$	N.S.
Casts	C.G. x G.A.	$P < 0.02$	$P < 0.05$
Sed. (0-2 cm)	C.G. x G.A.	$P < 0.001$	$P < 0.001$
Sed. (10-12 cm)	C.G. x G.A.	$P < 0.001$	$P < 0.001$

The organic content of casts was found to be significantly greater than that of the sediment below (Tables 3 and 4). A similar concentration of organic matter at the surface of cave sediments was noted by Juberthie and Mestrov (1965). The highest values were obtained for the casts at the Second Gothic Arch site where the underlying sediments are organically poorer than elsewhere. The coarseness of the sediments in this region suggests that here flooding is more severe than at the two other sites and it is likely that the thin layer of fine, rich material left on the surface by receding flood waters has been deposited more recently than the surface layers in Cellar Gallery.

When organic content was determined by wet oxidation rather than loss on ignition significantly lower values were obtained for casts and surface sdiment ($P < 0.001$), but not for deeper sediment ($P > 0.05$). However, both methods gave very similar values for the relative proportions of organic matter present in each layer. Organic contents were similar to those found by Juberthie and Mestrov (1965) and rather higher than those given by Cavaillé (1960) and Gounot (1960) for cave sediments. When compared with soils outside caves, for example a wide range of soils in the Preston area (Crompton, 1966), the organic content of these sediments is low. pH values varied very little between sites and with depth, and organic and moisture content were generally very uniform in any one layer at each site, in marked contrast to the heterogeneity found in most soils outside caves.

Earthworm Behaviour Experiments

The sediment banks in Cellar Gallery are in many places completely covered with earthworm casts, evidence that they have been extensively worked in the past. However, the analytical data has revealed that, despite this activity, a distinct vertical stratification persists, which suggests that the animals spend most if not all of their time at the surface. This is confirmed by the scarcity of earthworm burrows, and the frequent observation of animals crawling on or among the casts. Two factors which might play an important part in this peculiar behaviour are darkness and the nature of the subtrate. Their effects were investigated in the field in the following experiment.

At the cast-covered site in Cellar Gallery a carbide lamp was suspended 50cm above the surface and adjusted to provide a light intensity measured as very approximately 1% of that outside the cave. Two 10cm square areas were cleared of casts, and 10 specimens of *Allolobophora chlorotica* were placed on each area. The animals, collected from rich loam, had been stored for 3 days in cave sediment, changed daily, to avoid contamination of cave soil with that from outside. Another ten specimens were placed on each of two adjacent areas from which the casts had not been cleared. Each group of animals was quickly covered with an 8cm diameter glass crystallising dish to prevent any earthworms crawling away over the surface. Two of the dishes, one for each substrate type, had been lined with silver foil to exclude light. The numbers of animals disappearing completely from sight in 30 minutes were recorded to give an estimate of relative rates of burrowing. Six replicates were carried out, light-exposed animals being transferred to dark chambers and vice versa at the end of each trial to minimise the effects of the animals' adapting to light or darkness. A similar experiment was carried out at the opposite side of the gallery, where earthworm casts were scarce, to determine the influence of light on burrowing rate. The results are summarised in Table 5.

Table 5. Effect of light and substrate on burrowing of *Allolobophora chlorotica*. Significance values from X^2 analysis.
(The exact test where expected values are less than 5).

Substrate	No. replicates (10 animals per replicate)	Total no. animals burrowing out of sight in 30 min. Light	Dark	Total	
Cast covered	6	34	11	45	
		$P < 0.001$		$P < 0.001$	
					$P < 0.001$
Casts cleared	6	6	6	12	
		$P < 0.05$		$P < 0.05$	
Cast free	4	1	0	1	
		$P > 0.05$			

Burrowing tendency decreased significantly according to the series: cast-covered > cast-cleared > cast-free areas. For the first substrate type, where numbers burrowing were appreciable, significantly more animals burrowed out of sight in half an hour in the light than did so in the dark.

In a second experiment, samples of casts and sediment (from a depth of 0-2 cm) were collected from three sites in Cellar Gallery. Each material was loosely crumbled by hand and sub-samples placed in choice chambers each of which consisted of a polythene bucket 20 cm in diameter divided vertically in half by a removable partition. The chambers were filled to a depth of 8 cm. Two replicates were set up for each site. Ten specimens of *A.chlorotica,* freshly collected from rich loam, were placed on the surface of each substrate type and their rate of disappearance noted. The animals soon vanished away from the bright lights and relatively dry and warm (20°C) atmosphere of the laboratory. Analysis of the results (Table 6) by the X^2 test showed no significant different in burrowing rate with substrate type ($P > 0.05$).

Table 6. **Burrowing of *Allolobophora chlorotica* on casts and underlying sediment from three sites in Cellar Gallery, and partitioning between the two substrates in a choice chamber.**

Site	Substrate	Total no. animals burrowing out of sight* in					Nos. present after 2 days		P for partitioning
		2 min.	5 min.	10 min.	20 min.	40 min.	Expt. 1	Expt. 2	
I	Casts	3	12	14	17	20	16	14	< 0.01
	Sediments	5	13	15	18	20	4	6	
II	Casts	0	8	19	20	20	10	11	> 0.05
	Sediments	0	10	20	20	20	10	9	
III	Casts	0	8	16	20	20	16	9	> 0.05
	Sediment	0	12	16	20	20	4	11	

* Total for 2 replicates each of 10 animals

When all of the animals had burrowed the partitions were removed and the buckets covered with glass sheets to prevent the animals' escape. They were then transferred to a cool room (at a constant temperature of 10.5°C) where they were kept for two days in darkness. The number of animals in each material at the end of this period (Table 6) indicated no consistent pattern of preference. At only one site, the first, was there a significant difference in numbers present in one substrate; in this case the animals aggregated in the casts. In general they were vertically distributed evenly throughout the soil. Out of 120 specimens used, 5 were found crawling on the surface after 2 days in darkness (3 on the sediment, 2 on the casts).

From the above results, it seems reasonable to suggest that several, if not all, of the following may play an important part in the peculiar behaviour of earthworms in the sections of Ingleborough Cavern which have been investigated.

1. **Darkness** Davies (1948) examining the behaviour of earthworms underground, noted that the animals would (apparently) explore for food while retaining the hind segments in their burrows, rapidly retracting when exposed to artificial light of low intensity. *Dendrobaena rubida f. subrubicunda* showed no such reaction when crawling on open surfaces, and Davies suggested that earthworms which live completely underground may have a reduced light response.

The specimens of *A. chlorotica* used in the present investigation showed a clear avoidance of moderate illumination. It is true that they had been collected from outside the cave, but since this species normally lives more or less permanently below the soil surface, as does the other common species in Cellar Gallery, *A.rosea,* its reaction to light is probably not very different in the two types of habitat. Outside caves, burrowing will clearly protect the animals against predators such as birds, which hunt by sight. Underground, the animals are protected by darkness, and potential predators are very scarce.

2. **Moisture** Burrowing will also protect against desiccation, to which earthworms are particularly susceptible by virtue of their moist body surfaces. *Allolobophora chlorotica* and *A.rosea* may be more sensitive in this respect than many other species since both are fairly small (and hence have high surface area : volume ratios) and are frequently found in wet soils. Juberthie and Mestrov (1965), in a study of the earthworm populations of cave sediments, noted that density and activity were least in the drier areas. However, it seems unlikely that in Cellar Gallery, where atmospheric humidity and soil moisture content are constantly high, desiccation will have anything but a minor effect on surface-dwelling earthworms.

3. **Physical nature of the substrate** The soils in which *A. chlorotica* and *A.rosea* are found generally have a moderate or good crumb structure with numerous pore spaces and cavities created by plant roots which facilitate burrowing. Not only will compact cave sediments be more difficult to force a passage through, as suggested by the results of the behaviour experiments, but there will be little space beneath the surface to deposit egested material. Thomson and Davies (1974) have shown that *A.rosea* produces casts on top of soils which have been artificially compacted, in contrast to its usual habit of casting below the surface. The surface-casting behaviour of this species and *A. chlorotica* in Ingleborough Cavern may well be due to the same cause.

4. **Distribution of food** *Allolobophora chlorotica* feeds on decomposed organic remains (Piearce 1972), as does *A.rosea* (Bolton, 1969). In soils outside caves organic matter in a variety of states of decay will be distributed throughout the soil profile due to earthworms and other soil animals mixing surface detritus in with the soil below, and also as a consequence of the penetration, and eventual death, of plant roots. In contrast, in Cellar Gallery fresh organic remains are probably deposited on the surface of the sediments by floods at infrequent intervals and mixed in with underlying sediment to only a limited extent. The gallery is a long, slightly upward-sloping tube which floods during late autumn or winter in most years from the Second Gothic Arch end (Gidman, 1962; Jarman, pers.comm). The water rises slowly and, as it falls, deposits a thin layer of detritus on the sediment surface. This may be the principal source of food for the earthworms, although the possibility that a considerable amount is brought in with percolating water cannot be excluded. The concentration of organic matter at the surface might in part explain the animals' inhabiting this region althought the results of the soil choice experiment do not completely support this view.

5. **Nature of food** The quantity of organic matter in the casts and sediments examined was low in comparison with soils outside caves. Its quality was also different; recognisable fragments of detritus were seen only at the Second Gothic Arch, where flooding is most severe. In Cellar Gallery very finely divided amorphous humus was evenly distributed in the horizontal plane, declining in concentration with depth, and the same was generally true at the Second Gothic Arch site. It seems reasonable to suggest that only the most resistant organic material will have survived to reach this advanced state of decay, and that as a source of food it is poor qualitatively as well as quantitatively. Bolton (1969) has shown that a woodland population of *A.rosea* assimilated only 0.8% of the energy ingested in the diet. Assimilation efficiency for the population in Ingleborough Cavern may be even lower, and it is possible that for much of the year the animals are living close to starvation.

Shortage of food is a situation commonly faced by cave animals and many cavernicolous species are adapted to a low energy intake by having low rates of growth, reproduction and activity (Vandel, 1965). Although no information has been published on energy expenditure during burrowing by earthworms, the work done is likely to be considerable, especially where the substrate is compact, and it is possible that the restriction of animals to the sediment surface in caves is partly an energy conservation measure.

Inspection of the sediment surface in the cave suggests that the density of earthworms is low in comparison with soils elsewhere, probably reflecting poor food supply. Since collection of even a small number of these animals could have a considerable effect on the balance of the system, it is encouraging to note that useful information can be obtained on diet, activity, and interactions with the substrate, without removing a single specimen, simply by analysing casts and sediment. A similar approach might be adopted with other groups of cave animals, with interesting results.

Acknowledgements

I would like to thank Mr. C. Gidman for generously allowing me to use material from his unpublished report, the directors of Ingleborough Cavern, Mr. A. Hunworth and Mr. R.A. Jarman, for permission to carry out the investigation, Mrs. J. Shevelan for help with access to the cave, Mr. D. Checkley for assistance with field work and Mr. P.W.H. Flint for identification of arthropods. These, and Miss Mary Hazelton, have been a valuable source of advice and encouragement throughout the project.

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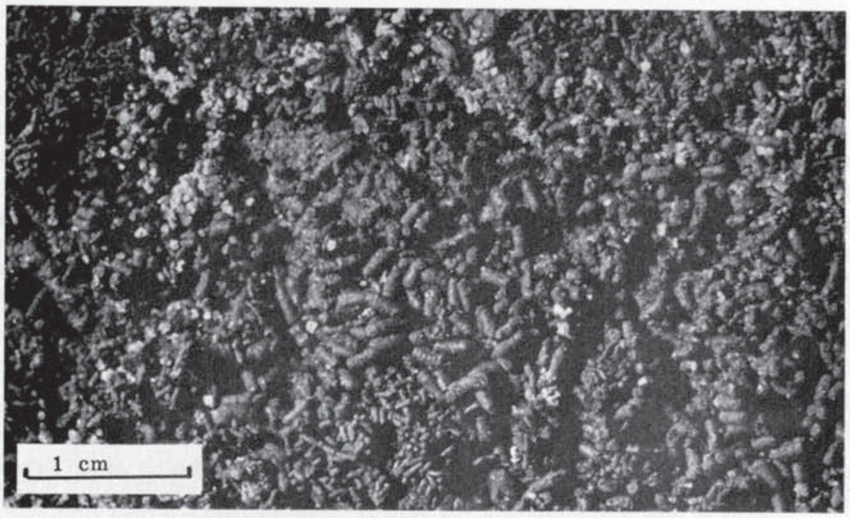

Fig. 1. Arthropod casts probably of the millipede *Polymicrodon polydesmoides* (Leach) on the floor of the bedding plane off the Second Gothic Arch, Ingleborough Cavern. Each faecal pile comprises many cylindrical pellets loosely clumped together, dry and crumbly to the touch (Photo by K. Oates).

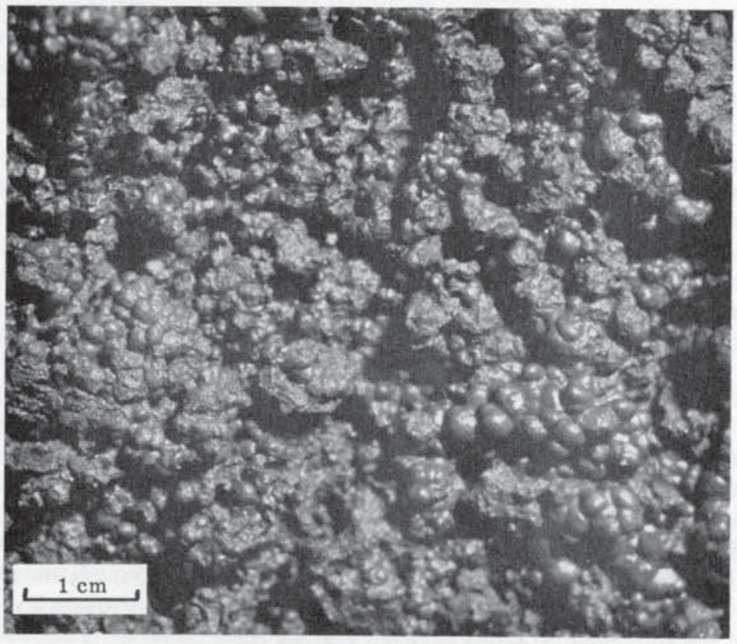

Fig. 2. Worm casts of *Allolobophora sp.* on a silt bank in Cellar Gallery in Ingleborough Cavern. Composed of aggregates of shiny, smooth rounded lumps of various sizes, sticky to the touch (Photo by J. Paice).

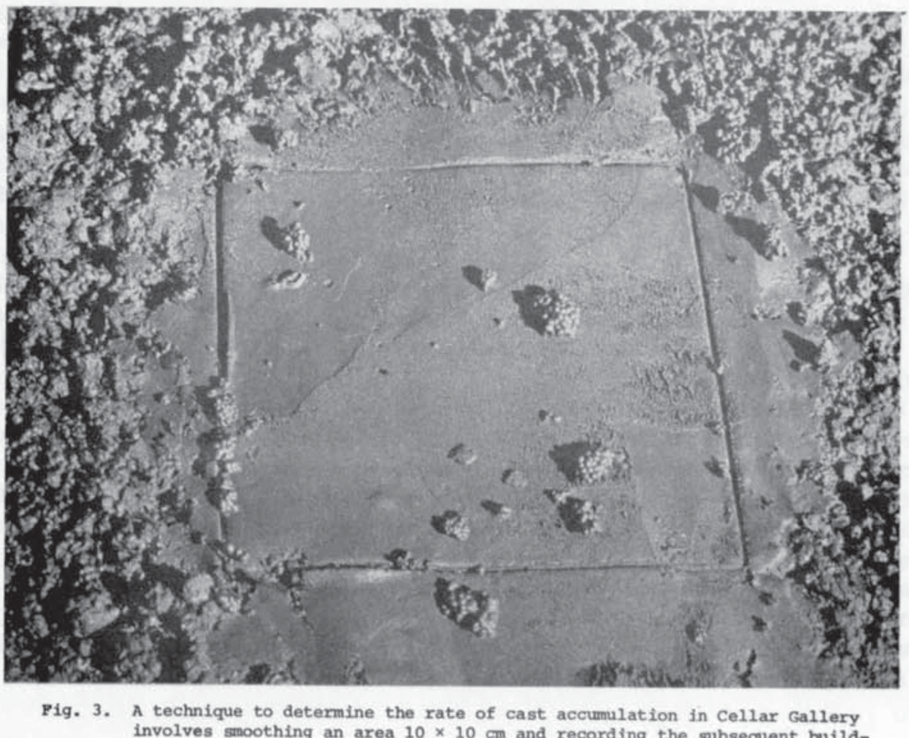

Fig. 3. A technique to determine the rate of cast accumulation in Cellar Gallery involves smoothing an area 10 × 10 cm and recording the subsequent build-up of casts. Those seen accumulated in seven months !

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BIOLOGICAL STUDIES IN INGLEBOROUGH CAVERN

by C. Gidman

Editor's note: The contribution which follows is the greater part of a student biological project carried out in 1962-3, and Dr. Piearce's discussion in the preceding pages has developed a number of the themes mentioned by Mr. Gidman, as well as others of his own. Mr. Gidman's report is published here as it is felt that such students' reports should not be hidden away in college files, but should be available to the scientific reader. It is hoped that other such projects will be unearthed as a result of this publication.

The Threshold

The impressive entrance of the cave has a southern aspect and is situated on the 850 feet contour line at 34/754711. The entrance path continues for some 20 yards until the overhang limestone cliff facing east and rising to well over 90 feet is reached. At this point begins a lowered porch which here is approximately 50 feet wide, 20 feet high and which extends for 45 feet up to the cavern door.

The porch area is covered by a rock canopy and has a permanent stream running through which, together with the reduced light, gives rise to shade conditions with a consequently fairly high humidity. But, even in this comparatively small area, conditions of temperature and humidity are not constant; owing to the increasing depth of shade as one moves inwards towards the dark zone of the cavern, the amount of evaporation on bright sunny days causes the humidity to vary from 80% to 90% depending on the weather. As the whole of this threshold area is roughly semicircular in shape with a very uneven terrain, a general survey was carried out first noting the humidity, temperature of water and air and recording the light intensity. Data was taken to correlate the succession of plant life with the degree of shade tolerance of the plants.

The whole area was therefore divided into three main zones as shown in Figure 1. From the beginning of the lowered porch and moving inwards to cave door, plus what will be termed the Fringe Zone i.e. the surrounding daylight area immediately beyond the 45 ft. point, the various Zones are as follows:—

From cavern enclosure to 45 feet (13.7 m) from door	Fringe Zone
From 45 feet to 30 feet (13.7 - 9.2 m) from door	Zone 1
From 30 feet to 15 feet (9.2 - 4.6 m) from door	Zone 2
From 15 feet to 0 feet (4.6 - 0 m) at the door	Zone 3

General Remarks on Zones

The 45 feet plus or Fringe Zone

In this area bounded by the limestone cliff and the steep sides of Clapdale the flora is similar to that of deciduous woodland with open clearings and including a small stream.

On the sides grow Hawthorn — *Crataegus monogyna* Jacq. Elm — *Ulmus glabra* Huds. Ash — *Fraxinus excelsior* L., Hazel — *Corylus avellana* L. and Elder — *Sambucus nigra,* the last with a covering of mosses predominantly *Hypnum* spp. On the top of the cliff are some very fine beeches — *Fagus sylvatica* L., whose leaves fall in the autumn creating humus between the limestone boulders in the 45-30 ft. Zone. The dominant moss found here on the limestone rocks is *Thamnium alopecurum* whose dendroid habit is much less marked than normally found incomparable habitats. Although only three or four plants of the Spear Thistle — *Cirsium lanceolatum* L. are present, it could quickly become the dominant plant in the area. This role is held by the nettle — *Urtica dioica,* with dense vegetation providing a home for many invertebrates, insects, molluscs, and arachnids. Grasses are rare although False Oat-grass, *Arrhenatherum elatius* (L) J&C Peel has been noted.

