3.00

BCRA TRANSACTIONS

BRITISH CAVE RESEARCH ASSOCIATION

Volume 2 Number 1 April 1975

Gimli's Dream, Carlswark Cavern

INSTRUCTIONS TO CONTRIBUTORS

These notes are meant for guidance of contributors in the hope of reducing the amount of labour for both the editor and the contributors! Adherence to the rules is desirable but not absolutely essential.

As far as possible all material submitted for publication in the Transactions should be typed on one side of the paper only with double spacing to allow for editorial corrections where necessary. Paragraph sub-headings should be clearly marked. Metric measurements should be used wherever possible.

A very short summary of the principal conclusions should accompany every contribution.

References to other published work should be cited in the text thus . . . (Bloggs, 1999, p.66) . . . and the full reference with date, publishers, journal, volume number and page numbers, given in alphabetical order of authors at the end, thus . . .
Bloggs, W., 1999. The speleogenesis of Bloggs Hole. Bulletin X Caving Assoc. Vol. 9, pp. 9-99.

Italics are not normally used and only the volume number should be underlined. Periodical titles should be abbreviated in accordance with the World List of Scientific Periodicals, obtainable in any public library.

Illustrations: line diagrams and drawings should be numbered fig. 1, fig. 2, etc., and referred to in the appropriate place in the text. All such illustrations must be drawn in BLACK ink on clean white paper, card or tracing paper. Anaemic grey ink will not reproduce! Illustrations should be designed to make the maximum use of page space. If photo-reduction is contemplated all letters and lines must be of a thickness or size to allow for this. Captions may be typed on a separate sheet if space is left for insertion on the final illustration.

Photographs are welcome. They must be good clear black and white prints with sharp focus, and preferably about 6 × 4 inches. Captions may be appended by means of adhesive tape on the back.

If illustrations are submitted which have already been published elsewhere, it is up to the author to clear any copyright and acknowledgment matters.

Contributors in Universities and similar institutions are reminded that grants are often available from those which may help towards the costs of publication. The Editor will be pleased to advise.

If you have any problems regarding your material please consult the editor in advance of submission.

Authors may order reprints of their own contribution for their own private use, such as circulation to colleagues or for exchange purposes. The Editor should be notified of the number required at the time of submission of the contribution. Ten reprints are allowed free, if asked for, but the rest will be charged to the author.

ISSN 0305-859X

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

Volume 2 Number 1 April 1975.

CONTENTS

Cover Picture — **Gimli's Dream, Carlswark Cavern, Stoney Middleton**
(by Paul Deakin)

Published by and obtainable from
The British Cave Research Association

Bryan Ellis,
7 School Lane,
Combwich,
Bridgwater,
Somerset. TA5 2QS.

One copy issued free to members
Extra copies to members £1·00
Non-members price £1·50

Trans. British Cave Research Association. Vol. 2. No. 1. pp.1-11. April 1975.

THE CAVES OF THE FOOLOW-EYAM-STONEY MIDDLETON AREA, DERBYSHIRE, AND THEIR GENESIS

by John Beck

SUMMARY

An outline description of the caves and the present state of exploration is presented. The caves are shown to have developed by the successive utilization of lower bedding plane and joint systems becoming active as the base level of resurgence fell owing to surface denudation. The caves or passages within them can be separated into (a) the active swallets, (b) the first and second remnant complexes, (c) the Carlswark Complex, and (d) the Lower Complex.

INTRODUCTION

Lying on the northeast flank of the Carboniferous Limestone outcrop in Derbyshire, the Foolow-Eyam-Stoney Middleton area has attracted cavers for many years, but few attempts have been made to analyse the evolution of the underground drainage systems. Outline accounts, rather speculative in places, have been presented by Jefferson (1961) and by King (1962) though these were concerned with development of the dales rather than the cave systems.

The caves of the area lie within the zones D2 and P1 zones of the Carboniferous Limestone, here comprising the top 100 metres beneath the cover of Edale Shales of the Millstone Grit Series. Details of the stratigraphic succession may be found in the Geological Survey Memoir for the Chapel-en-le-Frith sheet No.99 (Stevenson & Gaunt 1971) and in Orme's contribution to Neves & Downie's Geological Excursion guide to the Sheffield area (1967).

The evolution of the cave systems is undoubtedly controlled by the sequence of events in the Pleistocene Ice Age, but as yet no fixed points by which the cave evolutionary sequency can be linked to stages in the surface development have been found. All that can be said at present is that the area was glaciated in the Penultimate advance and that the dry valley system, presumably including Middleton Dale, has been incised since then. This incision progressively exposed lower beds of limestone and thus potential resurgence points to which the successive levels of the caves could drain.

This paper describes the general form and relationship of the caves and shows that a sequence of events can be worked out underground. It is hoped that future research will be able to relate this sequence to one worked out on the surface.

TOPOGRAPHY

The villages of Foolow, Eyam, and Stoney Middleton lie on the northern margin of the limestone outcrop. To the north, the prominent shale and gritstone escarpment of Eyam Edge rises to a maximum height of 1,407 ft. OD at Sir William Hill. Streams accumulating on the gritstone moors flow southwards to disappear, in most cases, into shallow holes on, or near, the limestone margin. A deep limestone gorge, Middleton Dale, drains eastwards, sub-parallel to the escarpment. It turns at its western end to run north eastwards as Linen Dale, dying out in the vicinity of the largest sink, Waterfall Swallet, at the shale/limestone boundary (Fig. 1).

To the south of Middleton Dale, the limestone rises to a maximum height of 1,297 ft. OD at the summit of Longstone Moor. This upland area is dissected by two dry valley systems, Hay Dale, which runs southwards to the Wye Valley, and Coombs Dale, much larger, and descending eastwards to the Derwent near Calver.

The deeply incised valley of Cressbrook Dale runs north-south along the western edge of the area. At its northern end, springs occur at the margin of a shale outlier at Wardlow Mires, and water flows southwards across the shale. It may often be seen to sink at various points, and in wet weather the stream is augmented by the flow from various artificial drainage levels, or soughs. Near the southern end, the large resurgence of Lumb Hole discharges a considerable volume of water.

The western part of Middleton Dale carries no surface stream, water first appearing at the tail of Watergrove Sough, at the bottom of Farnsley Lane. The sough was driven to de-water the inundated Watergrove Lead Mine, at the western end of Middleton Dale. Water from the sough flows eastwards as the Dale Brook, to be joined by water from resurgences both natural and artificial, and by water from two streams which flow for some distance over the limestone, the Jumber Brook, and the Hollow Brook. These streams flow from the shale, through Eyam, and continue southwards via the Delph, and Eyam Dale respectively. Both may often sink at various points in the valley floors, although the Hollow Brook in Eyam Dale has almost been completely culverted.

Opposite the Delph, on the south side of the road, the somewhat mysterious resurgence of Hawkenedge Well discharges a considerable and very consistent flow into the brook. The nature of this watercourse is unknown; it has been referred to as 'Oakenedge Sough' (Rieuwerts, 1966, Kirkham, 1967).

At Stoney Middleton, the brook is swelled by the water from Moorwood Sough, driven to de-water mines between Stoney Middleton and Eyam, principally Glebe Mine at Eyam. The sough runs close to the shale margin, and has captured water from the natural conduits via small phreatic tubes and joints. The sough tail lies in the grounds of Stoney Middleton Hall at a height of approximately 465 ft. OD (SK 2318 7545).