The 45 feet to 30 feet ... Zone 1

One or two very fine liverworts grow in this region including *P. asplenoides* and a small patch of *R. hemisphaerica* (L) Radii. This is the richest area for mosses and they are the dominant plants. The Angiospermae found here are those normally to be found growing in the hedgerow, owing to the shading by the cliff at this point, where the lowered porch begins.

The 30 feet to 15 feet ... Zone 2

Here the light is very poor due to the dip in the roof and the reduced space. The dominant plant in this region is a thalloid liverwort *Conocephalum conicum* which grows in large masses on the rocks by the stream course. Here also is an alga *Anacystes montana* (Lightf) D & L which is very tolerant to low light intensity, growing on the roof.

The 15 feet to 0 feet ... Zone 3

Lichens and Algae dominate this area of extremely low light. Some species of mosses occur on rocks and soil pockets along with Pteridophyta and *C.conicum.*

The above gives only a general overall picture of the area studied. The following detailed studies of stations through a transverse section of the threshold will demonstrate the plant succession in relation to light and humidity. Four stations for observations were established·—

A Where the limestone cliff rises and lowered porch begins. It includes a small area with a soil pocket containing leafmould.

B. **30 feet from entrance (Zone 1)** Where stream falls over a boulder of tufa as a small waterfall. It includes mosses, liverworts and the fauna of a small pool

C. **15 feet from entrance (Zone 2)** Mosses grow on and amongst the scattered limestone boulders and show the effect of light on their method of growth.

D. A region of extremely poor light conditions, both outside and inside the cavern where an iron door shuts out larger animals though smaller ones can pass a grill.

A standard was found necessary to record the light intensity and the following method was evolved, using equipment available to most amateur photographers.

Measuring the Light Factor

Light readings were taken using a Weston Master Photographic Exposure Meter 2. A series of relected light readings were made one foot away from a matt white board, hold at floor level in a vertical plane facing daylight, beginning at the point of overhang (45 feet from cavern door) and every five feet to inside the cavern, where no further readings were possible. The readings giving candles per square foot were converted to foot candles by multiplying by a factor of four.

At the same time exposures were made of the light reflected from the same matt white board, on Ilford F.P. 3 35 mm film with the camera set at 1/30th sec. and the diaphragm at f8.

The film was then developed in M & B Promicrol Ultra-fine grain developer for six minutes at 72°F, with agitation 5 secs. each minute during development. The film was then given a water rinse and fixed in acid hardener fixer for 15 minutes and afterwards washed and dried in usual way. The density of the film was found by using a densitometer, which gave the following readings.

Distance from Entrance	Foot Candles	Density of Film
45 feet	3,200	2.
40 feet	2,400	1.75
35 feet	1,600	1.55
30 feet	800	1.45
25 feet	400	1.25
20 feet	200	1.00
15 feet	100	.8
10 feet	52	.675
5 feet	26	.525
0 feet	12.8	.3
-5 feet	3.2	.2
-10 feet	1.6	.1
-15 feet	.0	.0

From the negatives corresponding prints on Kodak Bromide (Grade 2 Normal) paper were made.

The exposure was calculated from the densest negative, i.e. 3,200 foot candles and given the shortest exposure possible to develop a printable image using Kodak Velox Developer at 65°F and developing for 3 minutes. This same exposure and developing time was then used, to print from each negative in the scale.

A Detailed Study of Station A in Zone 1 ... 45-30 feet.

Substrate limestone — soil pockets. 1750 foot candles. 76% Humidity.

In this small area the following plants are in evidence.

ANGIOSPERMAE

On rock face — *Ranunculus acris L.* Beech seedling *F. sylvatica.*

Geranium robertianum — soil. seeding of *Sambucus nigra* — rock cleft.

Urtica dioica — soil

Lapsona communis — soil

Cardamine hirsuta or *flexuosa* — soil (quickly becoming the dominant flowering plant in this zone.)

Arum maculatum L

Fragaria vesca L

The above are all typical plants of the hedgerow.

PTERIDOPHYTA

Brittle Bladder Ferm — *Cystopteris fragilis* (L) Bench — common. soil pockets.

Maidenhair Spleenwort — *Asplenium trichomanes* L.

BRYOPHYTA

Thamnium alopecurum — on rocks.

Camptothecium sericeum — on rocks.

Cirriphyllum crassinervium — on rocks.

Trichostomum brachydontium — on soil.

LICHENS

Xanthoria parietina — rock.

Lepraria aeruginosia — rock.

A soil pocket containing rotting beech leeves was found to be the habitat of Isopoda, Chilopoda, Diplopoda, Collembola and occasional molluscs (very small species).

A Detailed Study of Station B in Zone 2 ... 30-15 feet.
Substrate tufa — 894.25 foot candles — 84% Humidity.
ANGIOSPERMAE
Graminae — *Melica uniflora,* seen in Wood Molick.
Annual Pearlwort — *Sagina apetala* Ard.
PTERIDOPHYTA
Asplenium trichomanes — by water side.
BRYOPHYTA
Pohlia albicans — rock tufa.
Trichostomum tenurostre — rocks — tufa.
Fissidens adiantoides — soil — tufa.
Fissidens cristatus — rock tufa.
Drepanocladus uncinatus — rocks — side of tufa.
Bryum pseudotriquetrum — tufa.
Leptodontium flexifolium — soil pocket — wet.
Eurhynchium praelongum — rock and tufa.
This list contains mosses which are actively producing tufa; and they were all collected from top, sides and base of tufa hummock, both in and out of the small streamlet which falls over the hummock. The most active bryophyte is *D.uncinatus* not previously noted as a tufa-forming moss on the Malham area. An unusual liverwort which is usually found growing near the sea, *Moerckia flotswiana* (Nees) Schiffn., is known at Malham growing on mires on the calcareous drift. The mires are dotted with tufa hummocks thought to have grown up around sites of springs and *Moerckia* occurs on the sides and bases of both drift and tufa hummocks. It is also growing on tufa at this Station in the Ingleborough Cavern threshold.

Below the hummock waterfall a pool has formed which contains detritus of fallen leaves. It is inhabited by the freshwater shrimp *G.pulex* and is the first one sees of them before entering cavern. Also in the pool are Odonata and Trichoptera larvae and several Coleoptera of the family Gyrinidae.

A Detailed Study of Station C in Zone 3 ... 15-0 feet.
Substrate — limestone rock and soil pockets. 42.5 foot candles. 88% Humidity.

The dominant plant at this point is a thalloid liverwort *Concocephalum conicum*. This bryophyte makes large masses of growth on the wet rocks and is kept moist by the dripping water. In this area of poor light the plant is very much reduced in size of thallus. Here also the mosses begin to show a marked change in their manner of growth, being much less compact if the species is of the cushion-forming variety. In this zone of reduced light other shade tolerant mosses make their appearance. No Angiospermae are present in this area and only one pteridophyte *Asplenium trichomanes* L.
BRYOPHYTA
Bryum capillare — soil pockets.
Anomodon veticulosus — soil and rock.
Neckera complanata — rock.
Eurynchium schwarzii — rock.
Eurynchium praelongum — rock and soil. Shade tolerant moss. (Watson.)
Drepanocladus uncinatus — rocks.
LICHENS
Lepraria aeruginsia is very common on the rocks at this station.
ALGAE
On the fairly low roof one of the blue-green algae *Anacystes montana* grows in large masses. Also in the stream can be found a filamentous algae, and an associated living colony of diatoms.

Thus the change over to shade tolerant plants is a gradual one, one or two species of bryophytes being quite capable of withstanding very low light intensity e.g. *E.praelongum.*

A Detailed Study of Station D ... 0 feet. 3.4 foot candles. Humidity 90%.
C.conicum is still the dominant plant but shows the effect of further reduced illumination by smaller lobes. Other associates in this zone are:—
PTERIDOPHYTA. Substrate, limestone rock with soil pockets.
Phyllitis scolopendrium — soil and rock clefts.
Crystopteris fragilis (L) Bench. Very common on soil pockets and in rock clefts.
Asplenium trichomanes L. Fairly common — rock clefts.
Asplenium viride Huds. Only one or two specimens present.
All specimens of ferns found in any part of the threshold are present here at zero feet though in extremely poor light conditions. One specimen of *A.trichomanes* growing in a cleft above cave door was completely covered with the lichen *L. aeruginsia.*
BRYOPHYTA
Fissidens bryoides — soil
Eurynchium schwartzii — rock.
Isopterygium depressum — soil.
Thamnium alopecurum — very much smaller — less dendroid.
Crateneuron commutatum — sides of stream.
Eucladium verticillatum associated with the liverwort *Lophocolea* spp.

This moss is absent from the Malham district (Field Studies Vol.1. No.2) yet is found here in the same region, in the cave threshold, growing in extremely poor light.

FAUNA

Here at the true entrance to the cave, resting on the roof are several Tipulidae, *Limonia nubeculosa* (Mg.) September 1961. Also resting on the cave roof on the other side of cave door were several large spiders, *Meta.* sp. Also several Isopods were present on several occasions when visiting cavern during October, 1961; by the middle of December however no insect life was noted in this region with the exception of a solitary collembolan found in the discarded broken head of a stiff broom. Spiders noticed again on February 10th 1962. and by August 1963 a good thriving colony of spiders was once again established in the threshold.

NOTE ON ALGAE

From scapings taken from roof of cavern in this zone the following plants have been determined by Dr. Drouet:—

"The scraping consisted mostly of *Coccochloris peniocystis* (Kütz) Dr. & Daily, *Anacystis montana* (Lightf.) Dr. & Daily, *Schizothrix calcicola* (Ag.) Gom., *Scytonema Hoffmanii* Ag., various moss protonemata and fungal hyphae".

Hibernation

Hibernating animals add to the interest of cave fauna and are attracted to a habitat where the conditions for hibernation are ideal.

1. Constant humidity — 92% Ingleborough Cave.
2. Constant temperature within one degree — 50°F.
3. Darkness as an aid to prevent predation.
4. Stillness of air (air currents perceptible)

In Ingleborough Cavern these factors are apparent at amost zero feet (threshold) within the cavern when the door is shut giving the effect of true cave environment.

Few bats have been seen in Ingleborough Cavern and they are rare in the whole of the Ingleborough region. In this area of the cavern as mentioned in the report on Station D, there are many spiders, all of one species, *Meta merianae* (Scopoli). This spider could have been inside the cavern during its absence from the threshold during November, December and January, possibly indicating a small seasonal migration of population. The situation for this species is an ideal one, as they seem to frequent places with little light and high humidity and where food is abundant. One tends to under-estimate this factor of food in caves where numbers of insects use such places to hibernate and to live in for long periods.

The above spider feeds principally on Tipulidae, midges, gnats, and other flies, all of which have been found in the cave threshold. A tipulid *Limonia nubeculosa* (Mg.) is common and their larvae inhabit moist soil. Another Dipteran, numerically dominant in this region is *Tephroclamys tarsalis* (Zett).

A group of moths, all of one species, *Triphosia dubitata* (Tissue Moth), were found hibernating all together resting on a rock surface 3 feet from the ground in a very dark situation. *T.dubitata* is a variable moth whose caterpillars feed on shrubs such as buckthorn, sloe and bird cherry. The moth is out in autumn and is seen occasionally at ivy flowers. After hibernation it is again seen in April and May. Noted from caverns in the south and from nearly all the English counties, it is rare from Yorkshire northwards.

Data on Stations within the Cavern

The humidity is constant at 93%. Although distance below ground level has been calculated from the surface contours, and the distance from the cavern entrance to a given station taken from a plan of the cave, it has not been found practicable to give the depth at Stations using cave threshold as a comparable reference point.

The Inverted Forest (Station E). Distance from ground level 50 feet and 180 feet from cave entrance. Stalagmite formations formed in the past were later under water in the dams. There is a small streamlet running through this section which has a low bedding plane, five feet from the floor. The sides of passage are covered in flowstone. There is a rough floor, stony, with pockets of sandy mud. Here *T. tarsalis* and *L.nubeculosa* are found within the numerous cracks and crevices of the stalagmitic material. It was also noted that many dead flies were apparently stuck to the top of the formation and the rock in the bedding plane. Several of these Diptera had apparently succumbed to attacks by one of the Fungi Imperfecta: Certainly only the chitinous covering and wing membranes were left, the fungus apparently having used up all the available nitrogenous material. This fungus *Stibella kervillei* (Quel) Ling, has also been found in limestone caves in France, from Pinhole Cave, Cresswell, Derbyshire, and from a cave at Yealhampton, Devon.

The floor of this section is constantly damp and the pockets of loose sandy soil provide a home for collembolan *Folsomia candida* and larvae, probably tipulid. From one of the adjacent formations were taken a Chironomid and Tipulid adults.

Some indeterminate objects appear to be of fungal origin being a dark-brown mass of filamentous threads.

Pillar Hall (Station F)

High humidity. Distance from ground level 100 feet and 525 feet from the entrance. Here the system is fairly extensive and is the widest part of the stream passage, the sides of which rise up scree slopes from 14 to 30 feet. At the top of the scree slope are one or two small rimstone pools which were not sampled.

The stream joins several inter-connecting pools one at least six feet in depth whilst others may dry up in spells of warm weather. The water flows from one to other of the pools until carried down the Abyss where it joins the river at a lower level.

Here in pockets of loose soil three small Staphylinid beetles were found. Collembola are also present, *Folsomia candida.* The pools contain a few shrimps, *Gammarus pulex*, and also in the deepest pool was found a colony of cyclopids, *Acanthycyclops viridis* Jurine. In this region a tipulid was taken from the surface of a large stalagmite boss, the Jockey Cap, *Lipsothrix remota* Walker.

For a short stretch the roof is rather low after which the next station is reached.

Gothic Arch (Station G)

This is a trinagular fissure with curtain formations. The floor is extremely sandy here and is affected by heavy flooding. Humidity almost saturation. 200 feet from ground level and 915 feet from entrance. At the end of this short passage are one or two small rimstone pools which did not appear to be inhabited by fauna. The sandy floor yielded a small brown beetle *Trechoblemus micros* (Herbst.), a very small mollusc (living) and three kinds of Collembola *Anarda* cf *granaria, Onychiurus fimetarius* and *Folsomia candida.*

Long Gallery (Station H)

225 feet from ground level and 1,110 feet from entrance. The stream makes several pools in which are *G.pulex.* The passage is high and the sides are extensive, the rock giving way to sand in which are the two Collembolans, *F.candida* and *O.fimetarius.* A millipede was also noted at this point. Seen in other parts of the cavern but especially at this station was an orangy-green substance found on the rocks walls. This material probably contains iron bacteria. If this is so there would be plenty of food available for cave animals, and it would make the first link in a food chain for this kind of environment.

Pool of Reflections (Station I)

250 feet from surface and 1,305 feet from entrance.

This is a large rimstone pool 1 to 2 feet in depth with a substrate of fine silt.

Shrimps and cyclops are abundant in this pool, namely *G.pulex* and *Acanthocyclops viridis* (Jurine). The shrimps taken from this pool appear to have less body pigment than the normal form of *G.pulex* found in cave threshold. Those shrimps found at Station L12 have more pigment, but considerably less than the normal type, certainly more than those found here at 19. The reason for this may be that the shrimps are in fact living and breeding constantly in the pool. Shrimps have been found in various stages of growth and occasionally large adult specimens have been netted, all very pale in colour. This pool in relation to *G.pulex* is discussed later. No other crustaceans were noted from this Station which is the last in the commercial section of the cave.

Cellar Gallery (Station J)

275 feet from surface and 1,455 feet from entrance, with a substrate of sandy mud. Here in a crevice was found fruiting *Coprinus lagonus* growing on a substrate of a half-rotten fruit of *Aesculus hippocastanum.* Worms are very abundant in the Cellar Gallery and thousands of casts prove that the population of annelids here must be indeed prolific. A sample of soil was taken for organic testing and found to contain 4% of organic material. This is fairly high considering the sandy nature of the soil. The two species of worms found here are *Allolobophora rosea* and *Allolobophora chlorotica* in about equal proportions. This extensive gallery is subject to severe flooding, so the worms must be semi-aquatic to withstand saturation point even for short periods. Collembola also inhabit the soil.

The Styx (Station K)

250 feet from surface and 1,620 feet from entrance. It is a fairly deep pool, up to four feet in depth. The substrate is of fine silt a good two feet in depth.

Cyclopids and *G.pulex* inhabit this pool, the water of which drains down to below Giant's Hall. The pool itself is fed by a small streamlet. The "Styx" rises to the roof in flood when any fauna the pool contains would be carried into other parts of cavern or lost en route. The crustaceans, however, would be able to burrow into the mud and silt, and be well protected from any storm with the exception of the major flood which might scour the bottom of the pool.

When the cave was first explored in 1837 this pool was non-existent. It must have been caused by a violent flood soon afterwards.

Lakeside (below Giant's Hall) (Station L)

300 feet from surface. 2,040 feet from the entrance. One reaches this very shallow extensive pool by dropping down about 15 feet below Giant's Hall to an almost prone position. Although difficult to negotiate, detritus was collected and observations made. Here *G.pulex* is in great abundance in all stages of growth and this is undoubtedly the breeding ground for this crustacean which in flood time is carried throughout the cavern. Other fauna found here include –

A small worm *Nais elinguis* – common.
A cyclopid – *Eucyclops agilis* (Koch)
A planarian – *Polycelis felina* (Dalyell)
A cyclopid – *A.viridis*
A worm – *Allolobophora rosea*
A Dipteran pupae.

It is feasible that other fauna could be found here amongst this detritus which consisted of broken plant stems, moss and silt, making an ideal substrate for many invertebrates. It is interesting to record that only once in several visits was detritus present. It would appear to collect here only during long spells of settled weather.

Discussion

Although a fairly representative collection of invertebrates have been found in the cavern, none of them are exciting finds such as are found in European caves, and all are epigean forms with perhaps one exception – that of *G.pulex*. It is quite possible for this crustacean to live and breed in cave pools as their requirements are so simple.

Two shrimps were taken in-cop from the Styx, Station K, on February 10th and placed in a hair-cream jar along with water from the Styx pool. On April the 12th they were still active and two young shrimps appeared on April 13th. By April the 30th all shrimps were lively. They were kept at a fairly constant temperature in deep shade. On being brought out into the light they would immediately burrow into silt. "Shrimps habitat is determined by a simple negative reaction to light. Reason for living in the dark is almost certainly because of protection from enemies since animal has no effective means of defending itself by running away or hiding." (Elton 1960.)

On May 16th the male shrimp died and had completely disappeared by the 29th May. The female shrimp died on June 2nd and was removed to prevent fouling of the water. The two young shrimps are still active up to October 18th. The shrimps appear to have made little growth, due to being without their proper diet and should normally have become adult taking seven months to mature even under winter conditions (Hynes 1955). Specimens born in March become mature in July and breed throughout August. It would seem from observations in cavern pools that this rhythm is carried out there, but much more work needs to be done before one can be satisfied on this point. It should be made clear that the two young shrimps received no solid food. The jar was topped up with water from the Styx from time to time.

Although *Gammarus* populations are periodically renewed from outside caves either by seepage water (small gammarids can be partly interstitial) or by flooding of cave pools, it is thought that the shrimps in the Pool of Reflections have been there for some considerable time. Even the most violent of floods bypass this pool. Evidence for this is available in the fact that candle-grease was seen on the surface of this pool the day before a violent storm and immediately afterwards, when storm had subsided, the candle-grease was still in same position. Further work is necessary to establish that the shrimp here in this pool is a troglophile, but the epidermis of *G.pulex* in this pool is certainly lacking in pigment as compared to normal epigean forms.