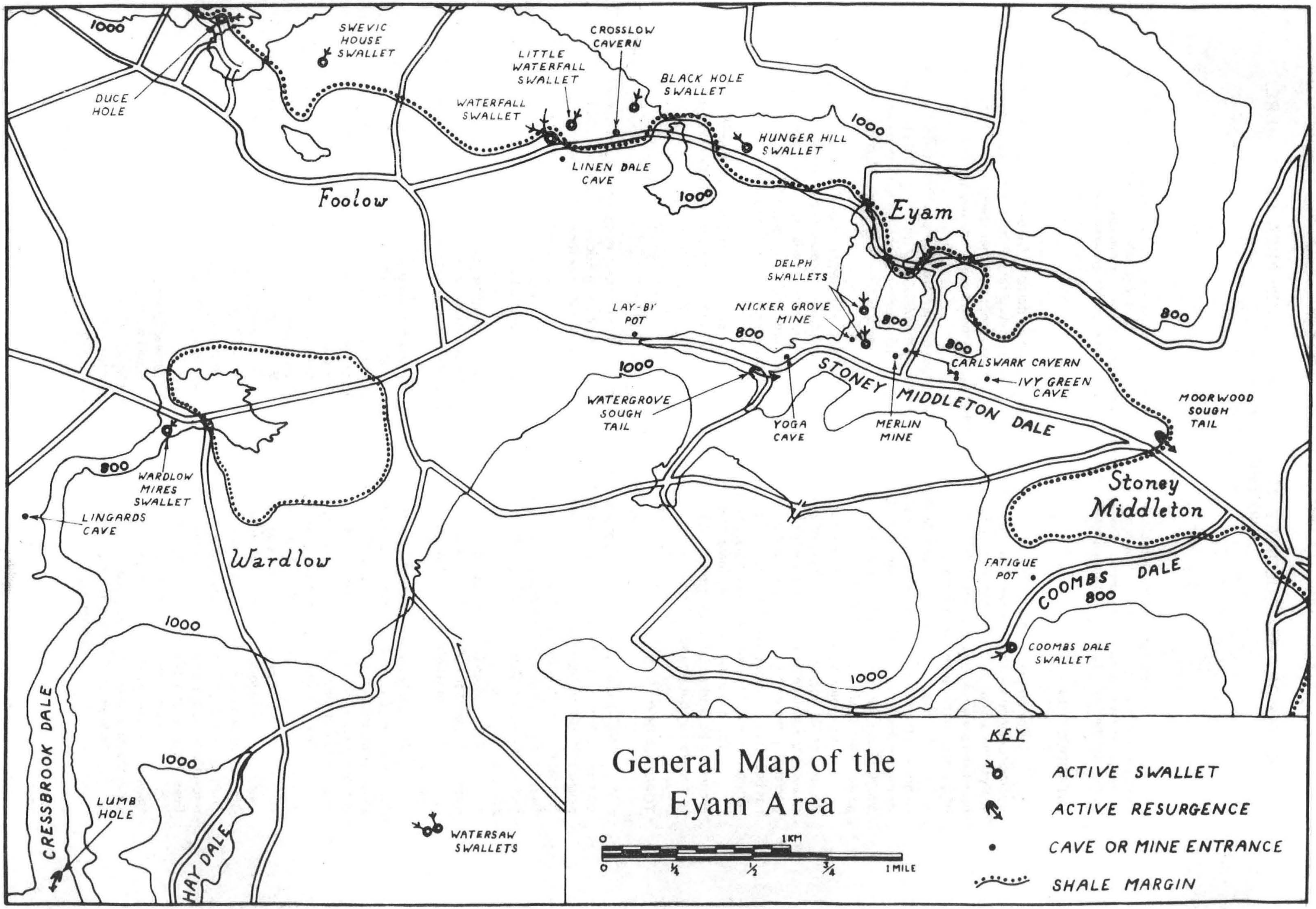

SWEVIC HOUSE SWALLET
DUCE HOLE
LITTLE WATERFALL SWALLET
CROSSLOW CAVERN
BLACK HOLE SWALLET
WATERFALL SWALLET
HUNGER HILL SWALLET
LINEN DALE CAVE
Foolow
Eyam
DELPH SWALLETS
LAY-BY POT
NICKER GROVE MINE
CARLSWARK CAVERN
IVY GREEN CAVE
STONEY MIDDLETON DALE
MOORWOOD SOUGH TAIL
WATERGROVE SOUGH TAIL
YOGA CAVE
MERLIN MINE
WARDLOW MIRES SWALLET
LINGARDS CAVE
Wardlow
Stoney Middleton
FATIGUE POT
COOMBS DALE
COOMBS DALE SWALLET
CRESSBROOK DALE
LUMB HOLE
HAY DALE
WATERSAW SWALLETS
1000
800
General Map of the Eyam Area
0
1KM
0
¼
½
¾
1 MILE
KEY
ACTIVE SWALLET
ACTIVE RESURGENCE
CAVE OR MINE ENTRANCE
SHALE MARGIN

Fig. 1.

The Northern Swallets

The most westerly swallet to be considered is Duce Hole, at Grindlow (1812 7767). This was penetrated by members of the B.S.A. into a choked stream passage, and it is said that the water flows westwards, to resurge at Bradwell via Bagshaw Cavern.

Swevic House Swallet lies half a mile north west of Foolow, at 1869 7746. Permission to visit the swallet is rarely granted, and rubbish is said to have been dumped there. The destination of its water is uncertain, but it is remotely possible that this is the most westerly swallet whose water flows to Stoney Middleton.

Waterfall Swallet lies half a mile north east of Foolow, in a large tree-lined shakehole at 1988 7705. A considerable stream enters the shakehole on the north west side. This normally sinks at three points in the shakehole floor, but during severe floods, as on 16th July 1973, water may back up above these small choked fissures and escape into Waterfall Hole, a cave system with its entrance in the north east wall. The stream is normally encountered 21 metres below the entrance, and can be followed through a chaos of displaced and eroded blocks to a depth of 43 metres, where it disappears among boulders and mud.

Waterfall Swallet is developed on an east-west fault plane, in places mineralised and mined. The fault divides into two components at the swallet, the more northerly branch passing eastwards through a smaller shakehole. This is Little Waterfall Swallet (2003 7710), but the water outlet here is impenetrable. Present attempts at further exploration are directed towards the probably union of the two streams underground. The water from Waterfall Swallet, and probably from the other swallets along the shale margin between here and Eyam, has long been known to reappear in Moorwood Sough.

Robey (1964) described Crosslow Cavern, which lay adjacent to the road a short distance to the east at 2030 7706. An 18 metre shaft led to a large cavern which had been used as a washing floor for ore, and was largely filled with miners 'deads'. Water in the cavern was stated to drain towards Waterfall Swallet. The entrance has now been obliterated by the farmer.

Black Hole Swallet was a large depression at 204 772, which took a small stream. The stream sink was impenetrable, but the depression has now been filled with rubble.

Hunger Hill Swallet lies closer to Eyam, immediately north west of Hunger Hill Farm, at 2096 7695. It appeared to have taken considerable water after the flood of 16th July 1973, but the stream sink is hidden under farm rubbish.

The small swallets in the floors of Eyam Dale and the Delph are very juvenile in character, the water having, comparatively recently, found routes down joints into cave passages beneath. These passages are part of the Carlswark Complex, a network of phreatic conduits developed at the base of a bed of limestone packed with large silicified brachiopods *(Gigantoproductus)* known as the Lower Shell Bed. During the 16th July flood, the Delph stream appeared to swell at the more southerly swallet, rather than diminish. It is possible that the main streamway, which lies only a short distance below the valley floor, was so overpowered that water was forced back up the swallet.

Carlswark Cavern and Ivy Green Cave

Close inspection of Carlswark Cavern, and of the other smaller phreatic caves in the sides of Eyam Dale, the Delph, and Middleton Dale, reveals that there have been several periods of cave development, resulting in a succession of cave levels. These may be referred to, in order of development starting with the highest, as the First Remnant Complex, the Second Remnant Complex, the Carlswark Complex, and the Lower Complex. The Carlswark Complex is the most extensively known, and the majority of Carlswark Cavern itself belongs to this level.

There are several entrances to Carlswark Cavern, those most frequently used being the Eyam Dale Shaft (opposite the electricity sub-station) at 2185 7595, and a mined joint on Wonder Scrin, a small north east – south west trending vein, at the western end of the terrace known as 'The Gin' in Middleton Dale, at 2208 7582. An easy scramble down the latter leads into the main phreatic passage (Smith 1971). The Lower Shell Bed is prominent here, walls and roof of most of the passages being covered with etched out fossil shells. This is Eyam Passage leading eastwards from the bottom of the Scrin entrance back towards the cliff face. To the west, it soon enlarges, and a hole in the floor leads via a tube and a joint-oriented rift down to a passage of the little known Lower Complex. A long deep sump at the bottom of the rift must **not** be free dived; its other end can be reached through higher passages. A phreatic passage leads out to the original Lower Entrance, which is also a flood resurgence, at 2207 7580.

Eyam Passage can be followed westwards to a large boulder choke, beyond which a right turn through a low and partly flooded passage brings one to a further junction. To the left is the large collapsed area at the foot of the Eyam Dale Shaft. Beyond the collapse, the passages continue, but the western section can only be reached by the nearby Merlin Mine. To the right access is gained to what is still known as the 'New Series', although it was entered by the B.S.A. in 1959. The major passage of the New Series is the large and vandalised Stalactite Passage, reached by a duck, and lying roughly parallel to Eyam Passage, lower down the dip slope. The passage ends at a rift, where a scramble down leads to the inner end of the sump in the Lower Entrance Passage.

A very tight series leads northwards from Stalactite Passage. Known as the Dynamite Series, it consists of a series of avens lying on joints trending north-west to south-east. The avens are connected by phreatic tubes of varying size, but generally very small. The Lower Shell Bed is left behind, and one progressively climbs through the limestone sequence into passages developed at higher and higher horizons.

A large passage containing an extensive fill of miners 'deads' is reached at the top of a tight climb, and soon leads to mine workings on Stub Scrin. The choked bottoms of shafts can be seen; their tops are close to, or under, the Eyam Dale road. The workings soon rejoin the natural passage, and three more avens can be reached before the connecting tubes become too tight. A constricted dig is possible here.

The natural passages at high level in the vicinity of the mine workings lie at a similar horizon to that on which Ivy Green Cave is developed. The entrance to the latter lies at the eastern end of 'The Gin' in Middleton Dale, above mine workings at 2224 7580. The cave consists of a phreatic passage trending northwestwards. It is heavily silted, but dedicated digging would probably connect it with the high level passages of the Dynamite Series of Carlswark. These passages are part of the Second Remnant Complex.

An even higher development can be reached by climbing into a high level passage in the fourth aven of the Dynamite Series. Traversing diagonally upwards through (in places) rather unstable looking boulders gives access to a large passage at the top of yet another aven. This passage is referred to the First Remnant Complex, and lies at the base of a limestone unit containing three persistent and closely spaced chert bands. Below, the limestone is fine-grained, and contains many corals, and the bedding plane between forms a useful marker horizon. The passage ends rather ludicrously, however, at a boulder choke through which traffic can clearly be heard bumping over the oft-repaired bit of road halfway up Eyam Dale.

The bedding plane on which the passage lies can be seen plunging steeply below the road by a small pull-in at 2192 7606. It shows extensive bedding anastomosis, and a small cave entrance lies at this horizon a short distance to the south.

The Merlin Mine

The entrance to the Merlin Mine lies high on the west side of Eyam Dale, just above the junction with Middleton Dale, and it is from here that the more westerly passages of the Carlswark Complex can be reached. The mine follows a pipe vein northwestwards, soon crossing Sycamore Scrin, on which levels run to right and left. To the left are natural cavities at the level of the Second Remnant Complex, leading to a 15 metre blind pitch.

Stub Scrin is reached approximately 50 metres from the entrance. To the l eft are more Remnant cavities, while to the right three shafts are found in the floor. The second shaft is 9 metres deep, and a further descent down a pile of boulders which were once, it seems, stempled into to roof, gives access to several hundred feet of passages at the level of the Carlswark Complex. This series includes the very active Merlin Streamway. Through most of the year, all that can be seen is a forbidding sump pool, and the stream can be heard, through an impenetrable bedding plane above water level, crashing into a rift. The route to the stream is obvious at the bottom of the stopes, for it can nearly always be heard, to the west.

The right hand (downstream) sump is eight feet long, but silted, and with a constricted entrance. It leads to a low bedding cave, which the stream crosses before falling into a permanently flooded rift. The outlet of the rift is tight, heavily silted, and dangerous.

The upstream sump is tight, deep, and sixty feet long. When the streamway was first discovered, a boulder choked rift in the main stream beyond this sump was able to take all the water, and there was just air space enough to wriggle through. Since that time, the weather has never been so dry, and the water has never receded. The main streamway was followed to another sump, which was subsequently dived to more encouragingly large streamway. The water from the Merlin Streamway reappears, like that from Waterfall Swallet, in Moorwood Sough.

The largest component of the flow of this stream is almost certainly accumulated percolation water over a long stretch of cave, for there are no large allogenic sinks to account for it. Dye testing revealed that the water from Waterfall Swallet does not pass through the known streamway, suggesting the presence of a separate system to the north. The water from the more southerly of the Delph Swallets was proved to enter the streamway, and its point of entry was believed to have been reached by divers.

Prospects for further exploration are good, for there are high level passages in the Sump Pool Chamber which are above the maximum water level. These are silted, but excavation would almost certainly by-pass the sumps. Care would have to be taken not to block the 'eight foot sump' with silt.

To the east of Stub Scrin, passages can be followed back to the blockage at the foot of the Eyam Dale Shaft. This stretch shows features which are clearly indicative of the cave's history; the developmental phases are shown in Fig. 2. During Phase 1, the water flowing at Lower Shell Bed level formed an elliptical passage by phreatic solution. Retreat of the water led to the removal of hydrostatic pressure in the conduits, and roof collapse began, the blocks being covered with the accumulating silt, as seen in Phase 2. Phase 3 represents a period of quiescence, when little water was flowing underground. A glacial phase is suggested as a reason; this would account for the high rate of flowstone formation. When the ice sheets retreated, extensive flooding took place, and the resultant secondary stream excavated a deep channel through the layers of silt and flowstone. This phase was followed by retreat of the water to the present Merlin Streamway route, and the passage was finally abandoned. Flowstone began to form on the remnants of earlier episodes, and also on the floor of the new channel. Clean sections through this material can now be seen, with large projecting cornices of flowstone. The stretch of well decorated passage was christened 'Gimli's Dream'.

The Delph

The small valley running parallel to, and west of Eyam Dale, known as the Delph, or Cucklet Dale, has many small cave passages and mine levels in its walls. The largest system is Nicker Grove Mine (incorrectly referred to as Great Cucklet Mine by Pearce [1974]) high on the west side at 2155 7595. Like the Merlin Mine, a pipe vein was followed northwestwards. This intersects a solution cavity developed on a north west – south east trending joint, and continues to a choke of sticky mud. A 'vein' such as this is not a pipe in the usual sense; it is essentially an open joint infilled with sediment. A large proportion of this sediment in some cases may be derived from in situ hydrothermal veins, and is thus a valuable source of lead. The Merlin Pipe, and the Watergrove Pipe are similarly developed.