It is now obvious that distribution of fauna in the cave depends solely on flood levels to begin with. Distribution may then take place through a slow migration. Although invertebrates such as *Asellus cavaticus* have not been found here, it is highly probable that it is present but has been overlooked.

In conclusion it is now known that the cave is populated by many species, sometimes in great numbers, e.g. annelids in Cellar Gallery. Quantitative work could be carried out on cave inhabitants and interesting data would result.

List of Flora

Angiospermae
Fagus sylvatica
Ulmus glabra
Fraxinus excelsior
Sambucus nigra
Corylus avellana
Crataegus monogyna
Urtica dioica
Cirsium lanceolatum
Geranium robertianum
Lapsona communis
Cardamine hirsuta
Arum maculatum
Fragaria vesca
Sagina apetala

Pteridophyta
Cystopteris fragilis
Asplenium trichomanes
Asplenium viride
Phyllitis scolopendrium

Lichens
Xanthoria parietina
Lepraria aeruginosia

Fungi
Coprinus lagopus
Stibella kervillei

Bryophyta
Thamnium alopercurum
Conocephalum conicum
Camptothecium sericeum
Cirriphyllum crassinervium
Trichostomum brachydontium
Polia albicans
Trichostomun tenurostre
Fissidens adiantoides
Fissidens cristatus
Fissidens bryoides
Drepanocladus uncinatus
Bryum pseudotriquetrum
Leptodontium flexifolium
Eurhynchium praelongum
Moerckia flotswiana
Eurynchium schwertzii
Isopterygium depressum
Cratencuron commutatum
Eucladium verticillatum
P. asplenoides

Algae
Anacystis montana
Scytonema hoffmanii
Schizothrix calcicola
Coccochloris peniocystis

List of Fauna

DIPTERA
Mycetophilidae *Rhymosia domestica* (Meigen)
Helomyzidae *Tephroclamys tarsalis*
Leria serrata (L.)
Tipulidae *Limonia nubeculosa* Meig
Lipsothrix remota Walker

COLLEMBOLA
Onychiuridae *Onychiurus fimetarius*
Isotomidae *Folsomia candida*
ISOPODA
Porcellionoidae *Porcellio acaber* Latr.

ARACHNIDA
Araneae *Meta merianae* Scop.
LEPIDOPTERA
Hydriomenidae *Triphosia dubitata* L.
COLEOPTERA
Carabidae *Trechoblemus micros* (Herbst)
Staphylinidae *Oxytelus rugosus*
Oxytelus laqueatus
Agabus biguttatus (Oliver)

AMPHIPODA
Gammaridae *Gammarus pulex* L.
CYCLOPOIDA
Cyclopidae *Acanthocyclops virides* Jur.
Eucyclops agilis
TRICLADIDA
Planariidae *Polycelis felina*
ANNELIDA
Oligochaeta *Allolobophora rosea*
Lumbricidae *Allolobophora chlorotica*
Naididae *Nais elinguis*

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THE EFFECT OF LOW HUMIDITY ON THE DISTRIBUTION OF *HETEROMURUS NITIDUS* (COLLEMBOLA) IN RADFORD CAVE, DEVON

by Jane Wilson

Summary

Relatively large chamber heights seemingly allow a drop in cave humidity due to air circulation. Many cave dwelling invertebrates, particularly troglobites, can tolerate only a slight departure from a relative humidity of 100%. Thus there may be an indirect correlation between the height within caves and the absence from that chamber of organisms requiring humid conditions. The evidence presented herein is drawn from studies of the troglophilic insect *Heteromurus nitidus* from Radford Cave, near Plymouth, Devonshire.

Introduction

It is well known that, in temperate regions, caves of any appreciable size provide high humidity, constant temperature (Baldwin and Beatty 1941) stable habitats (Poulson and White 1969), usually at the average rock temperature of the area. Radford Cave near Plymouth, averages around 12-13°C while 'cave conditions' in the United States have been quoted as averaging 14°C (Christiansen 1969). Geographical differences account for this discrepancy.

Cavernicoles are generally heterotrophic, large numbers of the macrofauna feeding on micro-organisms (see also Caumartin 1963), which decompose allochthonous material such as inwashed vegetation, cavers' rubbish and bat guano. This limited energy input into the cave environment tends to lead to low population densities and hence fairly simple community structures (Barr 1967). Unfilled niches are not unknown in cave food webs.

Coping with food scarcity is a necessary adaption to life underground and food distribution may be expected substantially to influence population distributions of various species. However, investigation showed that in Radford cave humidity was more important than food scarcity in determining which areas populations were able to occupy.

Radford Cave

Radford Cave SX/503527 (Figure 1) was first described by Hooper in 1954 as being 'situated in a relatively small belt of limestone barely half a mile long, which runs in an east-west direction, immediately south of Hooe Lake. This narrow belt, which is little more than one eighth of a mile wide, encloses the greater part of Hexton Wood and the cave entrance lies at the western end of this wood. The entrance is about 600 yards' walk from the Plymstock to Hooe road in a long-disused quarry.' Hooper recorded the total passage length as about 600 feet (180 m) but with subsequent discoveries within the cave, its passage length is now nearly 2000 ft (600 m) (Jeffrey 1967).

Frequent measurements of the physical conditions within Radford Cave showed there to be few fluctuations in temperature and humidity although air movements could be detected (Barbour 1965). The relative humidity of the cave is 97% for most of the year except where the height of the chamber, greater than about 25 ft (7 m) allows air circulation to cause a marked fall in the humidity in that chamber. During preliminary surveys of the cave's fauna, it was noticed that the Boulder Slope and Canyon area (a chamber with a maximum roof height of about thirty feet (9 m), thus the highest in this cave) supported very little life despite the presence of abundant food in the form of fungi. An attempt was made to demonstrate that humidity variations within the cave play an important part in determining the population distributions of species that are intolerant of reduced humidity conditions.

The humidities at various sites in Radford Cave were measured at fortnightly intervals. Figure 2 shows the averages of readings noted between September 1974 and May 1975. During periods of dry weather it is not uncommon for the humidity in the Boulder Slope and Canyon to fall to as low as 80%. A housing estate has been built above the cave and it may have reduced seepage and drip water entering the cave so it is possible that this comparatively very dry area is quite a recent development.

Heteromurus nitidus

The Collembola are a class of wingless insects commonly known as 'springtails'. The sensitivity of some of the representatives of this group to dry, unsaturated air (at a relative humidity of less than 100%) has been shown to be quite marked (Milne 1959). An attempt was made here to relate this sensitivity in one of the nine species of Collembola recorded from Radford Cave (Hazelton 1967, 1975), to areas of low humidity within the cave.

The Collembolan studied was a species with eyes from the family Entomobryidae: *Heteromurus nitidus* Templeton (1835), see plates. This lightly pigmented lively insect is common in Radford and many other Devon caves and is also found above ground (Gough 1975). *H.nitidus* is therefore a troglophile. It is able to withstand comparatively large environmental fluctuations, breeds prolifically in the laboratory and can withstand handling. The adults which reach a maximum length of about 1.7 mm were cultured using the technique described by Goto (1961). The other Entomobryid that is commonly found in the cave is the blind *Pseudosinella dobati* (Gisen (1965) a species which is thought to be troglobitic, is less abundant, more difficult to culture and is less amenable to handling than *H.nitidus*.

Experimental Procedure

(a) Tolerance

It is known (Winston and Bates 1960) that, at a given temperature, solutions of certain salts produce standard relative humidity in the atmosphere above those solutions. Saturated solutions of eight of these salts were made up in crystallising dishes, sealed with greased glass lids and the atmosphere above each solution allowed to equilibriate to its respective humidity.

Ten groups of five *H.nitidus* were placed in petri dishes which were then floated on the standard solutions. The glass lids were replaced and the time taken for the Collembola to begin to show signs of distress and desiccation were noted. The reaction of a control group was investigated by repeating the procedure replacing the saturated solution with distilled water and noting the survival time of these Collembola at 100% humidity, while the effect of enclosed laboratory air (relative humidity 52%) was also examined.

Despite the difficulty experienced in deciding precisely when the Collembola had died and the seemingly great differences in the humidity tolerances of similar individuals, LD_{50} values (= lethal dose for 50% of the population) were calculated as a crude method of standardising the results. The 'lethal dose' in each case was expressed as the average survival time at a given humidity.

The results are shown in the table. Graphical representation of these values, figure 3, clearly shows the lethal effects of even short term exposure to humidities below 90% relative humidity.

Table: Survival times of *Heteromurus nitidus* at various humidities and 21°C

No.	Salt Soln. used to maintain the given humidity	Relative Humidity	Time taken before effect was noted, LD_{50}
1.	Laboratory air	52%	36 mins.
2.	Glucose	55%	35 mins.
3.	NH_4NO_3	65%	46 mins.
4.	$NaCl$	76%	75 mins.
5.	NH_4Cl	79.5%	120 mins.
6.	$(NH_4)_2SO_4$	80.5%	130 mins.
7.	KBr	84%	160 mins.
8.	$MgSO_4.7H_2O$	90%	170 mins.
9.	KNO_3	93%	5 hours & longer
10.	H_2O	100%	no effect

(b) Behaviour

Both species of Entomobryid Collembola inhabiting Radford Cave can be shown to migrate up a humidity gradient. Individuals placed in a narrow bore (1 cm) air-filled tube with water at one end and a saturated solution of potassium hydroxide at the other, will aggregate at the end which is at the highest humidity, that is near the water. This behavioural response over-rides their tendency to move away from light. My previous experiments have shown *Pseudosinella dobati* and *Heteromurus nitidus* to be negatively phototactic*.

Milne (1960) demonstrated a thigmatactic* response in certain species of soil dwelling collembola when, during exposure to low (laboratory) humidity, they took shelter under microscope slides. Since these were glass slides this behavioural response is unlikely to be phototactic in origin. An attempt was made to demonstrate this thigmatactic behaviour in *Heteromurus nitidus* by placing cover slips in their culture vessels but no tendancy to shelter under these was noted. Even a reduction in humidity did not encourage this response so it could not be proved that adult *H.nitidus* avoid desiccation by taking refuge in high humidity cracks or under stones. However, the adults did show a strong preference for laying their eggs in grooves in their culture vessels, a fact which is of interest when it is realised that the eggs of *H.nitidus* are far less susceptible to damage from desiccation and high temperatures (greater than 25°C) than are the adults and immature instars. Without further physiological investigations, I am reluctant to attempt to explain why the eggs are more resistant to drought and high temperature. Analogy to the comparative resistance to environmental 'hardships' of a seed and an adult plant may help in understanding this. The resistance of seeds and some eggs (particularly those 'designed' to cope with an overwintering type situation) may be explained by one or more of the following:—

i) smaller surface to volume ratio in eggs
ii) lower exchange rate with the environment
iii) impervious 'skins'.

* Phototaxis is the response or organisms to light. Positive phototaxis means they move towards light; negative away from light.
Thigmataxis is the response of organisms regulated by a sense of touch.

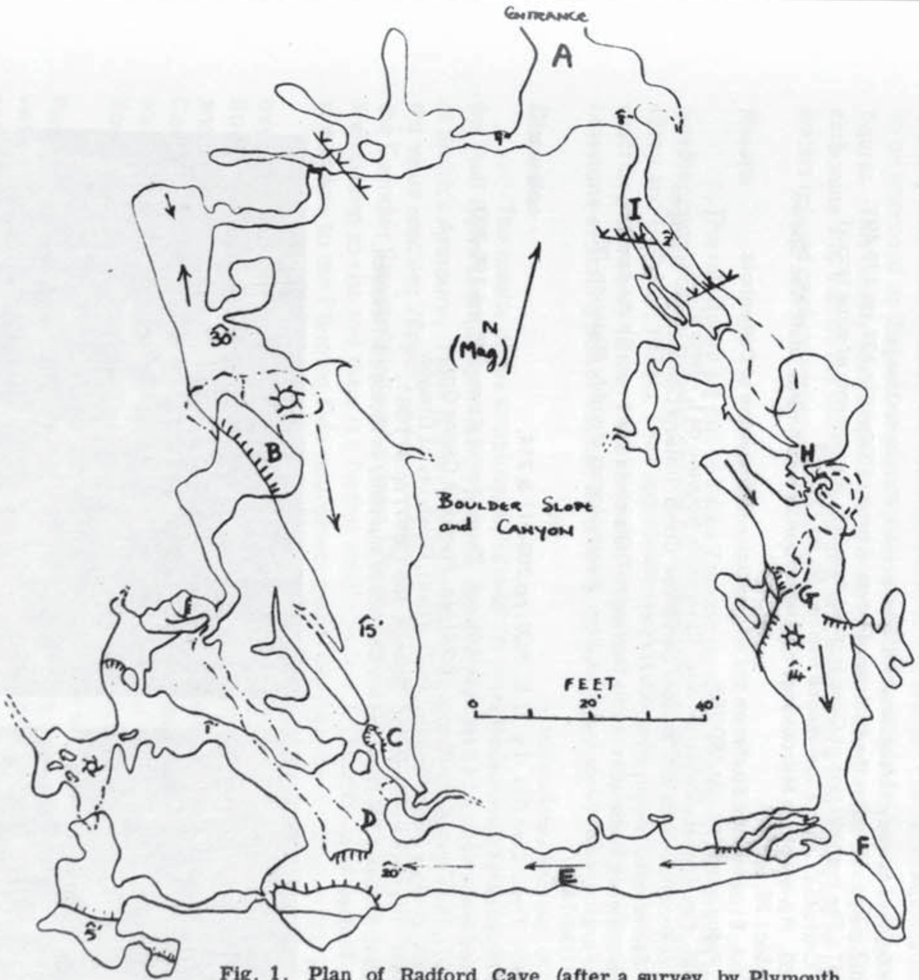

Fig. 1. Plan of Radford Cave (after a survey by Plymouth Caving Group - Jeffery 1967).

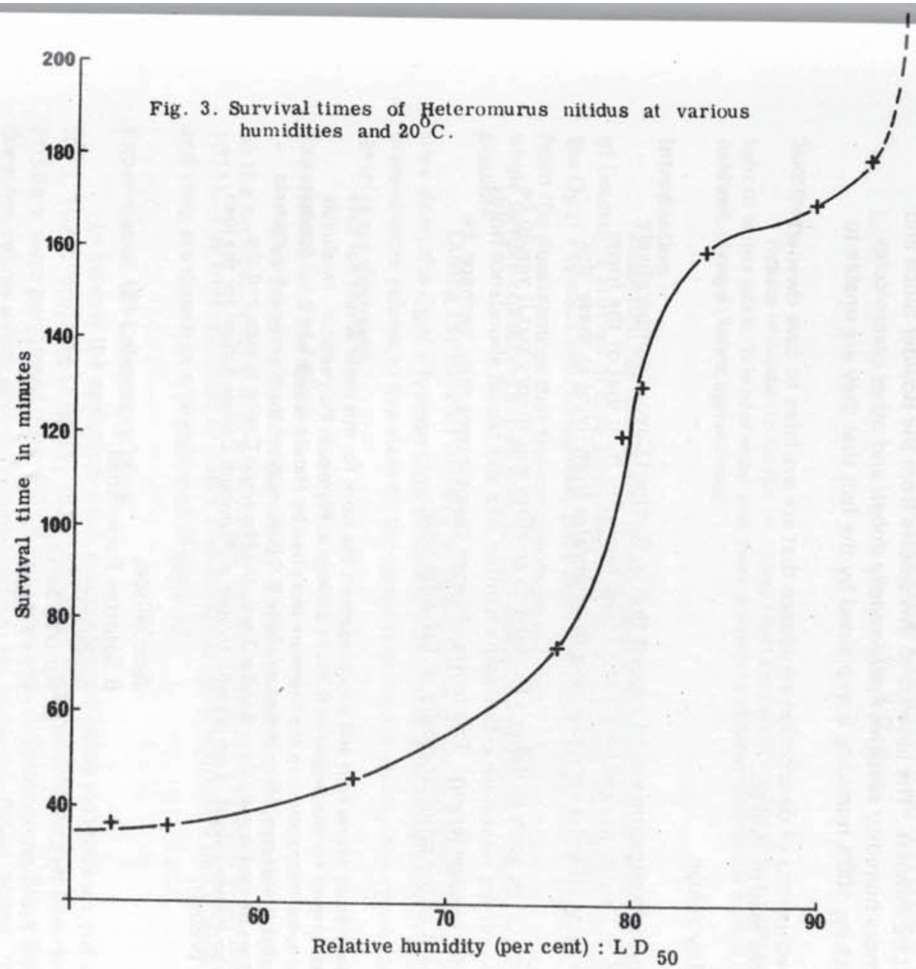

Fig. 3. Survival times of Heteromurus nitidus at various humidities and 20°C.

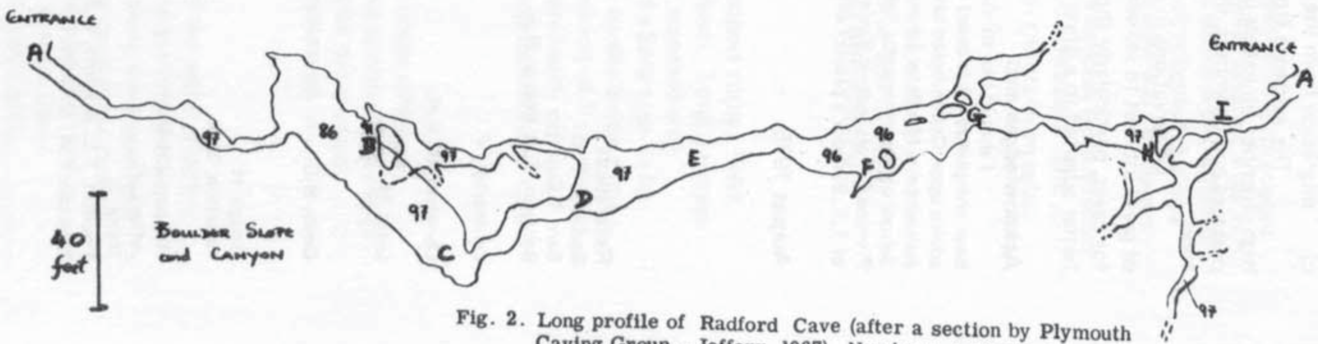

Fig. 2. Long profile of Radford Cave (after a section by Plymouth Caving Group - Jeffery 1967). Numbers indicate average relative humidities.

Conclusion

Heteromurus nitidus, then, is a species highly vulnerable to desiccation if exposed to less than 90% humidity for much more than about 80 minutes. The absence of this species from the Boulder Slope and Canyon area, as well as that of the more humidity sensitive *Pseudosinella dobati* and other cavernicoles requiring an environment of approaching 100% humidity is explained by the fact that they are unable to survive in this 'dry' atmosphere.

The various behavioural mechanisms of desiccation avoidance that are available to cave dwellers means that their absence from an area may be due to:

a) a lethal effect,
b) taking shelter in a high humidity refuge,
c) migration from the dry area.

The evidence from this short investigation would suggest that in Radford Cave, a comparatively high chamber (in excess of about 25 ft.) tends to contain air at a lower humidity than that of the lower passages and chambers, thus discouraging all but a very few cave invertebrates from living in these 'dry' areas.

Observations in other Devon caves, such as Baker's Pit tend to confirm this theory but it would be of great interest to see whether this indirect relationship between chamber size and faunal abundance holds for caves, particularly those of greater passage length. The fauna of larger cave systems may, perhaps, be better adapted to a dryer environment either physiologically or behaviourally.