Generalised Vertical Section showing Principal Horizons of Cave Development

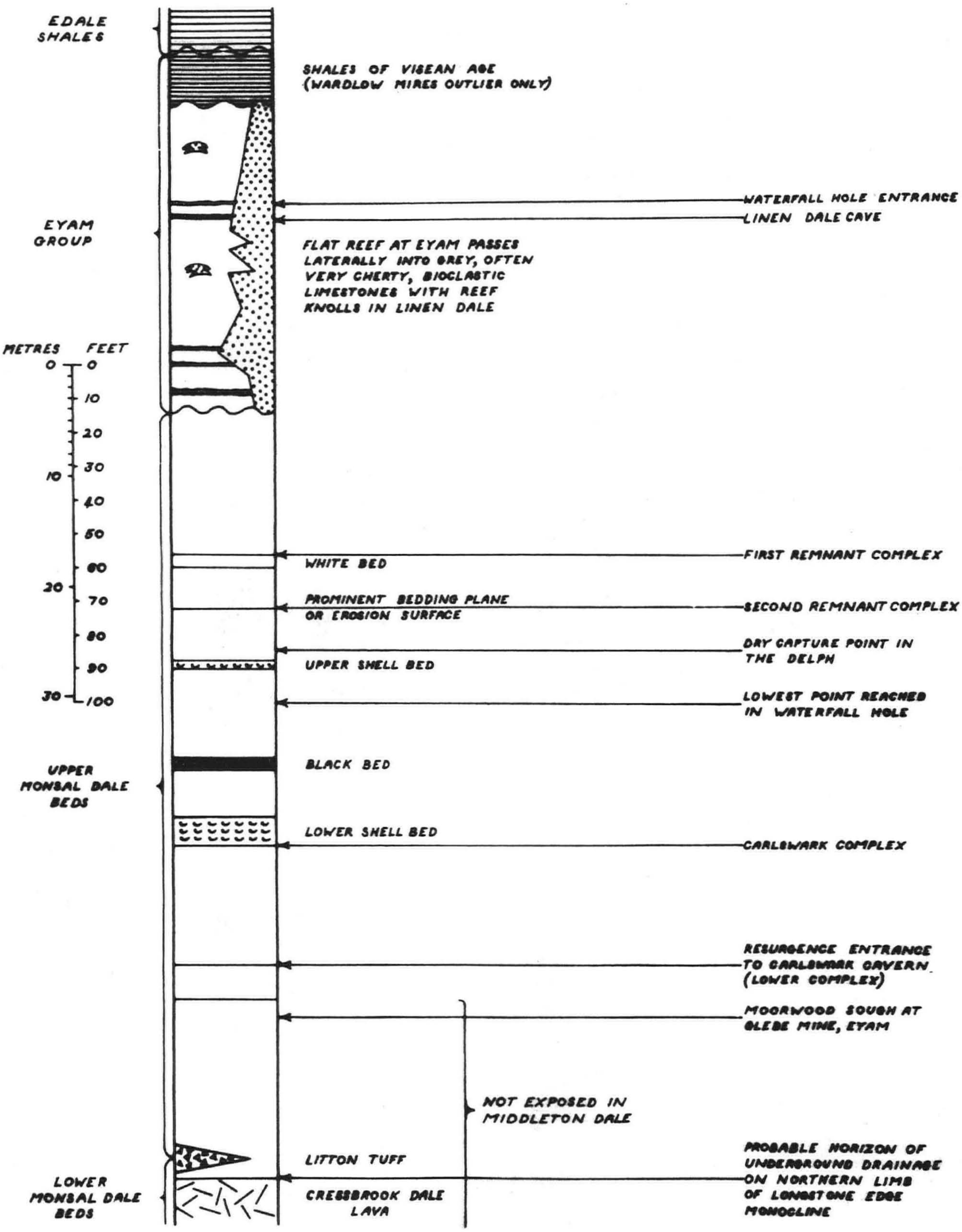


PLATE I

Photos by Paul Deakin

Fig. 1. Gimli's Dream, Carlswark Cavern.

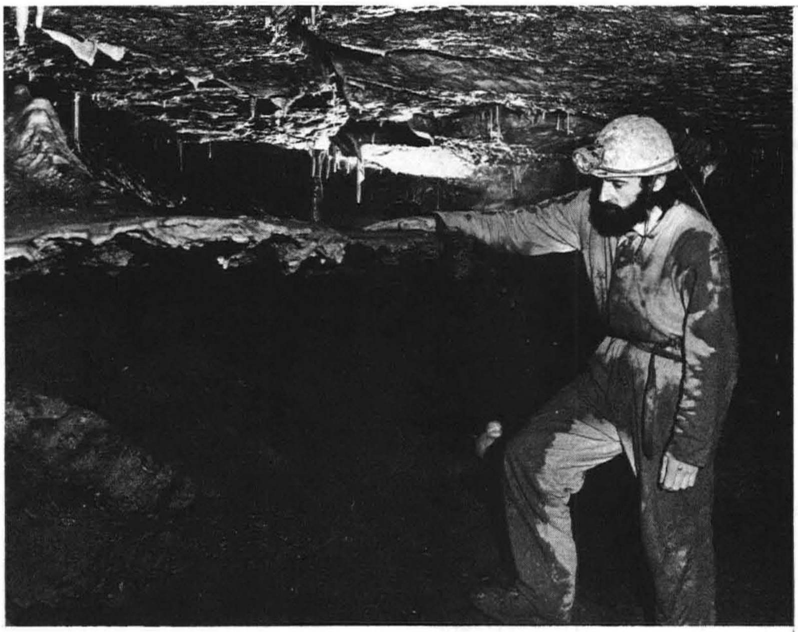


Fig. 2. False Floor in Carlswark Cavern.

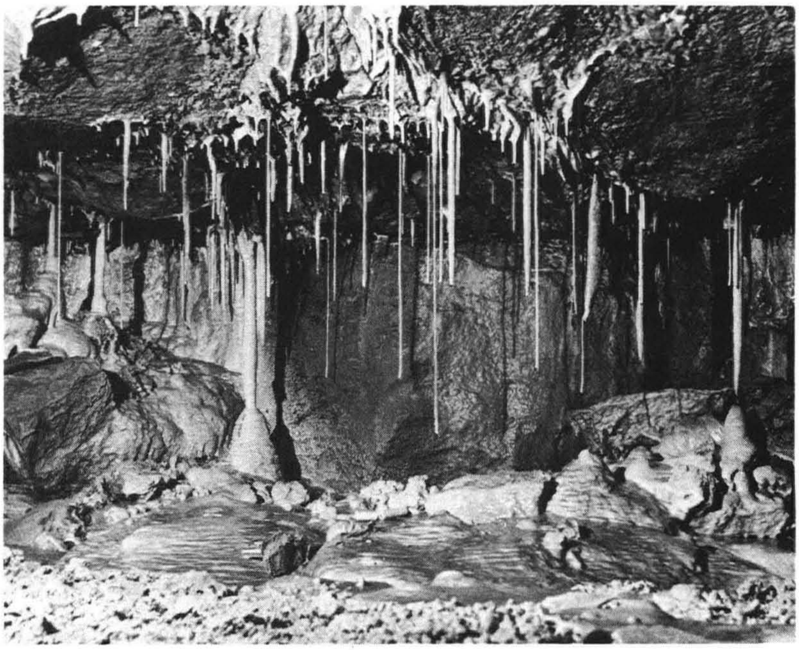


Fig. 3. Sarah's Cave, Stoney Middleton - now destroyed.

A shaft in the floor of the main level, roughly 75 metres from the entrance, leads to levels 8 and 16 metres lower. The lowest level leads to solution cavities close to the horizon of the Carlswark Complex. These show confused directional scalloping, and may be abandoned and silted portions of the Carlswark Complex, up-dip from the present streamway. The –8 metre level leads via another large solution cavity to a short shaft to daylight, with its top just above the valley floor.

Delph Hole (2163 7598), opposite Nicker Grove, shows Remnant Complex tubes intersected by mining, though it is of little extent. A cave in Eyam Dale, almost directly above the Eyam Dale Shaft, was recently excavated by members of the South Yorkshire Caving Club, and may represent the eastward continuation of the Delph Hole tubes.

High on the west side of the Delph is the Cucklet Church, a series of through arches in a prominent buttress, used by the Rector of Eyam, William Mompesson, for church services during the plague of 1665. This is a very high development, and is probably a part of the First Remnant Complex, although it lies a little above the exact horizon. Its appearance of vadose modification suggests that it may have lain near the head of that system, being fed by sinks at the then more southerly shale margin.

The stream emerges from a narrow ravine, known as the Saltpan, at the head of the Delph. This has all the features of a vadose streamway, with no roof. Its origin was probably as a stream passage, which was downcut under vadose, and then surface conditions, to give the present form.

Halfway down the Delph, on the west side, some 5 metres above the valley floor, is a small cave developed partly on the joint pattern. This may represent an early route by which the stream sank in the valley floor, or may have originated as a capture point by which water sank from the Second Remnant Complex into the Carlswark Complex which was developing below. The water has now found new routes in the present juvenile swallets.

Upper Middleton Dale

To the west of the Delph there are fewer high level caves, and beyond Farnsley Lane there are none in the valley walls. Passages of the Carlswark Complex are still present, and may be quite mature. The tiny entrance to Yoga Cave lies a few feet above the road, on the north side, just east of the sharp bend by Eyam Quarries (2125 7589). The Lower Shell Bed is obvious in this cave, and some passages are very similar in character to those of Carlswark Cavern itself. A tight entrance crawl leads after just over 50 metres to larger passages, including two large chambers. From here, the way on is blocked by mine workings in Streak's Vein, so unstable that they should not be touched.

A few small blocked tubes are found at the same horizon further to the west, but no major caves are found until Lay-by Pot is reached. The 15 metre entrance shaft lies north of the road, opposite the second lay-by west of Furness Quarry, at 2035 7600. The shaft intersects an abandoned stream passage at the bottom, which runs east and west. To the east, the passage soon ends at a deposit of clay and boulders in the valley floor, through which a narrow slabbed mine level continues for 60 metres to a complete collapse. To the west, access can be gained to a bedding cave at a higher level. This can be followed eastwards for a considerable distance to two large chambers. The crawl beyond the second chamber is silted to the roof. The total length of the cave is approximately 350 metres. The Lower Shell Bed appears to be poorly developed in the first large chamber, but does not exert the same influence over passage shape and size as in the Carlswark Complex passages further to the east.

Beyond Lay-by Pot, the dale rapidly becomes shallower until it turns northeastwards as Linen Dale. The only known cave here lies at the northern end of the valley, just south of the road to Foolow, at 1989 7696. It may be referred to as 'Linen Dale Cave'. A tight crawl was dug out for 13 metres to a small chamber, where the way on is hopelessly blocked with boulders and mud. It is probably an old engulfment point for water draining from the shale.

The south side of Middleton Dale reveals few caves. The most significant find here was Sarah's Cave, exposed by quarrying, and now removed. A well decorated passage was found, lying close to the level of the Lower Shell Bed (Lord, 1971).

A mineshaft above the quarries, on Middleton Pasture, intersects a natural passage at the horizon of the Second Remnant Complex, but this is hopelessly blocked with 'deads' and run in workings.

Coombs Dale

Coombs Dale has many small caves and mine workings in its walls, as well as the still functioning Sallet Hole Mine. The only natural system of any size is Fatigue Pot (Collier's Peril Cave), which lies on the north side of the valley at 2249 7473. Here, a tiny bedding controlled passage leads to the head of a tight pitch, which can be descended in three steps to a passage developed along the bottom of the rift, running northwestwards into the hillside. This ends at a choke of huge boulders, but two crawls lead off to north west and south east. The north west crawl is only 27 metres long, and turning is a considerable problem. The south east crawl leads for nearly 100 metres to a small rift chamber, with further crawls to a well decorated grotto, and a boulder choke in a small passage through which a draught emerges in hot weather. The level of this choke is approximately 17 metres below the valley floor, and would be a good but exhausting prospect for digging, as the crawls are very arduous.

The Lower Shell Bed cannot be recognised in Coombs Dale, and a coral band appears to have taken over its function as the principal horizon of cave development. It lies at a similar level, and is close to the Lower Shell Bed stratigraphically. It is unfortunate that insufficient cave passages are known to allow a sequence of events to be constructed.

Further west in Coombs Dale, at the confluence of two valleys, a large volume of water sinks in wet weather in the vicinity of old mine workings. It was thought that this water flowed through immature passages close to the surface, but a careful survey of Fatigue Pot showed that passages at a considerable depth are not flooded, and that the water table is much deeper than one would expect. The water table has not been artificially lowered to this depth by mining, for there is mature flowstone in the lowest parts of Fatigue Pot.

Other Areas

Longstone Moor is devoid of known caves or potholes. Abandoned swallows can be seen in a few places where opencast fluorspar workings have exposed them, but all are full of glacial detritus. Just north of Watersaw Rake, at 1925 7337 and 1928 7338, two small swallets take a considerable amount of water in wet weather. East of the open cut on the rake, another small swallet lies in a small but pronounced depression. The swallets appear to derive their water from the extensive cover of 'head' and peat. Current excavations here may reveal something of interest. Whether this drainage flows eastwards below Coombs Dale, or westwards towards Lumb Hole, in Cressbrook Dale, is uncertain. Percolation tests are needed to determine the extent of these two catchment areas.

Hay Dale has no known caves, but the valley sides are covered with a thick scree, and any entrances are likely to be buried.

Cressbrook Dale has a few small high level caves, but everything is either tight, mined out and collapsed, or heavily silted. Lingard's Cave lies high on the west flank near Litton, at 1706 7506, and consists of a chamber from which short descents into blocked mined sections may be made. This is part of a phreatic system long abandoned, collapsed, and silted.

Bull Tor Cave and Ravencliffe Cave lie high on the east side above Ravensdale Cottages. Neither is of great extent, but Ravencliffe Cave has been archaeologically excavated, and yielded interesting Palaeolithic implements. These were associated with remains of woolly rhinoceras, horse, reindeer, and bear (Fox, 1910; Braislford, 1959; Bramwell, 1973). The finds are among the oldest archaeological remains in the Peak District.

Abandoned resurgence passages are found opposite Lumb Hole, at 1723 7312. Digging here in the past has been unrewarded. These caves appear to be controlled by the presence of an underlying lava, in the same way as the active resurgence of Lumb Hole. The structure of the apparent catchment area makes it difficult to form any conclusions regarding the nature of this watercourse, and a very ambitious project would have to be mounted to penetrate it, judging by past efforts. When the water is low, it is possible to crawl into the lower entrance of Lumb Hole for a short distance, but the way is blocked by large boulders. The upper entrance, a few feet above, can be followed for some way to an uncomfortable end, again among large boulders. The stream can be heard here, at a lower level.

The dip in the northern part of Cressbrook Dale is to the north, into the basin of Wardlow Mires, and it is probable that the drainage of the moors on either side of the valley is down-dip into the basin. The centre of the basin is occupied by a shale outlier, and the water resurges at its margin, collects to form an integrated stream, and flows down the dale to the Wye. It appears that this down dip drainage may have been responsible for the large amount of water encountered in Watergrove Mine, which now flows eastwards via Watergrove Sough. It is also possible that the large flow of the Merlin Streamway may originate on the dip slope.