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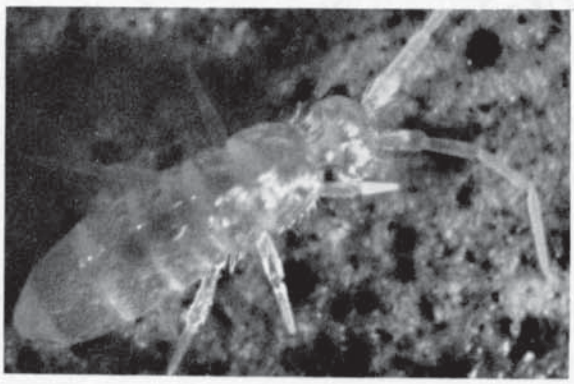

Heteromurus nitidus Templeton

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RECENT CHEMICAL WORK IN THE OGOF FFYNNON DDU SYSTEM: FURTHER OXIDATION STUDIES

by L.G. Bray

Summary

Results of oxidation studies on waters from the Ogof Ffynnon Ddu system are reported and are considered in the light of earlier work. It is confirmed that there is a gain in alkaline hardness as organic matter washed into the cave is oxidized, giving a "latent aggressiveness".

Introduction

Attention has been drawn to the possible importance of water-borne organic matter in theprocesses of limestone erosion in cave streamways (Bray, 1972) and the changes taking place between selected sites in the Ogof Ffynnon Ddu streamway have been discussed (Bray and O'Reilly, 1974). The earlier work suffered from the disadvantage that the samples from the Ogof Ffynnon Ddu streamway were not collected during a single sample-collecting expedition, so that direct comparison of results from individual sites was not always possible.

During the summer of 1973 an opportunity arose to collect within a few hours samples from selected sites along the Ogof Ffynnon Ddu streamway and from associated sites in a co-ordinated operation. The present work relates in the main to the samples collected during this operation, although results from other samples are discussed.

Experiment (a) Field Work

The sampling was conducted by 11 cavers working in 3 parties underground and by a party working on the surface. In all 9 sites were visited and samples were collected as set out earlier (Bray and O'Reilly, 1974). The sites are listed in Table 1 which gives some additional description of the sites where helpful, and they are shown in a Sketch map (Figure 1).

Experimental (B) Laboratory Work

In general the analytical work was performed using methods set out in earlier papers (Bray, 1969, 1971, 1972; Bray and O'Reilly, 1974; Stenner, 1969) and no further description is offered. Total hardness titrations were performed using EDTA as titrant with A Solochrome Black 6B indicator screened with dimethyl yellow which gave an exceptionally sharp end-point (West, 1969). The loan of a Solartron 4440 digital multimeter allowed the discrimination of the Walden Precision Apparatus CM 25 conductivity meter to be improved so that values of electrical conductivity could be found to a genuine precision of 3 significant figures. This facility gave a useful comparison between the conductivity of a sample treated with calcium carbonate and that of the untreated sample, and suggested a novel method of assessing aggressiveness of cave waters toward calcium carbonate (Bray, 1975).

Results

The results are set out in Table 2 which includes results from samples collected under different weather conditions and earlier results for comparison purposes. Units and terms are those specified elsewhere (Bray and O'Reilly, 1974). The "aggressiveness by conductivity" value has been derived by the method described elsewhere (Bray, 1975) and this is the first time in South Wales that a direct assessment of limestone-attacking power has not involved Stenner's method.

Discussion

The results of the sampling performed on 19/8/73 show the alkaline hardness of the water entering the Pwll Byfre sink (16ppm $CaCO_3$) to rise sharply to 60ppm $CaCO_3$ when the water emerges into the cave at Smith's Armoury. There is then a gradual rise in alkaline hardness as the water flows along the streamway the value reaching 76ppm $CaCO_3$ just before The Confluence. The entry of the relatively hard water from the Cwmdwr Stream (alkaline hardness 125ppm $CaCO_3$) causes the alkaline hardness of the water in the Mainstream to rise and there is a further small rise as the water flows through the Ogof Ffynnon Ddu I streamway to the Ffynnon Ddu resurgence, where the alkaline hardness of the water is 98ppm $CaCO_3$.

By contrast the concentration of the earily-oxidised organic matter in the water, as shown by the oxygen demand value, falls. At the Pwll Byfre sink the 4-hour 27°C oxygen demand value is 3.64mg per litre. This value has dropped to 1.62mg per litre when the water emerges into the cave at Smith's Armoury and there is, in general, a gradual decrease along the Mainstream to a value of 0.95mg per litre at The Confluence. The water in the Mainstream is joined at The Confluence by the hard but organically "clean" water from the Cwmdwr Stream (4-hour oxygen demand value 0.14mg per litre) and the combined waters flow to the Ffynnon Ddu resurgence where the value is 0.65mg per litre.

It is interesting to plot these changes as a graph using the approximate distance along of flow from Pwll Byfre as the horizontal axis, the alkaline hardness as one vertical axis and the 4-hour oxygen demand value as the other vertical axis (Figure 2). The cave section Pwll Byfre to Smith's Armoury is not known and the distance is shown as an arbitary 300m, which is approximately the "straight line" distance between the two sites. The graphs are shown as straight lines with discontinuities: whether this is an over-simplification will become apparent only after many more such experiments under weather and flow conditions similar to those at the time of the experiment under discussion. Until these experiments can be carried out, and until reliable information becomes available on flow times under near-drought conditions, little more can be done to illustrate a fascinating aspect of the work.

The changes taking place in hardness and organic matter content of water flowing between Pwll Byfre and Smith's Armoury are more rapid than those taking place elsewhere along the Mainstream. An estimate of the flow-time between these sites under low water conditions is about an hour compared with longer than a day for the flow-time between Pwll Byfre and Ffynnon Ddu. In terms of distance of flow the unknown section between Pwll Byfre and Smith's Armoury is perhaps one-twentieth of the length of the watercourse between Pwll Byfre and Ffynnon Ddu. However, the section between Pwll Byfre and Smith's Armoury is responsible for almost half of the hardness increase and organic matter loss taking place along the entire watercourse. This great chemical activity gives rise to the speculation that the section between Pwll Byfre and Smith's Armoury could well be a relatively open choke of limestone boulders over which the water flows, with the chemical/biochemical changes taking place on the considerable area of rock surface exposed by the boulders.

It was noted in an earlier paper (Bray and O'Reilly, 1974) that for successive sites in the Ogof Ffynnon Ddu streamway the ratio:

$$\frac{\text{alkaline hardness at site 2} - \text{alkaline hardness at site 1}}{\text{oxygen demand at site 1} - \text{oxygen demand at site 2}}$$

was very approximately constant: for 4-hour 27°C oxygen demand results the ratio was about 20.6, while for 1-hour 100°C oxygen demand values the ratio was about 10.6. The present work was conducted under different flow conditions in the cave (the experiment was performed only 10 days or so after a period of very wet weather) and close agreement with the earlier work could not necessarily be expected. In addition, as more sites along the streamway have been investigated on this occasion, the changes taking place between adjacent sites can be too small for the ratio to be valuable. Unfortunately the sample which was intended to represent the combined waters of the Mainstream and Cwmdwr Stream below The Confluence was taken too near the entry of the Cwmdwr Stream for proper mixing to have taken place and it has not been possible to correct results from the OFD I Sump and the Ffynnon Ddu resurgence for the influence of the added Cwmdwr Stream water. Some values of the ratio are given in Table 3 and agreement with the results from 1972 is felt to be acceptable.

During this work the reliability of the 1-hour 100°C oxygen demand test was questioned. It was found difficult to obtain satisfactory agreement between the individuals of duplicate determinations: this may have been the result of the glass bottles in which the samples are incubated being dirty (in spite of a concentrated sulphuric acid wash) or it may have been the outcome of using for the "blank" determinations and solution preparation distilled water which had been stored in polythene containers. No difficulties were encountered with the 4-hour 27°C oxygen demand estimations.

The apparent increase in oxygen demand between Swamp Creek and Maypole Inlet (from 1.11mg per litre to 1.25mg per litre) is not understood. The rise is small but it is confirmed by results from 1-hour 100°C oxygen demand estimations. Further work is needed to find out whether this is a feature of the cave or of the individual sampling experiment.

The general observation that, for the Ogof Ffynnon Ddu system, a water of low hardness had a high oxygen demand and vice versa led to the construction of a graph in which the 4-hour 27°C oxygen demand of w ater is plotted against the alkaline hardness of that water (Figure 3). Apart from isolated points, the points for hardness values of less than 20ppm $CaCO_3$ relate to Pwll Byfre, those between 90 and 100ppm $CaCO_3$ relate to OFD I and Ffynnon Ddu, while those for alkaline hardness values on excess of 120ppm $CaCO_3$ relate to the Cwmdwr Stream. Bearing in mind the varying flow conditions in which the samples were collected during a period of three years, this is an interesting correlation and one which merits further investigation.

The author's explanation for the increasing hardness and decreasing level of organic matter of water flowing through the from the Pwll Byfre sink through the streamway to the Ffynnon Ddu resurgence is that the water-borne organic matter entering the Pwll Byfre sink is oxidised within the cave streamway to give products which can attack limestone, thus giving rise to a "latent aggressiveness" developed within the cave (Bray, 1972; Bray and O'Reilly, 1974). The possibility exists that these changes could be brought about by the entry into the section between Pwll Byfre and Smith's Armoury of a small amount of percolation water having relatively high alkaline hardness and low organic matter content. If the general levels of alkaline hardness and organic matter of percolation water are taken to be those of the Cwmdwr Stream (125ppm $CaCO_3$ and 0.14mg per litre respectively) it is possible to calculate the approximate amount of water producing the observed increase in alkaline hardness between Pwll Byfre and Smith's Armoury (relative to unit flow rate at Pwll Byfre). If the fractional addition to the water flow is δ

(Flow at Pwll Byfre x hardness at Pwll Byfre) + (addition x hardness of addition)

= (Total flow at Smith's Armoury x hardness at Smith's Armoury)

so that

$$(1 \times 16) + (\delta \times 125) = (1 + \delta) \times 60$$

from which $\delta = 0.68$

and the flow at Smith's Armoury would be 1.68 times that into Pwll Byfre. This allows the hypothetical organic matter content at Smith's Armoury to be found from

$$\frac{(\text{Flow at Pwll Byfre} \times \text{oxygen demand}) + (\text{Added flow} \times \text{oxygen demand})}{\text{New total flow}}$$

SITE NAME	GRID REFERENCE	SITE DESCRIPTION
Pwll Byfre	8744 1660	Sink for moorland water entering the Ogof Ffynnon Ddu system
Smith's Armoury	8752 1628	First appearance in cave of water from the Pwll Byfre sink
Mainstream, above Swamp Creek	8656 1568	
Mainstream, below Maypole Inlet	8641 1561	
Mainstream, below Marble Showers	8591 1529	
Mainstream, above Confluence	8552 1519	Mainstream before entry of water from Cwmdwr Stream
Cwmdwr Stream, above Confluence	8562 1520	Cwmdwr Stream before its entry into Mainstream
The Sump, OFD I	8512 1531	Mainstream water at entry into OFD I streamway
Ffynnon Ddu	8472 1508	Resurgence for water from Ogof Ffynnon Ddu system

TABLE 2 COLLECTED RESULTS

SITE NAME	Date of sampling	Total hardness (ppm $CaCO_3$)	Alkaline hardness (ppm $CaCO_3$)	Non-alkaline hardness (ppm $CaCO_3$)	Sulphate (ppm SO_4^{2-})	Aggressiveness by conductivity (ppm $CaCO_3$)	Aggressiveness by titration (ppm $CaCO_3$)	Oxygen demand, 4-hour 27°C (mg O_2 per litre)	Specific Conductivity (μmho per cm at 25°C)	Sodium (ppm Na^+)	Potassium (ppm K^+)	pH
Pwll Byfre	19/8/73	19	16	3	5	+16	+19	3.64	59	2.9	0.11	7.10
Smith's Armoury	19/8/73	63	60	3	5	+3	+7	1.62	141	3.3	0.11	7.75
Mainstream, above Swamp Creek	19/8/73	72	66	6	5	+3	+4	1.11	152	3.3	0.11	7.70
Mainstream, below Maypole Inlet	19/8/73	76	70	6	5	+3	+2	1.25	159	3.3	0.11	7.75
Mainstream, below Marble Showers	19/8/73	82	75	7	7	+1	+4	0.95	173	3.5	0.11	7.80
Mainstream, above Confluence	19/8/73	83	76	7	7	+3	+4	0.95	173	3.5	0.22	7.75
Cwmdwr Stream, above Confluence	19/8/73	146	125	21	30+	-2	+1	0.14	318	8.8	0.55	7.95
The Sump, OFD I	19/8/73	106	93	13	13	-1	+2	0.65	228	4.7	0.33	7.90
Ffynnon Ddu	19/8/73	112	98	14	15	+5	+2	0.65	239	4.9	0.33	7.75
Ffynnon Ddu	6/8/73	64	58	6	7	+5	+8	4.49	141	2.7	0.22	7.75
Ffynnon Ddu	8/8/73	91	78	13	12	+2	+3	0.95	197	4.1	0.33	8.00
Ffynnon Ddu	17/8/73	110	96	14	13	-1	-1	0.65	236	4.7	0.33	7.70
Pwll Byfre	8/8/73	7	5	2	5	+13	+20	2.47	36	2.2	0.11	6.70
Ffynnon Ddu	10/8/71	66	55	11	12	---	+1	3.01	174	3.4	0.28	7.60

TABLE 3
RELATIONSHIP OF CHANGES IN ALKALINE HARDNESS TO CHANGES IN OXYGEN DEMAND

SECTION OF STREAMWAY	INCREASE IN ALKALINE HARDNESS $\Delta CaCO_3$	DECREASE IN 4-Hr 27°C OXYGEN DEMAND $\Delta OxDe(4Hr)$	RATIO $\frac{\Delta CaCO_3}{\Delta OxDe(4Hr)}$
Pwll Byfre to Smith's Armoury	44	2.02	21.8
Pwll Byfre to Mainstream, above Swamp Creek	50	2.53	19.8
Pwll Byfre to Mainstream, below Maypole Inlet	54	2.39	22.6
Pwll Byfre to Mainstream, below Marble Showers	59	2.69	21.9
Pwll Byfre to Mainstream, above Confluence	60	2.69	22.3
Smith's Armoury to Mainstream, below Marble Showers	15	0.67	22.4
Smith's Armoury to Mainstream, above Confluence	16	0.67	23.9
Mainstream, below Maypole Inlet to Mainstream, below Marble Showers	5	0.30	16.7
Mainstream, below Maypole Inlet to Mainstream, above Confluence	6	0.30	20.0

Hardness values in ppm $CaCO_3$,
Oxygen Demand values in mg O_2 per litre

TABLE 4
FLOOD COEFFICIENTS

	TOTAL HARDNESS	ALKALINE HARDNESS	4-Hour OXYGEN DEMAND	SULPHATE	SODIUM	POTASSIUM
Ffynnon Ddu 10/8/71	0.63	0.60	5.2	1.2	0.58	0.61
Ffynnon Ddu 6/8/73	0.57	0.59	6.9	0.53	0.55	0.66

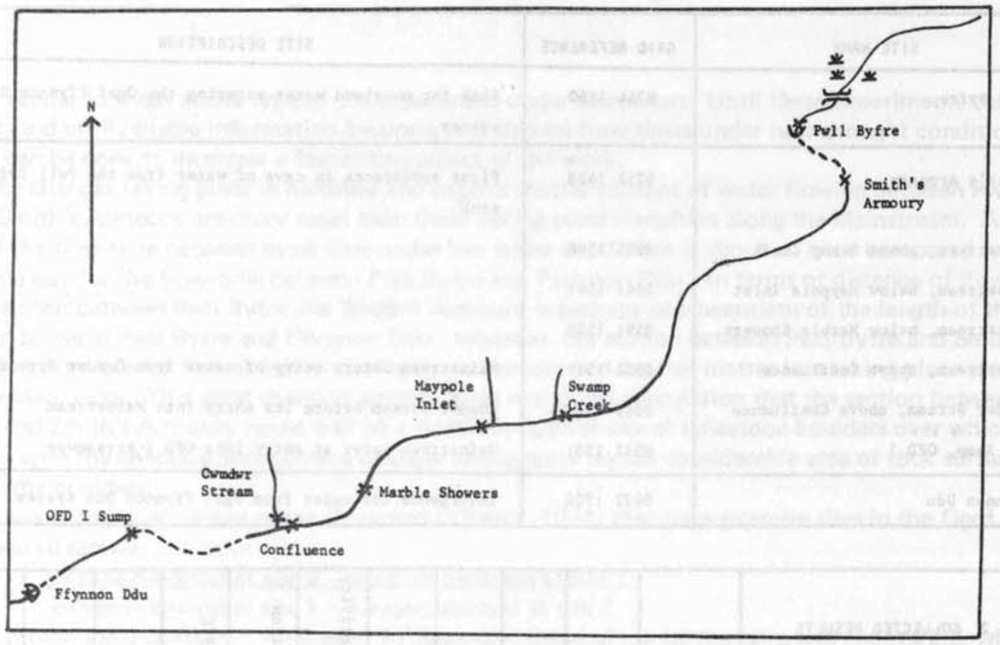

FIGURE 1

SKETCH MAP OF SAMPLING SITES IN OGOF FFYNNON DDU SYSTEM

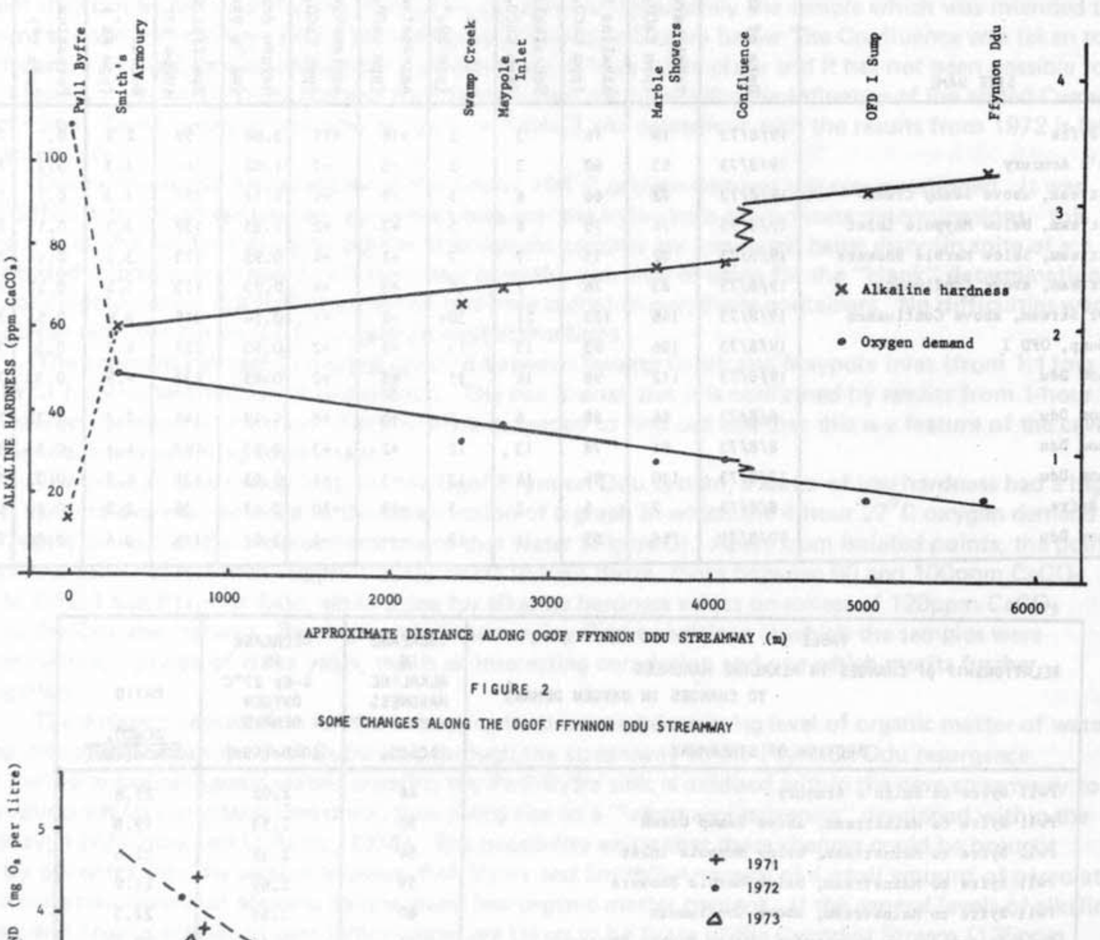

FIGURE 2

SOME CHANGES ALONG THE OGOF FFYNNON DDU STREAMWAY

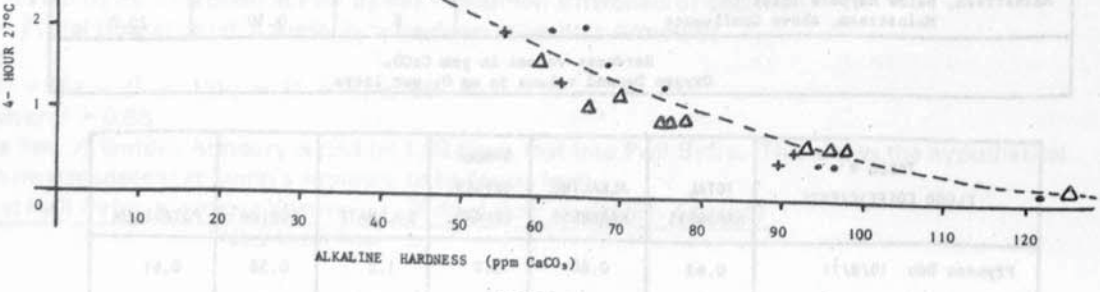

FIGURE 3

GRAPH OF OXYGEN DEMAND AGAINST ALKALINE HARDNESS so that

$$\frac{(1 \times 3.64) + (0.68 \times 0.14)}{1 + 0.68} = 2.22\text{mg per litre}$$

The experimental value is much lower than this at 1.62mg per litre.