SPELEOGENESIS

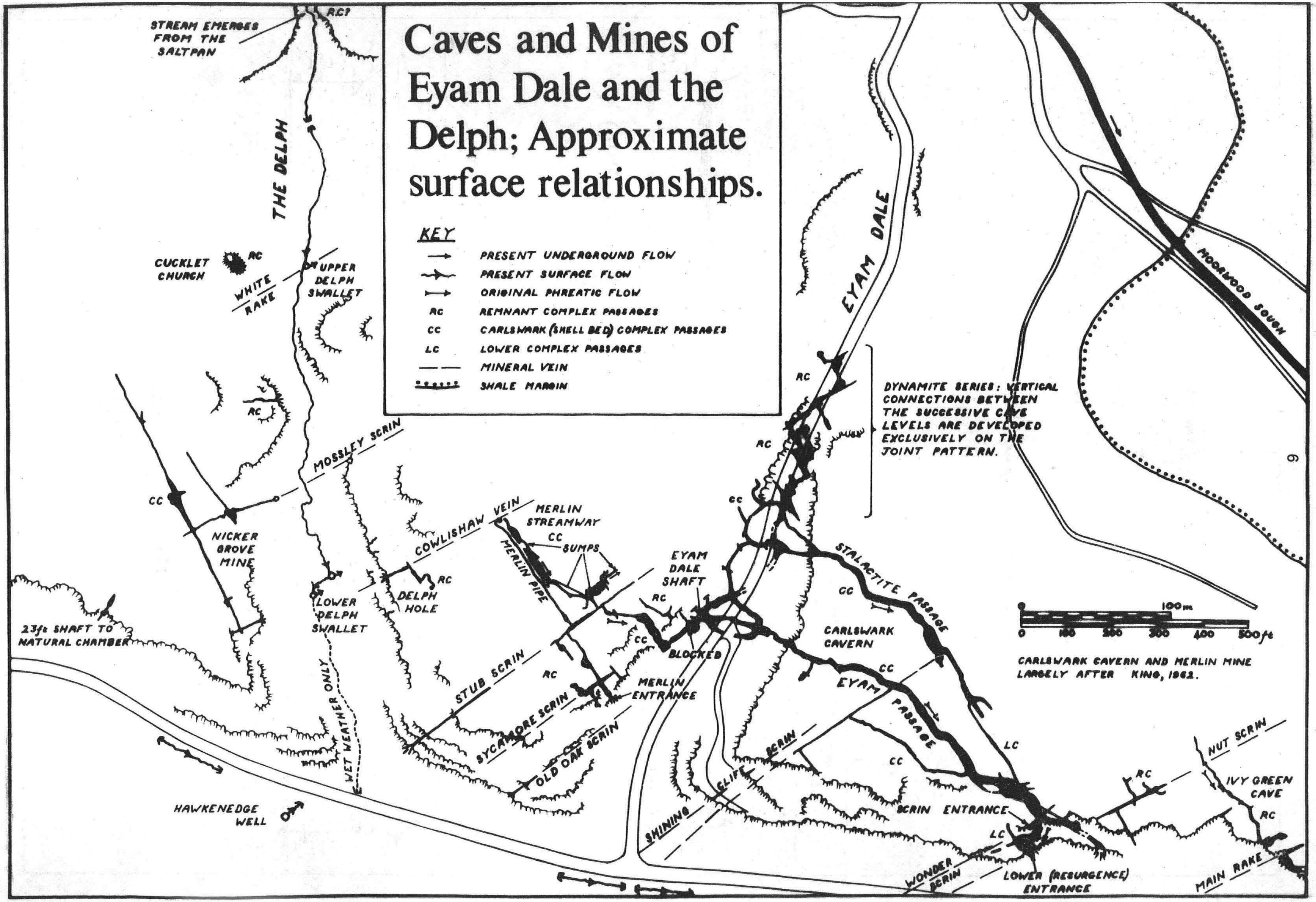
Developmental conclusions can only be drawn at present for the caves of Middleton Dale, where it appears that four distinct periods of phreatic solution occurred. During the earliest period, the shale cover was far more extensive, and only a relatively small area of limestone was exposed. A large catchment area gave rise to streams which sank, in the vicinity of Eyam, into swallets at the head of the First Remnant System, now represented by the Cucklet Church, probably the Saltpan, and the highest levels of Carlswark Cavern. The high level passages of Carlswark represent development just below the water table of this time, and the resurgence of this system probably lay in the region of the mouth of Middleton Dale.

The second phase occurred after more shale had been removed, diminishing the catchment areas, and lowering the base level of the limestone massif. The downstream passages of the first system began to degrade as the water was pirated by juvenile passages at a lower level, and shallow valleys began to form on the limestone. Their position was determined partly by the position of cave networks, and partly by the influence of a drainage pattern developed on the now removed shale cover. More sinks opened towards the west as the shale cover receded, and the passages of the Second Remnant Complex were initiated. Ivy Green Cave, the majority of the Dynamite Series of Carlswark Cavern, and the highest natural passages of the Merlin Mine belong to this level.

A further phase of erosion left the second system above the water table, and filled its passages with varying amounts of debris derived from the surrounding shale and gritstone. The Wardlow Mires outlier was probably at this time still connected to the main shale outcrop, so that the active allogenic sinks lay as far west as Linen Dale, migrating northwards with the shale margin, and giving rise to the present irregular valley as successive shakeholes degraded. Water now flowed eastwards along developing conduits at the level of the Carlswark Complex, and reappeared at base level, in Middleton Dale, just west of Stoney Middleton.

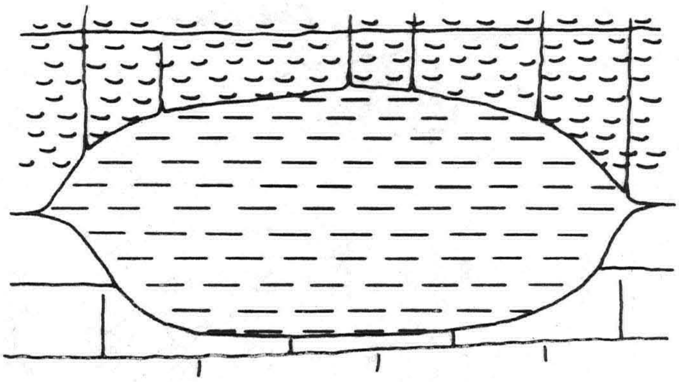
The shale cover retreated further, and the main sink finally established itself in its present position on the Crosslow Fault System, so that some of the more easterly passages of the Carlswark Complex were abandoned. The Lower Complex began to carry water to the resurgence, which is likely to have been the present Lower Entrance to Carlswark Cavern. The majority of this complex is still flooded, and attempts to explore it further have so far failed.

Caves and Mines of Eyam Dale and the Delph; Approximate surface relationships.

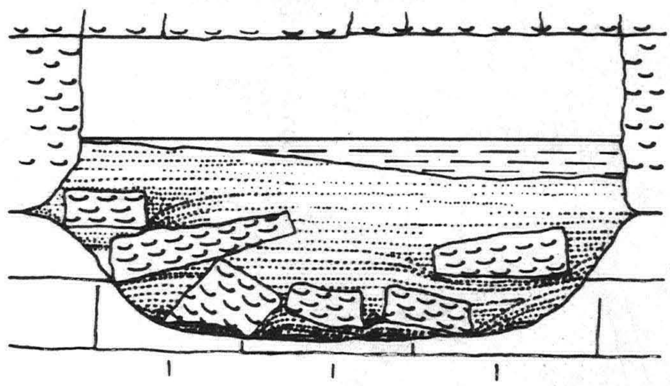


Developmental Phases of 'Gimli's Dream', Carlswark Complex (Merlin Mine).

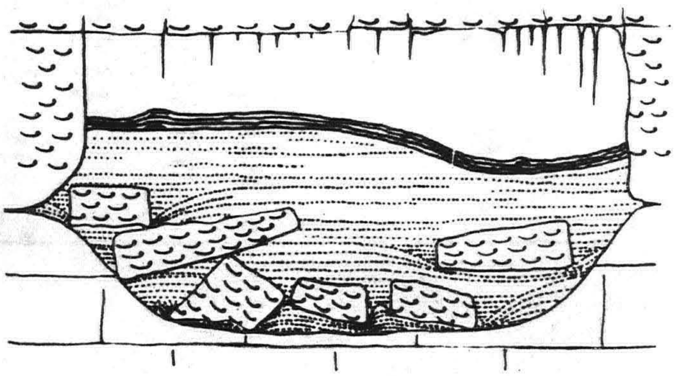
1; Phreatic.