The section Smith's Armoury to Above Confluence—Mainstream Above Confluence, where part of the hardness increase might well be caused by percolation water addition shows an increase in alkaline hardness from 60 to 76ppm $CaCO_3$. Here, using similar symbolism,

$$(1 \times 60) + (\delta \times 125) = (1 + \delta) \times 76$$

from which $\delta = 0.33$ and the approximate hypothetical flow in Mainstream Above Confluence would be 1.33 times that at Smith's Armoury. This would require the oxygen demand to be reduced to

$$\frac{(1 \times 1.62) + (0.33 \times 0.14)}{1 + 0.33} = 1.25\text{mg per litre}$$

a value which is higher than the experimental value of 0.95mg per litre. These calculations show that the fall in oxygen demand of the water as it flows through the streamway cannot be explained by "clean" percolation water addition alone.

The sample taken from Ffynnon Ddu on 6/8/73 was taken under flood conditions and those of 8/8/73, 17/8/73 and 19/8/73 represent the recovery of water at the resurgence from flood conditions. The flood sample is notable for the high level of oxidisable organic matter as shown by the 4-hour oxygen demand value of 4.49mg per litre. If this were oxidised and translated into terms of increased hardness, the alkaline hardness would increase by 4.49 x 20.6 to a value of 142ppm $CaCO_3$, a value found in the cave streamways only in part of the Cwmdwr Stream. The experimental alkaline hardness of 58ppm $CaCO_3$ for the 6/8/73 sample compares well with a value of 55ppm $CaCO_3$ for a sample taken under somewhat lower flood conditions on 10/8/71, although the oxygen demand then was lower at 3.01mg per litre. This suggests that there is a level below which the alkaline hardness of Ffynnon Ddu water does not fall, almost irrespective of the amount of flood water flowing from the resurgence. It seems reasonable to speculate that, in the critical Pwll Byfre to Smith's Armoury section where most chemical activity takes place, there might be an upper limit to how much water can pass through the watercourse before it becomes fully occupied and, once this limit is reached, the amount of chemical attack which can take place there in a given time is approximately constant. Under high flow flood conditions it would follow that any unreacted organic matter would be swept through the Mainstream very quickly and further reaction would be relatively less important.

In an earlier paper the author put forward the idea of "flood coefficients" for waters leaving Ffynnon Ddu, in which

$$\text{Flood coefficient} = \frac{\text{Value in flood}}{\text{Value in low water conditions}}$$

The flood coefficients for various parameters are shown in Table 4 which shows also results from the earlier work (Bray, 1972). It is interesting that values of flood coefficient for alkaline hardness, sodium and potassium contents should be so similar. The sulphate content of water at Ffynnon Ddu seems to be influenced almost totally by fluctuating sulphate levels in the Cwmdwr Stream rather than by changing sulphate levels at the Pwll Byfre sink, and the reasons for the fluctuations offer scope for investigation.

The results and arguments presented here make very clear one aspect of cave chemistry. The various equilibria existing within the chemical system in a cave streamway are dynamic equilibria and respond to perhaps quite small changes in weather and/or flow conditions. It is totally unreasonable to expect between successive cave experiments the sort of agreement which can be obtained in laboratory experiments using highly purified materials under carefully controlled conditions. At present it is being appreciated only very slowly that certain changes take place at all: to work out how and why these changes take place will require a very great deal of painstaking work.

Conclusions

(i) The general trend for water to lose organic matter and to gain alkaline hardness during flow through the cave has been confirmed.

(ii) The idea that, for a given loss of organic matter, the water gains a definite amount of alkaline hardness has been confirmed.

(iii) The suggestion that percolation water addition might account for these changes has been shown to offer an inadequate explanation.

(iv) A speculative explanation has been advanced for the near-constancy of hardness values at Ffynnon Ddu during flood.

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THE EVOLUTION OF BRADWELL DALE AND ITS CAVES, DERBYSHIRE

by Trevor Ford, Cynthia Burek and John Beck

Summary

A preliminary study of the interrelationships of the limestone structure, the stripping of shale cover, evidence of glacial and periglacial weathering, the form of Bradwell Dale, the dry valley pattern, the phreatic potholes of Long Rake, the pipe caversn of Smalldale and Hazlebadge, and the stream cave system of Bagshaw Cavern, suggest a sequence of events in the Pleistocene which can be correlated in part with the various phases of the Ice Age elsewhere.

Lying along the northeast boundary of the Carboniferous Limestone outcrop of Derbyshire, Bradwell Dale drains northwards into Hope Valley, where Bradwell Brook joins the River Noe, a tributary of the Derwent. The central part of the Dale is a deeply incised limestone gorge without a stream, making it a striking dry valley. The "upstream" part of the Dale is the more gentle dry valley of Stanton Dale which serves as the focal point for a number of smaller dry valleys. There is one choked swallet near the head of Stanton Dale taking a little water underground at Nether Water, close to an old mine and a present day mineral processing plant. Another swallet at Quarters Farm also takes a stream in one of the tributary dry valleys, but it is so unstable that digging attempts have failed to penetrate more than a few feet.

To the west of the Dale rises Bradwell Moor, a dip slope some 2 km long topped by a flat area at about 1300-1400 feet O.D. The limestone beds here are in the D_2 zone and dip at slightly more than the average slope, so that the beds highest stratigraphically outcrop lower down the slope and in the Dale. The main part of the D_2 zone is composed of fairly regularly bedded rather cherty limestones referrable to the Monsal Dale Group (Stevenson & Gaunt 1971); these are overlain by the limestones of the Eyam Group (the latter were called the Nunlow Limestones by Shirley & Horsfield (1940) and correlated with their Eyam Limestones in 1945). These beds are more irregular, lenticular and contain many bioherms or reef mounds, giving the highly variable lenticular limestones on the east side of the Dale. The reefs are composed of calcilutite (algal mudstone) or of crinoidal debris, or sometimes of banks of coarse calcarenite.

To the east of Bradwell Dale there rises the long escarpment of Millstone Grit rocks of Bradwell and Hucklow Edges. Capped with sandstones, the lower slopes are composed of Edale Shales. Drainage from the scarp face forms a series of short surface streams disappearing into choked swallets, as at Quarters Farm and Deadman's Clough, or simply fading away in their alluvium not to be seen again. A shale-floored valley lies along the extreme margin of the limestone about 0.5 km east of the gorge section of Bradwell Dale, but it carries only a wet weather trickle of a stream which flows north to join Bradwell Brook in the village. A low col lies between the head of this valley and the gorge section of Bradwell Dale at Hazlebadge.

The regional dip of the limestones and Millstone Grit is eastwards but there is a slight anticlinal warp plunging eastwards roughly across the central part of Bradwell Dale. A complimentary syncline plunges southwards through the area of Little Hucklow.

The limestones on both sides of the Dale are cut by a number of mineral veins, mainly fissure veins or rakes with a WSW - ENE trend through there are a few pipe veins with a NW to SE trend. Mineral vein cavities occur in both. Toadstones (basaltic lavas) are present in the area but at considerable depth, so that they nowhere outcrop, but with the dip carrying them eastwards beneath the Dale, some 100 metres or so below its floor, they form a western boundary to the underground catchment, with outcrops on the western edge of Bradwell Moor. To the north there is no clear demarcation of either surface or underground catchment from that of Castleton, though it probably lies roughly along a line extending southwestwards from Earle's Quarry. To the south the catchment, both surface and underground, seems to be roughly along the line of Hucklow Edge rake, west of Great Hucklow.

Previous studies of this area have been very limited in scope. Only Crabtree (1964) has considered the mines and cave together, but only two instalments of his article have been published, and it is as yet unfinished.

The Underground Drainage system

Bagshaw Cavern has the only underground stream accessible in the area (Baker 1903). The cavern is entered through a mined-out vein, once known as the Mule Spinner Mine, west of Bradwell Village. From the foot of the entrance stairway a phreatic tube still partly full of sediment leads southwards to the main cave, which is reached after a short descent at the Dungeon, a 6 metre pitch. Below this a U-tube rises into the downstream section of the cave which can be followed through a series of static pools and ox-bows to within 50 metres or so of the Bradwell Brook resurgence at the south end of the village. The running stream is not seen in this part of the cave though it clearly uses the cave in times of flood. Upstream from the top of the Dungeon the cave can be followed in a generally south to southwest direction along the strike in a vadose trench cut into the floor of a phreatic tube, both somewhat affected by the collapse of roof blocks. Turning eastwards down dip brings to the active stream, flowing northwards. Downstream the passage is impenetrable owing to boulders, but the survey (Fig. 2) (of unknown accuracy) shows it to be close to a small series of pipe caverns in Bradwell Dale – Burton's Pingle Pipe, entered via a hole in the old quarry floor. Upstream the roof gradually lowers into running water in an alluvium-filled cave, but it has been dived for more than 100 metres through a series of low bedding cave sections into some east-west rift passages with "canals", and two further sumps (Cobbett 1971). Adding on the divers' grade 1 survey suggests that the west-trending rift section could have been in the chambers developed in Earl Rake, and it is notable

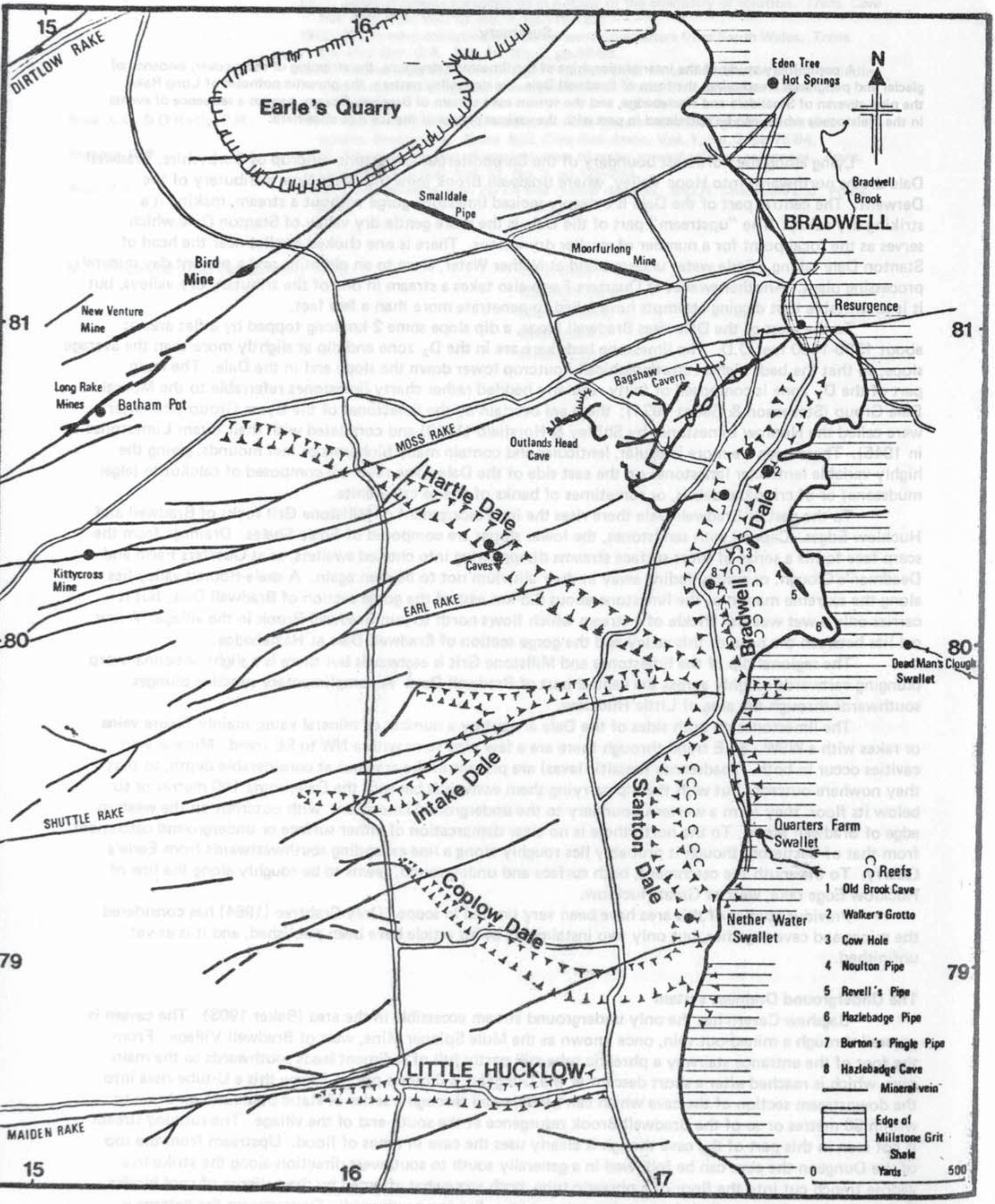
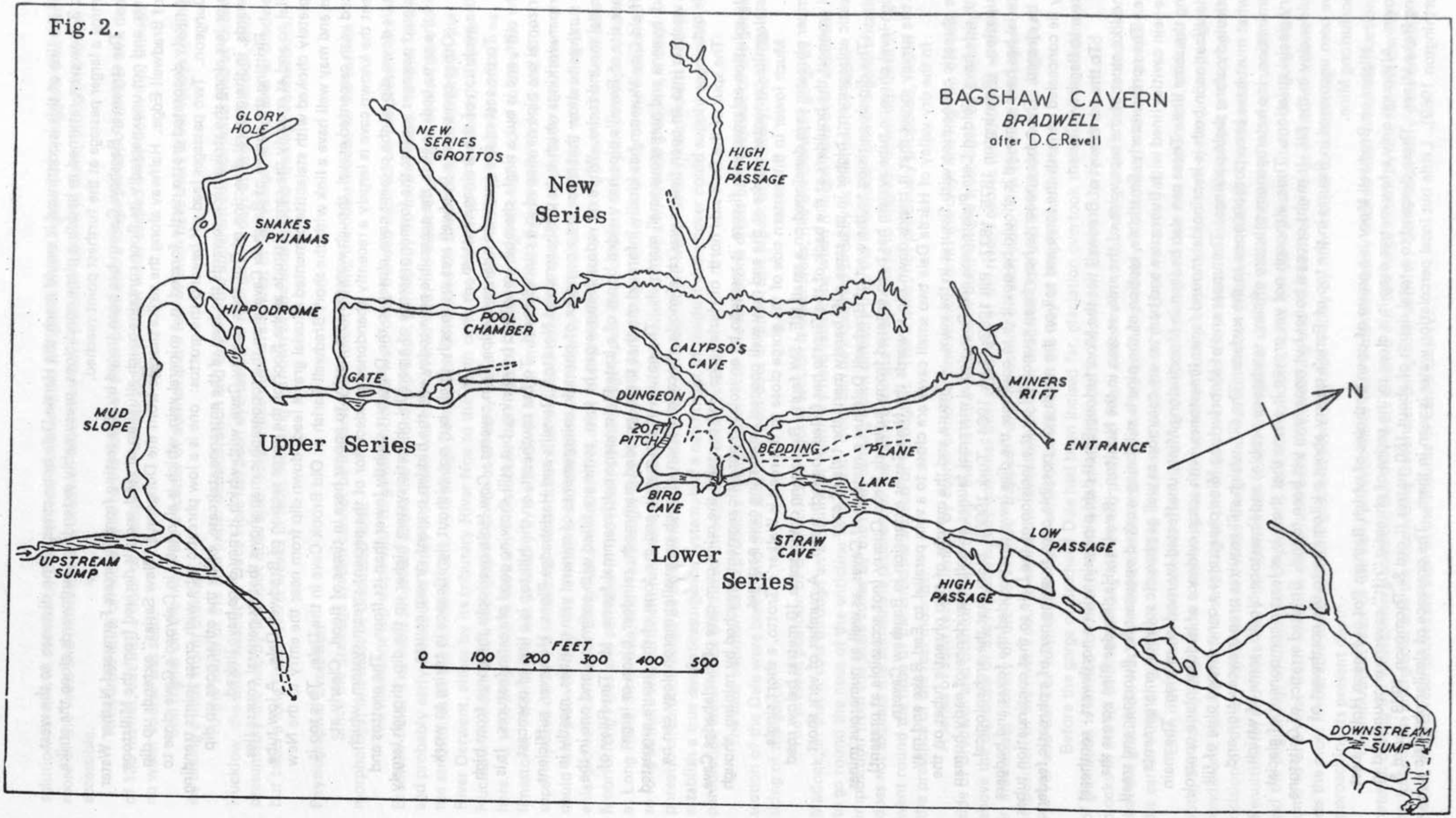


Fig. 1. Sketch-map of the Bradwell area showing the limestone outcrop, reefs, mineral veins, dry valleys, caves, swallets, and the resurgence.

Fig. 2.


BAGSHAW CAVERN
BRADWELL
after D.C.Revell
GLORY HOLE
NEW SERIES GROTTOS
HIGH LEVEL PASSAGE
New Series
SNAKES PYJAMAS
HIPPODROME
POOL CHAMBER
CALYPSO'S CAVE
MINERS RIFT
GATE
DUNGEON
N
MUD SLOPE
20 FT PITCH
Upper Series
BEDDING PLANE
ENTRANCE
BIRD CAVE
LAKE
STRAW CAVE
LOW PASSAGE
Lower Series
UPSTREAM SUMP
HIGH PASSAGE
FEET
0 100 200 300 400 500
DOWNSTREAM SUMP

135

that if the line of this is continued it would reach the Hartle Dale bone caves, some distance to the west. Sump 3, however, returned to bedding plane conditions, presumably extending southwards along the strike, becoming a larger passage at the furthest point reached.