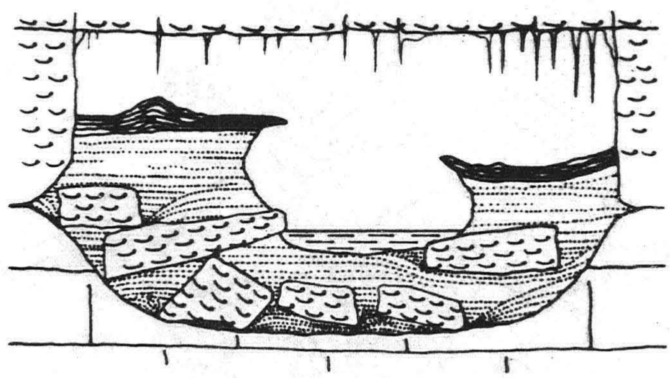
2; Paraphreatic.



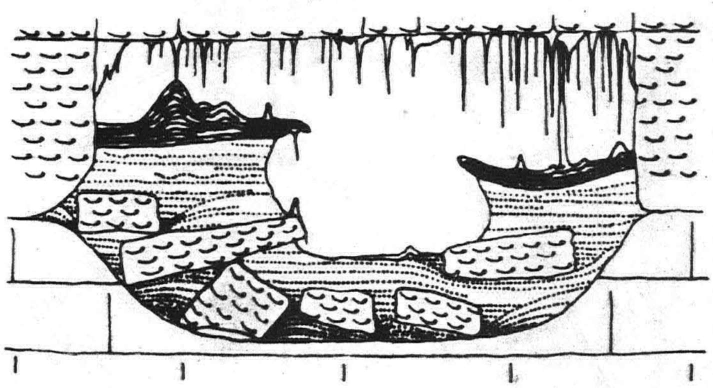
3; Quiescent.



4; Vadose.



5; Abandoned.



It has often been assumed that the pre-Moorwood Sough resurgence of the Waterfall Swallet stream was the Lower Entrance to Carlswark Cavern, but Short (1734) described the entrance, and the passages within, exactly as they are known today, except that the size of the entrance has been reduced to the present grovel by rubbish tipping.

Short's description runs as follows: "A little west of this is Charleswork, this has a Majestic Appearance, lies at the Foot of a very steep Rock, ninety three Yards High, and five Yards above the Level of the Brook, its Entry is six Yards high and eight wide, here you walk on for forty two Yards and a half, where you arrive at an unpassable deep stagnant Lake, this Cave reaches quite through the Mountains and opens into Eynedale, which is above half a Mile; by another of its Grottoes, it opens near Fowlow which is a Mile and a half, passing quite under Eyan church."

The entrance could not then have been a resurgence, for water must flow up-dip to reach it, and the passages would certainly have been completely inaccessible. Moorwood Sough was not carrying this water in 1734, and the stream must therefore have already abandoned Carlswark's Lower Entrance. No definite conclusions can yet be drawn regarding the position of the actual resurgence, but it is hoped that further work will help to complete the picture.

All the phreatic passages in the area which are of any size lie roughly parallel to the strike of the beds, sloping very gently towards the east. Scalloping generally indicates flow from west to east, except in the smaller passages which may connect larger passages at 90° to the strike. Since it appears that phreatic passages are formed only a short distance below the water table, this is what might be expected; the main conduits would develop on the dip slope of a preferred bedding plane, just down dip from the intersection of the bedding plane with the water table of the time. As the water table was lowered by erosion, a succession of parallel passages would develop at lower and lower positions on the dip slope. Lower bedding planes would also be opened, and later lowering of the water table would allow formation of a new complex at a lower horizon in the limestone sequence. As each passage was abandoned, most of the 'dry' passages would be silted by flood waters which re-invaded them via the smaller down-dip connections. One route generally remains open to cope with such floods. Further exploration of Carlswark may reveal the latest passages in the succession.

If high level passages should be discovered in the other smaller valleys of the area, and the active routes finally explored, it may be possible to construct similar sequences of events for them.

ACKNOWLEDGEMENTS

The research described herein was partly carried out during the tenure of a Natural Environment Research Council research studentship.

Thanks are due to the many cavers, diggers, surveyors, and other helpers for the many happy hours spent underground.

REFERENCES

Brailsford, J.W. 1959. Ravencliffe Cave. Derbys. Arch. Journ. vol. 77, pp.55-56.

Bramwell, D. 1973. Archeology in the Peak District. Moorlands Pub. Co. Hartington. 87p.

Fox, W. Storrs. 1910. Ravencliffe Cave. Derbys. Arch. Jour. vol. 32, p.141 (also in vol. 50).

Gunn, J. 1974. A model of the karst percolation system of Waterfall Swallet. Trans. Brit. Cave Res. Assoc. vol. 1. no.3, pp.159-164.

Jefferson, D.P. 1961. The development of Middleton Dale. Bull. Peak Dist. Mines Hist. Soc. vol. 1. no.4, pp.37-43 & no.5, pp.35-36.

King, B. 1962. Carlswark and the Cave system of the Foolow-Stoney Middleton area. Cave Sci. vol. 4. no.32, pp.377-383.

Kirkham, N. 1967. Oakenedge, Streaks and Watergrove Soughs. Bull. Peak Dist. Mines Hist. Soc. vol. 3. no.4, pp.197-218.

Lord, P.J. 1971. Sarah's Cave. Jour. Sheffield Univ. Speleol. Soc. vol. 2, no.1, pp.24-25.

Orme, G.R. 1967. The Carboniferous Limestone of the Stoney Middleton area. pp.23-31. in "Geological Excursions in the Sheffield area". ed. R. Neves & C. Downie. Univ. Sheffield. 163p.

Pearce, A. 1974. An ecological survey of mines in Cucklet Delph, Stoney Middleton. Bull. Peak Dist. Mines Hist. Soc. vol. 5. no.5, pp.243-257.

Rieuwerts, J.H. 1966. A list of the Soughs of the Derbyshire Lead Mines. Bull. Peak Dist. Mines Hist. Soc. vol. 3. no.1, pp.1-42.

Robey, J.A. 1964. Discovery of a cavern on Crosslow Rake, Foolow. Bull. Peak Dist. Mines Hist. Soc. vol. 2. no.3, pp.151-2.

Short, T. 1734. Mineral Waters of Derbyshire... London. 359 p.

Smith, M.E. 1971. Bamforth Hole, Stoney Middleton. Bull. Peak Dist. Mines Hist. Soc. vol. 4. no.5, pp.370-374.

Stevenson, I.P. & G.D. Gaunt 1971. Geology of the country around Chapel-en-le-Frith. Mem. Geol. Surv. U.K.

Tottle, P. 1954. Colliers Peril Cave, Coombs Dale. The Speleologist (1st extinct series) No.3, pp.85-91.

February 1975

John S. Beck,
Geology Dept.,
University of Leicester,
Leicester LE1 7RH.

Trans. British Cave Research Association. Vol. 2. No. 1. pp.13-27. April 1975.

SOTSBÄCK CAVE. THE LARGEST KNOWN CAVERN IN SWEDEN.

by Ulf Helldén

ABSTRACT

A karst area on Artfjället, Lapland, northern Sweden, was investigated for morphology, hydrology and chemical processes during the period 1970-1972. It includes the largest known cavern in Sweden, the Sotsbäck Cave, described herein with a summary of the morphology, hydrology and chemical processes of the area. Parts of the cave, which is situated in an arctic environment, are supposed to be of late glacial to post-glacial age and sub-glacial origin. In particular the significance of mix-corrosion, corrosion, and cavitation erosion are discussed.