The stream in Bagshaw Cavern has been traced by dye testing from Quarters Farm and Nether Water swallets, and not unexpectedly its floor contains much alluvium of sand and silt derived from the Millstone Grit of Bradwell Edge. Halfway along the strike passage from the Dungeon a "New Series" extends up dip into a nicely decorated grotto partly formed in a mineral vein, which is also seen in Calypso's Cave close to the Dungeon. Two passages lead off beyond the grottos: one is a low phreatic tube with cross-joints trending more or less along the strike back towards the foot of the entrance staircase, while the other goes up dip westwards, in the general direction of Outlands Quarry Cave, with which it may once have linked.

Plotting the survey of Bagshaw Cavern on the topographic map shows that its general course lies parallel to and at roughly the same altitude as the floor of the gorge section of Bradwell Dale. A low tube completely choked with stalactite-cemented alluvial gravel leads down dip from near the entry to the New Series and may well have a link with the short Bradwell Parish or Old Brook Cave in the Dale. This too is choked with cemented gravel, though water is said locally to appear here in times of flood. Clearly at present the known cave is largely a recently abandoned predecessor of the present stream system, which must lie down dip of the present cave, closer to the Dale, but slightly lower than its floor. The grottos and associated passages suggest the former presence of a parallel phreatic system higher up the dip, though largely still in the same beds as both the accessible cave today and the hidden present stream course.

Other caves in the Bradwell area are mostly small, but not without significance in trying to work out the evolution of the drainage pattern.

To the east of the gorge are a series of Pipe Vein caverns. Cow Hole overlooks the gorge from high on the cliff, and is but a single chamber, modified by mining, but still showing good phreatic features. It is a horizontal ore-pipe developed in a crinoidal reef. To the southeast, on the hill top is a line of opencast fluorspar workings which have partly removed Noulton, Revell's and Hazlebadge Pipes. However, sufficient cave survives to show that these are a complex of phreatic enlargements of mineral vein cavities, mostly in crinoidal mound facies. While no vadose features can be seen, some are filled with sediment, and one in the former site of Revell's pipe has yielded bones of a Late Pleistocene cold mammal fauna. Mr. Tim Riley of Sheffield City Museum has kindly informed me that these included mammoth, reindeer, bison or large bovid, hyaena and numerous small mammals. The nature of the matrix and the form of the fissure suggested that washing into an open fissure was chief mode of accumulation, though no swallet morphology can be made out.

The spur of the Dale side north of Hazlebadge Hall contains the mine-cum-cave of Hazlebadge Cave. Partly solution-enlarged vein fissure, it seems to be an isolated phreatic segment breached by mining, though the stalagmite-cemented choke at the end may well conceal interesting cave passages.

Much lower in the eastern side of the gorge close to the road is Walker's Grotto, a short single chamber phreatic cave developed on a small NE - SW fault. Burrowing down some 10 metres below road level amongst the boulders at the back of the Grotto has failed to reach water. A number of very short phreatic enlargements higher in the same cliff barely merit the title of cave.

The dip-slope rising to the west of Bradwell Dale has a number of Caves, as well as numerous mines. A high-level phreatic tube system has been entered from Outlands Head Quarry (not accessible at present), and the survey shows that it trends down dip towards the New Series extension in Bagshaw Cavern.

In the dry valley of Hartle Dale two small caves are close to a vein parallel to Earl Rake and may have phreatic connection with fissures in the veins. A fissure and the mouths of two phreatic tubes on the south side have yielded Late Pleistocene and Post-glacial mammal faunas as well as evidence of early human occupation. (Pennington 1875, 1877; Pill 1963; Turk 1964; Turk 1966). Now that the archeological material has been removed it should be possible to continue the digs inwards, provided the foxes and badgers can be ejected. The tubes appear to have been truncated by the incision of the Dale so that continuation tubes may lie concealed beneath the scree and soil on the north side, possible once forming part of a phreatic feeder system to Bagshaw Cavern.

To the northwest of Bradwell lies the Moorfurlong-Small dale pipe vein with a northwest - southeast trend like most of the pipe veins of the area, as seen in the Noulton - Revell's - Hazlebadge Pipe across the Dale. The northwesterly, Smalldale, section of the pipe is still being worked opencast for fluorspar and small pipe-vein cavities lined with fluorspare and barytes are common as well as phreatic solution enlargements along the same line. These can also be seen in Moorfurlong Mine, unaffected by modern mining. The main mineralization in both is in crinoidal mound facies limestones, with some evidence of bedding plane control, particularly along shale partings. The upper end of Moorfurlong Mine penetrates a cone-shaped plug of fill in what must have been pothole open to the surface. The fill, which still requires proper excavation and examination, is a heterogenous mixture of clay, sandstone pebbles and limestone blocks, some of which carry glacial striations. Thus, although not yet proven it seems that there is at least a component of glacial boulder clay in the fill. It might conceal bones but none have yet been found. Striated erratics of Gritstone have been uncovered in fissures in the top of Earle's quarry about a kilometre to the northwest of Moorfurlong Mine.

Higher on Bradwell Moor is a group of open potholes of which Batham Pot or Pigeon Hole is best known. Although only a few metres deep it is close to the series of phreatic "rift" caverns encountered in Long Rake Mines. These descend to a total depth of about 150 metres (Lord & Thompson 1968; Lord & Worthington 1969). Little but local percolation water is seen in them. The presence of similar phreatic solution caverns in the nearby parallel New Venture mine (Wright & Worthington 1971) suggests that many more of the veins and mines high on Bradwell Moor may have phreatic caverns in them, though no longer accessible.

Kittycross Mine on Moss Rake to the south of these penetrated a single phreatic chamber at a depth of 135 metres, cut into a floor of toadstone. Puddles suggested that water seeped away down dip, though no water course was seen.

Still higher on the moor are a scatter of dolines and a few of them have short blind valleys leading in, taking a little storm drainage.

To the south of the area under consideration and beyond the apparent surface watershed at Great Hucklow, the small swallet of Duce Hole has been dye-tested to resurge in 4 days at Bradwell Brook, and presumably the nearby Shodpot does also. High Rake mine shaft, west of the village, also drains to Bradwell but takes a long time, several weeks in fact. Nothing is known of the underground drainage connections.

Physiographic Evolution

Since the drainage system cannot be understood without fitting the observations to the surface morphology, this must be discussed first.

The limestone dip slope with its gentle anticlinal warp once trended right across the present site of Bradwell Dale. The reefs projected above the regional dip slope, perhaps by 10 metres or so. In late Tertiary and probably early Pleistocene times the whole was still covered with the Edale Shales and at least part of the sandstones of the Millstone Grit. A drainage pattern was developed on these rocks, converging on the River Derwent, either by its tributary River Noe to the north or to the River Wye on the south, with the Hucklow monocline as a topographic divide at an early stage. The southern drainage need not concern us here. As time progressed in the early Pleistocene the rivers cut down through the shale cover to bare the limestone. At first this was probably in the Bradwell Moor area where the streams were incised and thus superimposed on to the limestone. With little relief available only slow deep-seated phreatic circulation could take place through the limestone and the solutional activity was probably restricted to forming the enlarged vein cavities of Long Rake mines at first, with later phreatic solution taking place in the Smalldale-Moorfurlong Pipes and still later in the Revell's-Hazlebadge Pipes. Each of these three phreatic pipe systems, at Long Rake, Smalldale, and Hazlebadge, may represent separate stages in the unroofing of the limestone: so long as there was sufficient limestone exposed, with enough relief to have a hydraulic gradient, a deep phreatic circulation could be established via primary vein cavities. There was probably insufficient flow to establish a true swallet-resurgence system, but a catchment of residual shale cover could supply aggressive percolation water to be channeled through a phreatic system.

The later solution caves probably formed soon after the limestone crests on either side of the gorge section of the Dale were bared, and thus they may post-date an important aspect of the story, the initial siting of the gorge.

The present position of Bradwell Dale's gorge section is anomalous, like the Derwent gorge at Matlock, in that it cuts through an anticline of relatively hard limestone when it might have been expected to go round the nose of the anticline to the east. Both can be explained broadly as the result of superimposition from the shale cover by the rivers cutting down directly into the limestone. But this generalization does not explain the immediate problem of the failure for the river's course to migrate down dip until it went round the nose of the anticline instead of through it. The answer, not previously proposed, lies in the presence of the reef mounds.

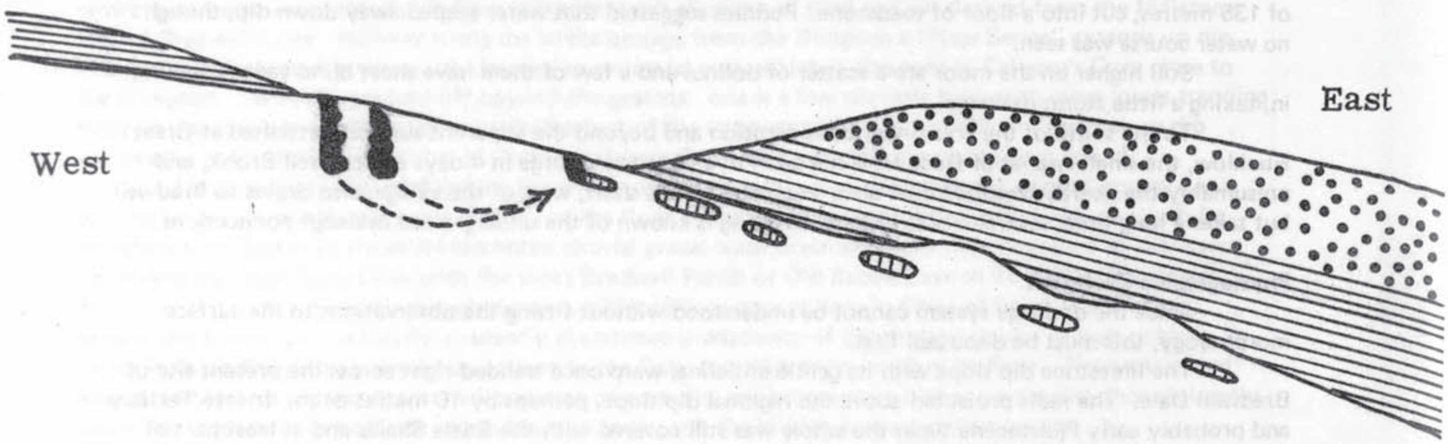
A series of such reefs, flanked by coarse crinoidal limestones, forms the crest line high on the east side of Bradwell and Stanton Dales, though there is little evidence of them on the west side. By projecting above the dip-slope of the limestone, any uniclinal shift down dip of the river's course was blocked so that in immediate vicinity of the reefs it was "trapped" with limestone on each side. This focussed the superimposition of the river's course across the limestone both in Bradwell Dale and at Matlock where High Tor, Pic Tor and Cat Tor form an analogous series of obstacles in the way of simple uniclinal shift.

Before the gorge of Bradwell Dale had been incised far, glaciation overtook the area. The evidence of glaciation is limited to the silty drift with striated blocks in fissures in Earle's Quarry and the striated blocks in the fill of Moorfurlong Mine's old pothole. From evidence in surrounding areas it can be deduced that the glaciation was older than the Devensian (Late Pleistocene) probably Wolstonian, and even possibly the earlier Anglian glaciation. No dating evidence is available in the Bradwell area yet.

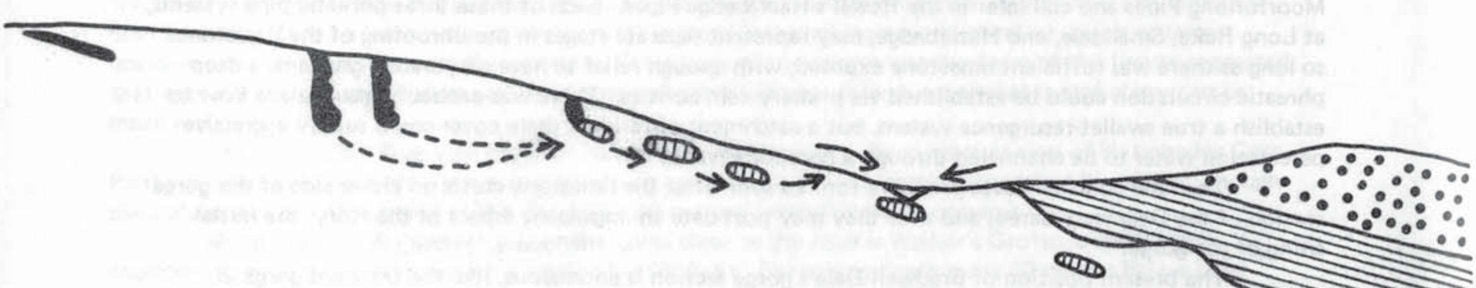
Even if it is uncertain whether the Anglian or the Wolstonian glaciation was responsible, perhaps both, the waning stages show a marked phase of run-off of both precipitation and melt-water under periglacial conditions, causing the final stripping of the shale cover from the present limestone dip-slope, with progressive incision of the dry valley network while the ground was still frozen (Warwick 1964). The Hoxnian (Penultimate) and most likely the Ipswichian (Last) Interglacial saw the establishment of normal run-off and the beginnings of utilization of phreatic solution conduits, some along the present site of the gorge and some to one side. Such conduits could have been both bedding and vein cavities or large joints, whichever was the most favourable for a hydraulic gradient towards Hope Valley by now incised to something approaching its present depth.

The mouths at least of the early phreatic caves were almost certainly choked with till or solifluction material during the Wolstonian glaciation, but they were cleaned out to a large extent by the run-off during the Ipswichian interglacial and the succeeding Devensian periglacial activity. Some such early pots are still choked, and representatives are seen in the fissures in Earles Quarry.

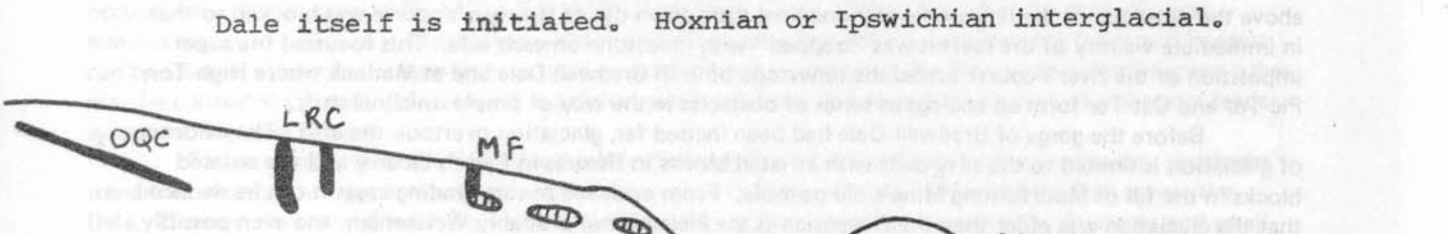
Fig. 3. Diagrammatic sections to illustrate the evolution of Bradwell Dale and its caves. B.C. = Bagshaw Cavern; OQC= Outlands Quarry Cave; LRC= Long Rake Caverns; MF= Moorfurlong Mine; RP= Revell's Pipe; HP= Hazlebadge Pipe; BD=Bradwell Dale.



Stage 1. Early unroofing of part of the limestone permits phreatic circulation via primary vein cavities, and develops the Long Rake Caverns. Probably Pre-Anglian or Pre-Wolstonian glaciation.



Stage 2. Further unroofing of the limestone permits development of phreatic circulation via Smalldale and Moorfurlong Pipes, while surface drainage is trapped by uniclinal shift down the main dip slope until impeded by the reef mounds on the east side of Bradwell Dale. The Dale itself is initiated. Hoxnian or Ipswichian interglacial.



Stage 3. Phreatic systems all abandoned. a, b, and c represent the Bagshaw Cavern drainage system: (a) the old up-dip cave passage parallel to the main cave, with a feeder tributary from Outlands Quarry Cave; (b) the presently accessible and intermittently active cave; and (c) the inaccessible down-dip active stream passage, probably still mostly flooded. The system developed mainly during the Devensian.

The return of a cold climate in the Devensian glaciation did not result in glaciation in the Peak District but in much periglacial activity. Owing to frozen ground meltwater streams were maintained on the surface and the dry valleys were incised to their present depth, some, as at Hartle Dale, breaching phreatic caves. Frost opened a few fissures and mammal bones were washed in together with a loam derived from a widespread loess cover.

As climate ameliorated in post-glacial times, the frozen ground thawed and run-off, doubtless still high, went underground via the phreatic systems causing modification to vadose conditions at least in parts of Bagshaw Cavern. A lower phreatic system, down dip of Bagshaw Cavern, now takes the normal flow, though Bagshaw Cavern is still active in flood times. The higher parts of the limestone plateau, west of Bradwell, which earlier had had phreatic drainage via the Long Rake cavities, via Moorfurlong Pipe and the tubes of Outlands Head quarry cave, now had their percolation taken directly to depths of 150 metres or more, to a new deep phreatic circulation of which very little is known. With a relative lack of impervious strata such as toadstones or wayboards, water was not held high up and vadose stream caves apparently did not develop. An additional factor is that Bradwell Moor has no allogenic streams draining on to it, as in the Rushup Edge swallets of Castleton.

It is possible that some of the present day deep phreatic drainage resurges at the Warm springs behind the New Bath Hotel, at Eden Tree, north of Bradwell village (Edmunds 1971). The high temperature (12°C) and tritium content suggest that the small quantity of water resurging here is of meteoric origin but has been underground as much as 15 years, and it is possible that it has been warmed by the exothermic reaction of the oxidation of pyrite in volcanic rocks such as underlie Earle's Quarry. Though still small the conduits concerned may be the fore-runners of phreatic "rift" caverns like those of Long Rake, but which are still buried beneath the Edale Shales.

Soughs

A number of lead miners' soughs discharge small quantities of water into Bradwell Brook more or less in the centre of the village. Rieuwerts (1966 & 1969) gave the details of the discharge points but unfortunately little is known of their courses or of their effect on the natural drainage system. Pic Tor End Sough was driven more or less southwards to Pic Tor End Mine, a 200 ft. shaft, close to the south end of the Hazlebadge Pipe workings. A planned extension to continue this sough more than a mile to the south to unwater mines at Great Hucklow was never carried out. Two other short soughs are said to go to mines on Moss Rake, and this is quite reasonable as road discharge from near the quarries there apparently reappears in the Brook in the village. An unlikely sough is supposed to go to Moorfurlong Mine, but as the known workings are so much higher and were dry before mining, this is either incorrect or it suggests a down-dip extension of Moorfurlong Pipe at present unknown.

Clearly there is room for thorough exploration of the sough problem and it may throw light on the evolution of the underground drainage pattern, but at present it is difficult to deduce what, if any, effect the soughs have had on underground flow patterns and water-levels.

Acknowledgements

Thanks are due to Noel Christopher and Bill Whitehouse for useful discussions, and to Rachel Elliott for drawing the map. One of us (John Beck) was in receipt of a N.E.R.C. studentship during the course of the study.

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COLD WATER MINERALIZATION PROCESSES IN AN AUSTRALIAN CAVE

by Julia M. James

Summary

Unusual environmental conditions comprising high carbon dioxide in the cave atmosphere and low oxygen in the cave water have led to a number of unusual chemical and biological processes occurring in sediments in Odyssey Cave, New South Wales. The sediments are layered with bands rich in organic matter, in iron oxides and in heavy metal sulphides, and the trends shown may be related to the chemistry of the cave atmosphere and waters; preliminary results are noted. The sediments are shown to have accumulated within the last thousand years in a quiet pool at the bottom of a tortuous pot fed by intermittent but rapid run-off of streams laden with vegetable debris. The pool level was lowered and the sediments exposed by digging at the resurgence. The poor air circulation has permitted the establishment of the unusual atmosphere; though floods may return the cave air to normal outside conditions, carbon dioxide builds up rapidly with a few weeks.

The unusual chemistry has necessitated the establishment of an underground monitoring station to record changes in the composition of the cave waters and atmosphere. The design and problems of installation and maintenance of underground station JULES are described.

In 1972, it was realised that iron mineralisation processes were taking place in the newly discovered Odyssey Cave, in Bungonia Caves Reserve, New South Wales, Australia. Sulphides and oxides of iron and other heavy metals were accumulating. The minerals had formed in a definite sequence and were exposed as layers in sediment banks in the final chamber of the cave. A study of the sediments was undertaken in association with work in progress on the cave waters and atmospheres of Bungonia Caves. This paper discusses the results of these studies as a background for the establishment of an underground geochemical recording station in the cave.

Odyssey Cave is located on the Bungonia plateau in Silurian limestone. The vegetation in the area is dry sclerophyll forest which at times has heavy undergrowth. Bungonia has an average annual rainfall of 740 mm which is usually distributed fairly evenly throughout the year. However, in some years there are deluges which flood the cave. Such an exceptional year occurred in 1974 when there were several severe storms, one of which delivered 500 mm (about 20 inches) of precipitation in two days. Bungonia caves are noted for their foul air: in the lower sections they contain several percent carbon dioxide in the cave atmosphere (Halbert, 1972). Odyssey Cave is no exception and since its discovery has never been found to have less than 1% carbon dioxide in its final chamber. The carbon dioxide in Bungonia caves is not cleared by the streams found there, because these streams are largely percolation waters and already have high dissolved carbon dioxide. In addition the cave waters move very slowly through the caves, as is illustrated by water tracing experiments which at times of normal flow take months (James, 1973). Furthermore, poor air circulation makes conditions ideal for the accumulation of carbon dioxide, the concentrations of which drop only in flood, in prolonged rain, or in the winter. Bungonia caves also contain a large variety of bacteria (Dyson and James, 1973). A preliminary bacterial survey of Knockers Cavern has been undertaken by the Baas Becking Laboratory (CSIRO), Canberra, owing to their special interests in sulphate reducing bacteria. However, the readily visible iron bacteria from red-brown gelatinous colonies which invade the terminal pools and these have on at least one occasion been mistaken for rhodamine dye.

Odyssey Cave (Figure 1) does not have any appreciable horizontal development. After initial passage through collapse material (Plate 2) it consists of a series of shafts with short interconnecting passages. A complete description of Odyssey Cave, together with its geology and hydrology, will be given by Montgomery and James (1976). The Enipeus, a stream entering into the middle section of the cave, has a small catchment area composed only of siltstones, mudstones and a small area of ferruginous sandstone. In the cave much of the stream bed is composed of siltstone and only for a few metres does it flow over limestone. The cave ends in a large chamber Knockers Cavern, in which the main sediment beds are found. Here, the Styx, a small but permanent stream, enters from a side passage. This stream has been traced and drains the other foul air caves in the region (James, 1973). The surface catchments of these caves are on the shales, limestone, slates, phyllites, quartzites, mudstones and siltstones (Jennings et al, 1972).

The Sediments

Location and description

The sediments described are all from the final chamber of the cave which, at present, is the only location where they have been found. At the bottom of the 18 m pitch in Scyllas Cleft the sediments could be seen as coloured bands in the sides of earth pillars produced by the dripping Enipeus (since destroyed by a flood). In Knockers Cavern the sediments have partially dried out and undercutting of one of the sediment banks by the Enipeus has led to a clean vertical section 2 m high (Plate 1). The Scyllas Cleft sediments have been oxidized and are full of small introduced fragments of wood and stone, and therefore are unsuitable for any preliminary chemical study. In Knockers Cavern the sediments contain no such coarse debris and oxidation appears to have only occurred at the surface. Over the years the exposed face has further weathered and crumbled, but digging into the sediments produced an unchanged sample. A drawing of part of the exposed section is shown in figure 2.

The bands have been placed in a set of broad categories according to the mineral and chemical composition. Carbon-14 dating has confirmed early predictions that the deposition of the sediments occurred within the last thousand years. Sixteen centimetres of sediment contain more than forty different layers

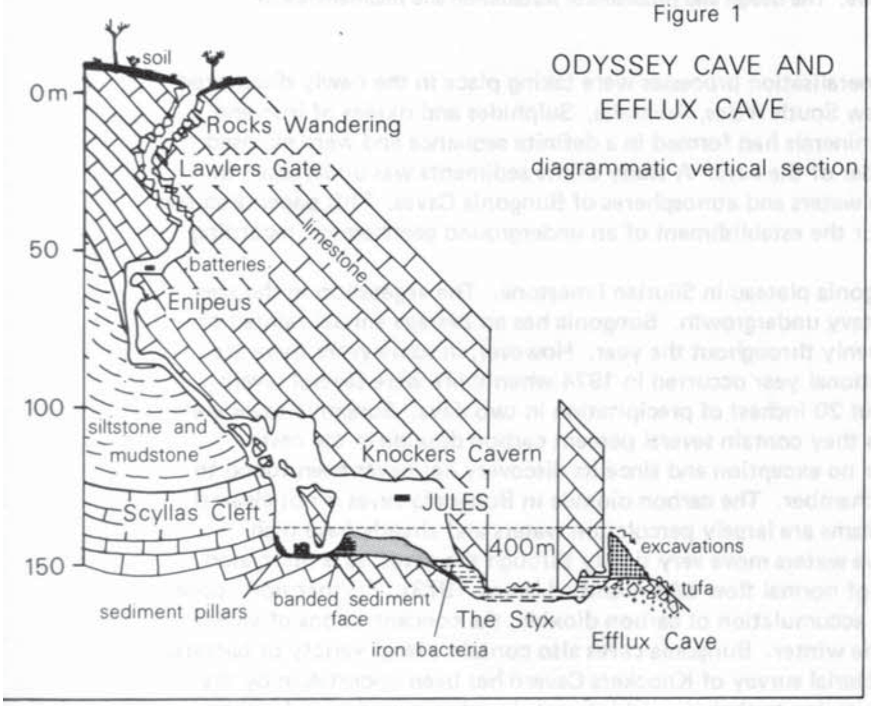


Figure 1

ODYSSEY CAVE AND EFFLUX CAVE

diagrammatic vertical section

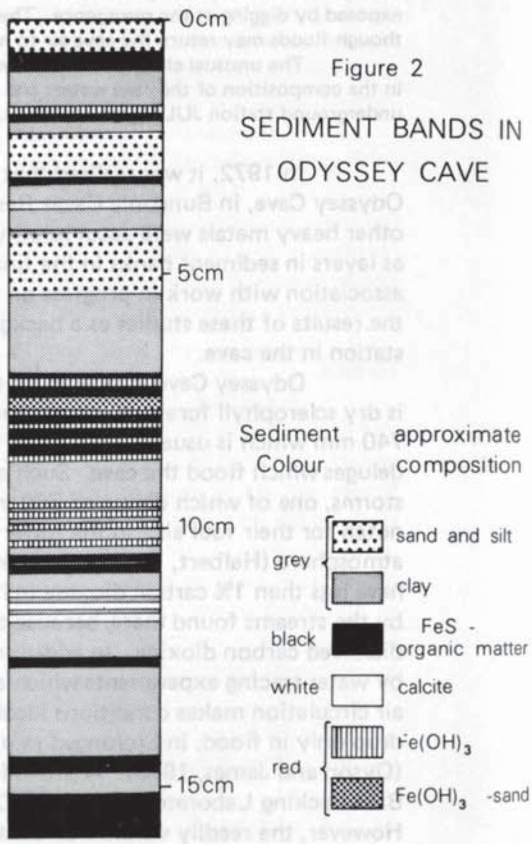


Figure 2

SEDIMENT BANDS IN ODYSSEY CAVE

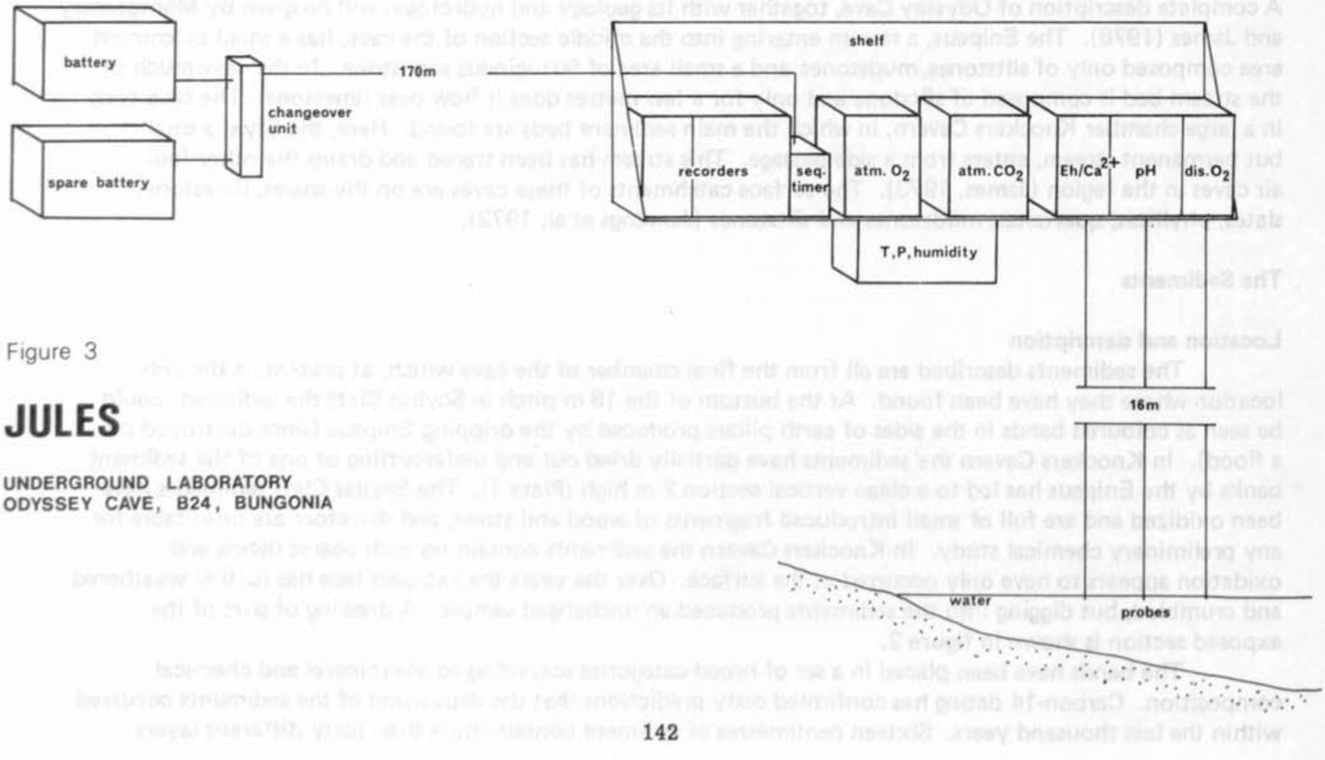


Figure 3

JULES

UNDERGROUND LABORATORY
ODYSSEY CAVE, B24, BUNGONIA

and were deposited in less than 100 years (within experimental accuracy). These bands may not however be a complete record of the changes in the cave as there may have been re-solution of some of the sediment layers.

Sediment sampling

Samples were taken from the sediment bank in Knockers Cavern. Those taken from a freshly exposed face were found on analysis to have mixed and oxidized after sampling. However, the analyses were sufficient to obtain broad chemical groupings. A sediment core was taken from the centre of the bank, but, unfortunately, it was only half the length of the 1.3 m deep hole. This compression of the core or the sediments underneath meant that it was difficult to relate chemistry to sediment depth and age. Precautions were taken against oxidation of the core by sealing it immediately on removal from the sediment bank and freezing it on removal from the cave. Many suggestions have been made as how to overcome our sampling difficulties, and some of these will be tried.

Chemical characteristcs of the sediments

The sediments illustrated in figure 2 show the following chemical characteristics:

a) The majority of the black bands analysed do not have large quantities of sulphide. The maximum value obtained has been 3% — this low figure may be a consequence of the poor sampling technique. The situation is ideal for high sulphide sediments, as the cave waters contain 2-5% of their total dissolved solids as sulphate, a similar figure to the 7% obtained for marine bays, which produce far higher sulphide concentrations in the same type of black bands (Oppenheimer, 1960). The organic matter in these layers is similar to that found in black shales and is in the range 20-40% (Krauskopf, 1967).

b) Other black bands contain carbon but no sulphide and on ignition after drying lost 55% weight. It is possible that these bands are the remains of vegetable debris from bush fires. Three of the bands were used for carbon dating.

c) The red bands are largely iron oxide and values of up to 60% have been obtained for Fe_2O_3; they always contain a small percent of MnO_2 but never more than 2%.

d) The white bands in the sediments are calcite, some of the layers give high analyses for magnesium although the X-ray powder pattern is still that for calcite. It is possible that these are magnesian calcites. These calcite bands are contained between clays.

e) The grey bands are either clays, silts or sands. The clay layers contain more organic material than the sands. Kuenen (1950) attributed this phenomenon to the protective action of the clays and greater porosity of the sands.

f) In both the iron oxide and sulphide layers there are markedly less calcium, magnesium, potassium and sodium than in the other bands. It is to be expected that the precipitation of compounds of these elements would be inhibited in these layers. Manganese appears to be distributed between the oxide and sulphide layers in the same way as iron, a result of their similar chemistry. The oxide layers are lower in Copper and Nickel than the sulphide layers, confirming the scavenger nature of the sulphide ion for heavy metal ions (Oppenheimer, 1960).

The deposition of the sediments.

The formation of the sediments may be related to the blockage of the Efflux Cave (figure 1) by a cliff collapse which was later consolidated by massive amounts of tufa. As the tufa pile at the spring grew higher, the depth of water in Knockers Cavern increased and the sediment layers began to form and build up slowly. It is clear from the sharp laterally continuous bands in the sediments that they were deposited in a permanent pool of water rather than during transient floods. The bands in the sediments appear to arise from several major processes:

1) The layers of clastic material (sands, silts and clays) represent intervals of erosion during which physical disintegration of the land surface is a more effective agent than chemical weathering. For example, floods bring into the cave both particulate and organic matter as well as the ions normally brought in by percolation water. The particulate material sinks to the bottom of the cave pool, forming sands and clays, and some of the organic matter rises to the top.

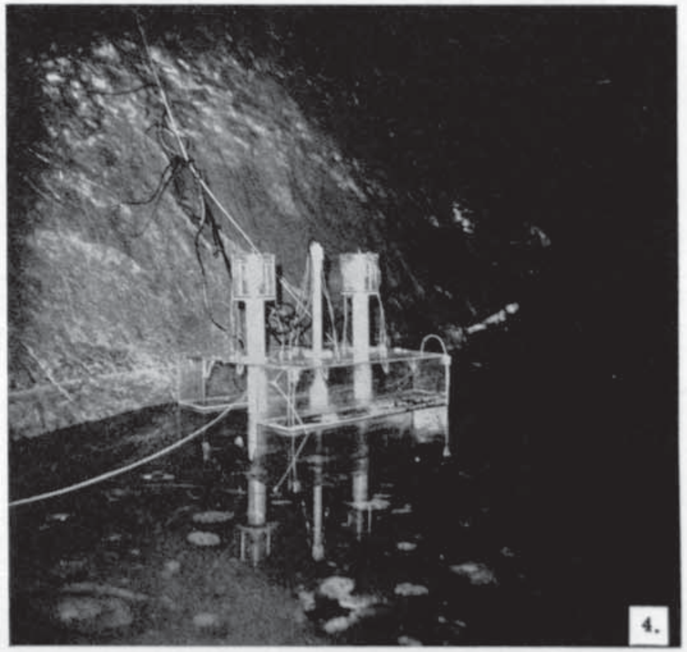
2) Immediately after the flood waters subside, bacteria begin the decomposition of organic material using up oxygen and producing carbon dioxide. The cave waters become acidic and dissolved oxygen concentrations are lowered producing ideal conditions for the growth of iron bacteria (Wolfe, 1964). The rate at which these micro-organisms produce hydrated iron III oxide from the meagre amounts of iron III in the cave waters is markedly greater than for equivalent colonies of the same bacteria on the Bungonia surface. This could be due to:
   a) The reduced concentration of dissolved oxygen in the cave waters as the bacteria have to compete for Fe^{2+} ions with any oxygen present (Wolfe, 1964).
   b) the greater availability of ferric iron (III). The increase in the quantity of CO_2 from the 0.03% (by volume) found on the earths surface to the 4% of the cave atmosphere vastly increases the efficiency of the solution of iron minerals as the bicarbonate, and hence increases ferrous iron (II) mobility.

3) As conditions tend towards anoxia (oxygen lack in the cave waters and atmosphere) and the partial pressure of carbon dioxide continues to rise, siderite (Iron (II) carbonate) is observed floating on top of the terminal pool in Odyssey Cave. This is consistent with the observation that siderite is a common mineral in blackbanded or claybanded iron deposits derived from primary sediments deposited in marine swamps or brackish waters in the presence of abundant vegetable matter (James, 1966).

4) After a period of drought, the dissolved oxygen of the water falls below 1 mg/l; hydrogen sulphide may be detected in the cave atmosphere and sulphide in the cave waters. If the supply of organic matter is

ODYSSEY CAVE
New South Wales

1. Layered sediments in Knockers Cavern (photo: P. H. Caffyn).
2. The entrance to Odyssey Cave. (photo: A. J. Pavey).
3. Placing the instrument shelf for JULES.
4. The floating electrode holder (photo: H. Coleman).



sufficient and poor air and water circulation persists, the cave waters become totally anoxic. The bacteria now functioning are anaerobic: that is, they are able to utilise their organic and inorganic fuel materials in the absence of oxygen. Under these conditions, carbon compounds are only partially decomposed and accumulate as a black mud. Some anaerobes produce hydrogen sulphide from organic sources and others will produce it by the reduction of sulphate. If there is no oxygen present the sulphide ion combined with heavy metal ions to form insoluble sulphides. Totally anoxic conditions may never develop within the cave waters but certainly do exist in the muds when they have been covered by clastic sediments (Oppenheimer, 1960). Sulphate-reducing bacteria have been isolated from the cave mud (H. Jones, pers. comm.).

5) When the concentration of carbon dioxide in the cave atmosphere drops, through a variety of chemical and physical mechanisms, the saturated solutions of $CaCO_3$ may precipitate calcite which floats as rafts on the surface of cave pools.

In Odyssey Cave during the last four years, processes 1-4 have occurred, but process 5 has not been observed in the cave and would not be expected, since the carbon dioxide concentration has not fallen below 1%. However, this process has occurred in other Bungonia Caves during the same period.

The exposure and destruction of the sediments

The exposure of the sediments and hence their ease of study can be directly attributed to the desire of a number of speleologists to drain the caves of foul air (Bonwick, 1972). The excavation of the Efflux Cave has lowered the water level in Knockers Cavern by 7 m, exposing the sediment banks (figure 1). The excavators did not succeed in draining the caves of carbon dioxide. From 1971 to 1974 there were no floods and the sediment banks remained undisturbed, then in August 1974 a record rainfall of 500 mm in two days was recorded near Bungonia Caves. When the floods subsided dramatic changes had occurred in the final chamber of the cave. The earth pillars in Scyllas Cleft had been eroded from 2 m high banks to 0.5 m of crumpled sediment. In Knockers Cavern the sediment banks had collapsed and a stream from the roof was flowing down the sectioned face, while much of the sediment had been washed away. Such storms are rare in Bungonia; however, a minor flood in October 1974 caused considerable movement and collapse of the sediments in Knockers Cavern. This catastrophic destruction of the sediments by even minor floods indicate that it can only be a matter of decades before the accumulated sediments are removed.

The study of the cave waters and atmosphere

A study was commenced to try to define the conditions under which maximum mineral production occurred in the cave and from this to find a set of parameters for deposition of specific minerals. This involved sampling the atmosphere and waters in Knockers Cavern every month. However, insufficient results were obtained by this widely spaced sampling programme and occasionally a set was missed when it was impossible to sample because of dangerous concentrations of carbon dioxide or floods.

Both of these periods are significant stages in the evolution of the sediments. Clearly the research needed continuous monitoring techniques. As the time period involved in the deposition processes was short enough to make continuous measurement feasible, an underground recording station was proposed. Finance for the station was obtained from the Australian Research Grants Committee and it was built by Ian Johns at The Baas Becking Laboratory (CSIRO), Canberra. Design problems are many when the apparatus is to be situated at the bottom of a deep cave with no mains supply, in 3-6% carbon dioxide, and in 95-100% humidity. The difficulties are made more acute when the size of each segment of the station is restricted by the narrow entrance passages.

JULES

JULES (Julia's Underground Laboratory Experiment Sedimentation(has at all stages in the design, construction and maintenance of the unit benefited from ideas contributed by many. The collaboration with Les Field and Ian Johns on the electronic aspects of the project must be especially acknowledged.

The design of JULES

a) selection of parameters for measurement

The chemical system CO_2-H_2O — $CaCO_3$ is of major importance in the reactions that occur in cave waters. Several of the variables associated with this system were to be measured, including the pH and the Ca^{2+} concentrations of the cave waters. The system was not at equilibrium so to define its state more clearly the partial pressure of the carbon dioxide above the cave waters was required. In addition a chemical analysis of all major components and many trace metals in the cave waters would be performed once a month.

For chemical and biological reactions involving metals of multiple oxidation states it is necessary to know how much oxygen is available and/or the reducing power of the system. In the early design stages dissolved oxygen measurements were chosen instead of the more customary reduction potentials because the Redox potentials of oxygen containing environments are generally lower than the equilibrium values, and there is no simple way to apply a correction factor. However, when a spare channel was available on the unit it was also possible to measure redox potential (Eh).

In order to study variations in the caves atmosphere it was necessary to measure oxygen as well as carbon dioxide. Data for both these gases together gives information concerning the source of the carbon dioxide. It is hoped to gain information concerning the relationship between oxygen in the cave atmosphere and dissolved oxygen in the cave waters.

Air temperature in the cave was also measured; the variation observed so far has been small, 18° ± 0.5. It is possible that greater variations may be expected at times of high bacteria production. Humidity also has shown little variation but extreme drought and flood may produce greater variation. Measurements of pressure are needed to define the cave atmosphere completely and it is hoped that they will give results as to how the cave "breathes".

b) range of parameters to be measured

parameter	expected range	parameter	expected range
pH	4-9 pH units	dissolved O_2	0-100% saturation
Ca^2	40-200 mg/l	Eh	-0.5 – 1.0 volts
atmospheric CO_2	0.5-10% (by volume)	temperature	17-19°C
atmospheric O_2	8-21% (by volume)	pressure	950-1050 mb
		humidity	0-100%

c) selection of instruments for the unit

The following aspects were considered: size and robustness; a working voltage of 12 volts DC or the possibility of modification to 12 volts DC; current drain; stability of the instrument over a one month period.

Two Rustrak Multichannel recorders were chosen. The two channel recorder measures 9x10x14 cm and the four channel recorder 19x10x14 cm. The total weight of the recorders is 4.5 kg. They are supplied with a strong aluminium case. The DC motors run from a 12 volt supply and only use 20 milliwatts of power. They have a chart speed of 2 mm per hour and the chart paper is of an "inkless" pressure sensitive type. The recorders have been used in many field stations and have proved extremely reliable.

Two Philips Universal pH meters were selected; these were not the smallest available but size had to be sacrificed in favour of stability. They were contained in robust fibre glass cases approximately 23x13x10 cm and weighed 3.5 kg. Although designed for a 220 volt AC supply, information was given for modification to 12 volts DC. Laboratory tests showed that the instruments were stable to 0.1 of a pH unit over one month. One meter was to be used for calcium ion measurements and the other was to be time-shared for pH and Eh. The electrodes (mainly Philips and Orion brands) were selected for reliability and ease of replacement of membranes and electrolyte solutions.

The dissolved oxygen meter is also a Philips model in the same robust case as the pH meters and of a similar weight. This was recommended for use in systems requiring automatic remote monitoring of dissolved oxygen. The probe is extremely robust and replacement of the electrolyte solution and the membrane is easy. The current drain is high, in the order of 60 mA. It was successfully modified for a 12 volt DC supply, although this operation proved more difficult than for the pH meters. An International Biophysics Corporation (IBC) meter and sensor, a cheaper unit than the Philips was selected for measurement of the gaseous oxygen in the cave atmosphere. This portable meter turned out to be unnecessarily large as it was supplied complete with alarm (the model initially ordered had been discontinued). The alarm system was easily disconnected but was not removed. The instrument was designed for a 12 volt supply and the current drain was a few milliamps. Laboratory tests showed that the instrument varied only by 0.1% oxygen over a one month period.

Mines Safety Appliances (MSA Aust.) designed a carbon dioxide meter specifically for use in the underground unit. Carbon dioxide concentrations are measured by a comparison of the thermal conductivity with that of a reference gas. It is built in a 10x10x18 cm perspex case and works from a 12 volt supply with the thermistor temperature measuring device using only milliamps of power. The sample and reference chambers are sunk into an insulated aluminium block which is kept at 1° above ambient. The heater for the block requires over 100 mA of power when heating. It is sensitive to changes of 0.1% CO_2 and is calibrated using water saturated samples of gas of known composition. The instrument requires calibration at least once a year.

It was clear that the power supply was a major problem because the equipment was to run unattended for one month and the experiment was expected to last for at least five years. Lead-acid batteries were unsuitable because they have a long lifetime only when working close to full charge. It was expected that towards the end of each month the constant current drain would discharge the batteries. Therefore six Alcad nickel-cadmium batteries were obtained; these 12 volt and 15 amp-hour batteries have a long lifetime under the conditions expected. Two were to be used for the main set in the cave, one each for the positive and negative rails of the electronics. Another two batteries would be a standby set in the cave while a third pair was being recharged. The heater unit of the CO_2 meter was to be run by the lighter (5 kg as opposed to 27 kg for the Alcad batteries) but much more expensive silver-zinc cells; these are 27 volt 30 amp-hour batteries. One of them would supply continuous power for the CO_2 meter heater for 3½ months.

A hydrothermobaragraph with a 31 day mechanically run chart was selected as already the power demands of the unit were excessive.

The construction of JULES

All the instruments of the complex are cased in perspex as this material had proved ideal for cave conditions. For sometime we have replaced the wooden, steel, aluminium and leather containers of our portable instruments by perspex. It does not rot or rust, is not affected by abrasion and does not dent when dropped. One instrument encased in perspex and surrounded by foam rubber was not damaged when it fell down a 20 m pitch. The boxes are designed so that cleaning is easy and all the perspex requires is a hot wash. All perspex boxes were sealed with rubber and silicone grease compressed by brass screws 5 cm apart. This system works well for our portable instruments and allows them to be immersed without harm. However, it had been reported that after a time perspex allows water to penetrate, so the following experiment was performed:—

An experimental box of 6 mm thick perspex whose junctions were sealed with ethylene dichloride was prepared. Inside the box was freshly dried blue silica gel. The box was then placed in a beaker of water and left. The silica gel was still blue after three months. The experiment was discontinued at this stage.

To protect the instruments from the high humidity of the cave, calico bags of silica gel will be added to the perspex boxes and will be changed every month. It is also proposed at times of high CO_2 to place containers of sodium hydroxide in the boxes to prevent corrosion by the carbon dioxide. The perspex boxes and other parts of the station that required mechanical engineering were made by P. Watson who was responsible for many of the design ideas.

How the instruments were assembled to make up station JULES is shown in Figure 3. When the instruments were tested, it was found that the complex drew a current of 260 mA on the positive rail and 142 mA on the negative rail. It was realised that the power supply was totally inadequate. Two alternatives were possible: continuous recording and many more batteries, or recording half an hour in twelve hours. The latter was chosen as there was no money, insufficient space in the cave, and not enough labour available for the former. Half an hour was a generous time period for the instruments to warm up and twelve hour intervals would provide a safety margin on the power supply. As a further precaution against battery failure or the batteries not being changed after one month, a battery changeover unit was designed and built such that when the voltage in the main battery set dropped below a set threshold value, the standby set cuts in thus maintaining a constant source of power. A timer was designed to switch the unit on and off after operation.

The meters were modified to 12 volts DC and tested to see if their performance was adequate on 10 volts the expected voltage at JULES (the total cable resistance was 1.5 ohms). All of the meters outputs had to be made compatible with the recorders input. A time sharing circuit was attached to one pH meter so that it could be used for Eh and pH alternately, each being measured for 15 minutes. All cables were inserted into the perspex boxes through waterproof sockets and these were colour-coded for easy assembly in the cave.

The instruments were first bench-run in Canberra where they performed successfully. They were then dismantled and transported to Sydney to see if they could be transported and reassembled by cavers correctly and without damage. This operation was carried out successfully although during bench-running a mechanical part of a recorder failed. This was easily rectified and the repair could have been made underground. At this stage the instruments were calibrated and tested for stability. JULES was now ready to be sent underground when the cave was ready to receive the unit.

Preparation of the cave for JULES

The cave was gated in 1974 by Sydney Speleological Society with the approval of the Australian Speleological Federation (ASF) and with the permission of the Bungonia Caves Trust. Lawler's Gate is a simple bar of hardened steel placed across a constriction in the most unstable section of the Rocks Wandering. Keys were supplied to all New South Wales member clubs of ASF. The cave was gated for two more important reasons than the protection of JULES. It has beautiful decorations in the higher parts and as a result of its recent discovery has not been vandalised as have other Bungonia Caves. It is also a dangerous cave for the inexperienced. The Rocks Wandering, coupled with several difficult climbs and long pitches in foul air make it a strenuous cave. Few experienced cavers reach the bottom unless they descend with a project working party, so even without the gate the main instrument complex is effectively protected by the difficult approach.

A detailed survey of the terminal pool in Odyssey Cave was carried out and a stainless steel cable was placed 10 cm above the surface of the pool. A series of measurements and samples were taken at a variety of depths and positions to establish the best location for the electrodes. The wire was then used to hang a series of microscope slides to determine the distribution of active micro-organisms. A perspex tank was placed in the pool to collect the sediments as they formed.

A Dexion shelf was constructed and galvanised to protect it from corrosion; this was to be placed in the cave on the wall above the terminal pool. It was first placed at a height of 7 m with the aid of a scaling pole (Plate 3). The first flood of 1974 reached to within 1 m of this shelf, the second covered it to a depth of 5 m! A feat of mechanical climbing placed the shelf on a natural ledge 17 m above the water level. Access to the ledge involves prusiking up a 12 mm terylene three-in-one Marlow rope, which is changed and washed on alternate visits, while the anchor tape is changed every 6 months. In order to protect the instruments from mud and keep the cavers clean for working on them the cave wall was scrubbed.

The electrode immersion assembly holders were bolted to the cave wall so that the tips of the electrodes would be 10 cm under the surface of the terminal pool (since the discovery of the cave the water level in the pool had remained constant). The immersion assemblies disappeared below the first flood but this was not considered to be a major problem. The assemblies are designed for total submergence and would continue to measure as they did in the next flood, After two months of them remaining under water preventing routine maintenance a floating electrode holder was designed and the cave divers were called in to recover the units.

The floating electrode holder is illustrated in Plate 4. Calculations involving the weight of the electrodes and the immersion assemblies gave the volume of air required to be trapped in perspex to float them. The size of a suitable single unit was too large to pass through the Rocks Wandering, so a katamaran was designed. The perspex floats are 35x35x100 cm and these are joined by a platform of perspex into which holes were drilled for the electrodes. The immersion assemblies are clamped so that 10 cm of the electrode is below water level. The katamaran unit is very stable and even when the tall immersion assemblies are in position it is extremely difficult to upturn it. The katamaran is attached to a 2 m cable attached to a floating slider which moves up and down a fixed wire to the instrument shelf. When the water rises the slider drags the floating electrode holder up with it. The katamaran floats over the deepest part of the terminal pool where the bacteria colony grows. It can be hauled on to a sediment bank for routine servicing of the electrodes.

Bit by bit containers, holders and associated equipment were taken into the cave, with no package greater than 35x75x100 cm. Occasionally problems would arise despite careful sizing up of the squeezes in the Rocks Wandering: the battery boxes were too large to pass through this section. Not wishing to remove the obstruction the boxes were sawn in half and stuck together with ethylene dichloride in situ. (Another advantage of perspex — having previously tried many materials and glues underground this was rapid and stuck).

A heavy copper cable had to be laid from the battery boxes at the top of the second pitch to JULES. Initially it was hoped to have the batteries in the final chamber but difficulties were encountered moving heavy and bulky equipment through the carbon dioxide region of the cave. To facilitate the battery change it was decided to place them 150 m from the terminal chamber out of the high CO_2 region. A route was planned for the cable which was neither an eyesore nor would it interfere with the normal movement of cavers. The cable was laid by Mike Martyn, who adopted a professional approach and disguised the cable with results that would shame many tourist caves.

In order to leave the cave as undisturbed as possible during the experiment a combined effort by many cavers saw all the known unexplored passage in Odyssey Cave entered. Exploration was completed except for the underwater passage in the terminal pool in Knockers Cavern. The diver into this passage has produced a further underwater chamber and prospects of more cave passage. Therefore until this exploration is complete the final pool will periodically be disturbed. The preparations took six months, but fortunately during this period the rains that made the "dry" caves unpleasantly wet, also kept the carbon dioxide low.

Installation of JULES

Two vital statistics for JULES are its weight, 225 kg., and the limiting dimensions of any section of the unit 35x75x100 cm. For transport into the cave any dead space in the instrument box was filled with foam rubber and the lids were greased and sealed. To protect the outside of the boxes they were wrapped in expanded polystyrene, then three layers of plastic. Each package had strong hauling handles on four sides. This packaging survived the extremely rough trip to the final chamber and the instruments arrived in mint condition even after being juggled through the Rocks Wandering and descending the pitches on the back of an abseiler. On manouvering the heavy batteries upright (although sealed batteries were kept upright as a precaution against spillage) through the Rocks Wandering, the decision not to take them into the foul air was endorsed. The instrument packages were hauled up to the ledge and unpacked, then lashed to the Dexion shelf with wire and string. The colour coded connections were made and, amazingly, when the battery connection was made, they began to function. After thirty minutes the timer switched the machine off. Now came the problems of underground calibration and maintenance.

Routine maintenance and calibration

Servicing of the unit is scheduled to occur once a month and each visit involves one day's work in the cave. For the monthly visit it is necessary to obtain voluntary labour, as porters into the cave. It is also safer for the investigators not to enter the foul air too frequently (James *et al*, 1975). Each month the main battery set is removed from the cave for charging, the standby set becomes the main set and the freshly charged set becomes the standby set. If all four batteries are fully charged the unit will run for three months without battery change. On reaching the final chamber the instruments are started operating by manually operating the timer. If the machine starts and stops this checks the power supply, the timer and the time-sharing unit. While the machine is in operation the meters, electrodes and recorders are checked against standard solutions or the portable instruments. A timetable exists for routine change of membranes and electrolytes. After the above operations are carried out fresh silica gel is placed in the perspex boxes. The silver-zinc batteries are situated in the final chamber and they are changed every three months. Each month water samples are taken in the cave for complete chemical analysis and routine measurements are made with the portable instruments. The batteries can always be changed except during the flood peak, the other routine operations require low (less than 4%) carbon dioxide.

The problems

JULES has been in the cave for 9 months and during this period all the meters and recorders have worked well. For the first few months the instruments with their electrodes underwater could not be calibrated. The meters continued to record but the results were meaningless. After the electrodes were recovered and floated one by one they have developed cable corrosion resulting from inadequate sealing during their long period of immersion. The electrodes as yet have showed no signs of fouling but the iron bacteria colony has not reappeared after the floods. The pH electrode has required a larger than expected number of potassium chloride crystals to keep the solutions saturated.

Electronic breakdowns have caused the largest number of failures. As calibration was well underway the instrument was found to be recording continuously. A new era of electronic repairs underground involved collecting together miniature electronic equipment such as multimeters and soldering irons. After the first repair the machine was operating on a half hour in four hours cycle which meant frequent battery changes. A second attempt to return to the old time interval caused complete failure. The timer had been fitted to the recorders and this was one of the heaviest units so the decision had to be made whether to remove it from the cave and replace it. The result was a new timer was constructed in a small separate container and fitted bypassing the old timer and it works well. The small separate container approach is the best, when the battery changeover unit failed it was removed from the cave and rapidly repaired. The Eh/pH time-sharer was found to be measuring on a 5/25 time ratio: again, this had to be returned to a 15/15 time ratio underground as the unit was attached to the meter box. Les Field's description's of lengthy electronic repairs tied to a narrow ledge 17 m up, with limited light and in 2% carbon dioxide are graphic!

Other sections of the equipment have also had problems, the Alcad batteries have performed reliably and only one one occasion when they were charged in parallel instead of series have they failed. However, recently the silver-zinc batteries have been failing to hold their charge and as yet this has not been solved. The ink of the hydrothermobaragraph absorbs water and if the container is full it overflows. During 1975 a flood caused the floating electrode holder to float up its fixed wire for 10 m; this flood had two pulses which were recorded, but the second hung the floating electrode holder several meters above the pool surface! This had been remedied by relocation of the fixed wire.

The future

When the existing instruments are running trouble free it is hoped to increase the number of parameters measured. An important parameter to include is dissolved carbon dioxide; there are now electrodes available for this but as yet they have not been adapted for use in JULES. Many karst solution studies include conductivity measurements so it will be easy to include this measurement. It will be significant to relate this to other parameters in the CO_2-H_2O-$CaCO_3$ system under the curious conditions that are peculiar to Bungonia. The air and water temperatures have always been close and varied in the same manner in the preliminary studies but for absolute confidence in the solution chemistry results it is necessary to measure water as well as air temperature. The timer is to be adapted so that during floods the machine records continuously. As the machine can run for forty hours on the standby batteries and the floods so far have only lasted for a day or so there should be no problems of power supply. Water level and flow measurements in the cave and the Efflux are the projects of others and somewhat slow to start as these results are essential for interpretation of data. If they are not in progress by 1976 they will become part of project JULES.

Conclusion

The cave appeared at first to be a model system for the study of the deposition and precipitation of black banded sediments without many of the perturbing factors present in marine bays and peat bogs. The sediments are being deposited in a restricted temperature range in a saturated atmosphere and it was thought that even floods had lost their violence by the time they reached the final chamber. The floods occurring after the project had started showed the last was an incorrect premise and floods have proved to be a continual source of problems. The problems associated with the size and difficult nature of the cave and the carbon dioxide were largely anticipated and solved before the unit entered the cave. Electronic problems that appeared after the unit were more difficult to solve resulting in slow progress of the project and the data obtained has been minimal. However, when a set of parameters has been established for deposition of specific minerals in the cave and the conditions that produce maximum concentration of metal ions through biological and other agencies are defined, it may be possible to use these in the extraction of low grade metal ores. Laboratory experiments are to be designed with this aim in view. Odyssey Cave appears to be a suitable model for the study of the origin of iron minerals formed during Precambrian times when the oxygen content of the atmosphere was much lower than at present. James (1966) proposed three mechanisms for the derivation of the iron in "ironstone" and "iron-formation", two of which could be observed in or inferred from natural systems existing at present. The third required an atmospheric modification. He suggested that during the Precambrian while the sediments were being deposited the earth's atmosphere was higher in carbon dioxide. This atmospheric modification currently exists in Odyssey Cave.

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