INTRODUCTION

A karst area on Artfjället (Fig. 1) was investigated for morphology, hydrology and chemical processes during the period 1970-1972. The karst area is situated in the Caledonian Mountain range, south of Lake Över-Uman in the county of Västerbotten. This paper deals mainly with the Sotsbäck Cave, the largest known cavern in Sweden.

GEOLOGY

The bedrock is an integral part of the low-grade metamorphic series of the Seve-Köli nappe, bordering the high-grade metamorphic bedrock of the Rödingfjeld nappe. The former is mainly composed of micaceous schists, phyllites, greenstones, migmatites, quartzites and limestones (Kulling 1955). The karst belt, which is 2.4 km^2 in area, is built up of partly crystalline, folded limestones, probably of Ordovician age forming beds varying in thickness from a few cm to more than 0.5 m. The karst beds are surrounded by migmatitic greenschists interspersed with winding bands of quartz. The contact zone between the limestone and greenschist consists of calcareous and quartzose phyllite. The chemical composition of the limestone varies considerably in the area and the bedrock is sometimes dolomitic (Helldén 1974 a).

The top parts of the succession strike in a north-easterly direction but at the tree line they turn off in a west-north-westerly direction in the form of a large fold. As the strata are deeply folded, the dip fluctuates and its values vary from about 10-50° having a mean value of about 35°W (Fig. 2). The joints strike NNW to NE.

During the maximum of the latest glaciation parts of the inland ice moved from E to W or WNW in this region, which was situated to the west of the ice divide. As the thickness of the ice sheet gradually decreased due to melting at the end of glaciation, the highest summits were laid bare above the ice surface and acted as barriers deflecting the ice flow. At a more advanced stage of deglaciation the ice is thought to have been channelled by the main valleys and to have formed valley glaciers. These gradually retreated towards the east thereby creating the pre-requistites for the formation of large ice-dammed lakes in the valleys.

The till cover within the limestone zone has a depth varying from zero to about 30 cm above the tree line, and between 30 and 40 cm below this level. The till is sometimes underlain by a thin layer of frost weathered soil. About 75% of the area above the tree line is covered with soil, while the area below is almost entirely covered.

CLIMATE

The climate of the area belongs to the type ETH, tundra climate, according to Köppen's classification (Köppen 1936). The mean annual precipitation is 1 000 mm and the mean annual temperature −2.2°C. The coldest month of the year is January (−16.0°C) and the warmest July (+9.2°C) (Helldén 1973). Only five months of the year are frost-free. It should be noted that no permafrost now exists in the region.

MORPHOLOGY

Since the morphology of the area has been dealt with earlier by Helldén (1973, 1974 a, 1974 b), only a brief summary of the subject is given below.

The karst zone (Fig. 3) has partly been formed through selective glacial erosion, which has given rise to a step-like morphology. Because of corrosive action and frost weathering a karst landscape has developed, characterized by pronounced karst depressions, karren and a highly differentiated subterranean drainage system.

The landscape forms have been processed statistically and presented by means of morphometric parameters (Helldén 1974 a, 1974 b). The results give reliable information regarding the landscape which, although an arctic one, is strongly karstified and displays a large number of karst features. The depression density is great (57/km^2) even if the size of the depressions is relatively small (Plate 1, fig. 1). Different types of karren occur but they are fairly rare. The results of morphometric analyses from the karst area of Artfjället, which can be classified as glacio-nival mountain karst according to Sweeting's (1972) classification, indicate that karst in arctic environments is not always characterized by such a lack of surface karst phenomena as suggested, amongst others, by Corbel (1957, 1960), Bögli (1960) and Sweeting (1972).

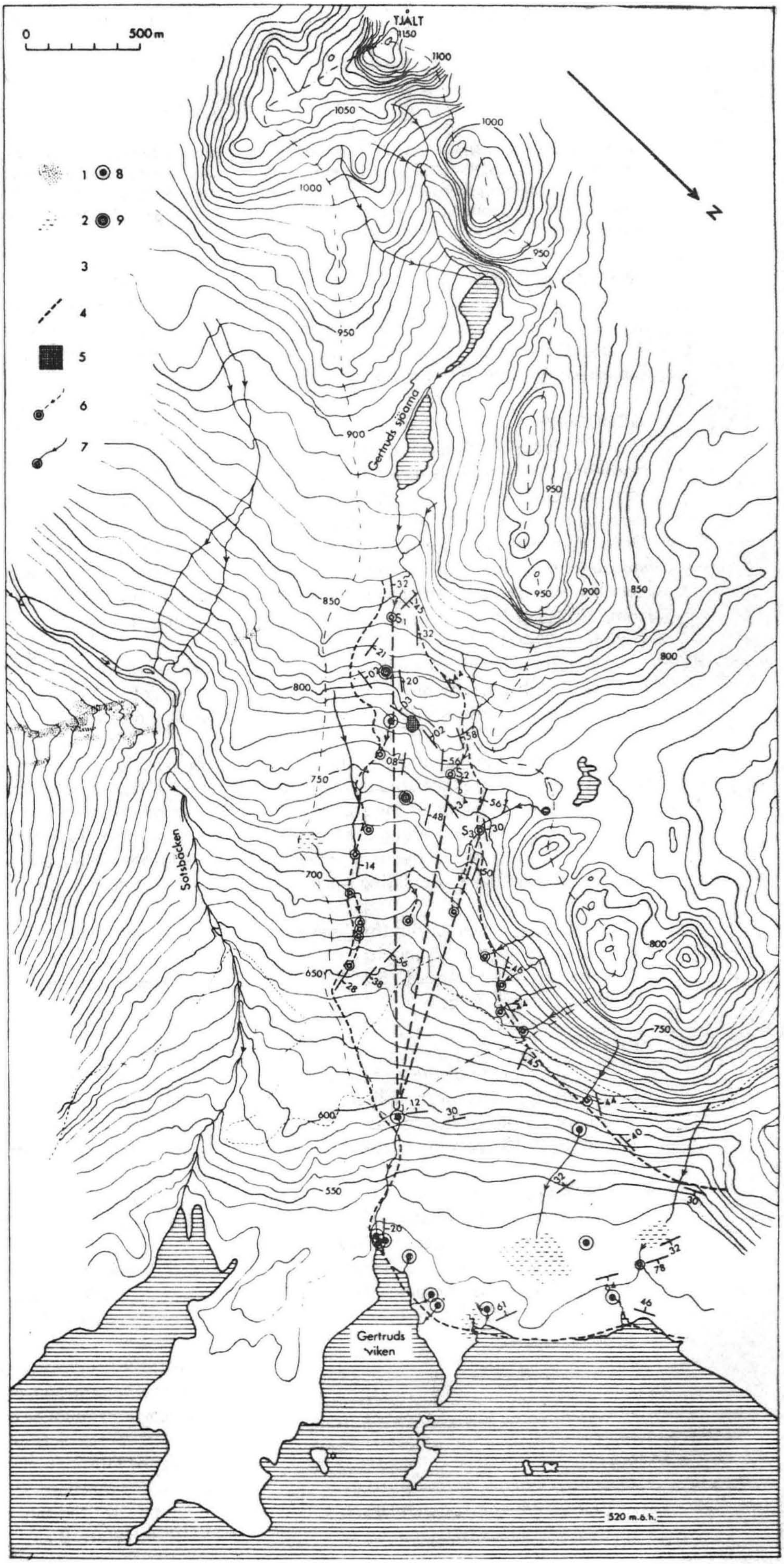


Fig. 1. The location of area studied in Sweden.

Fig. 2. The karst area of Artfjället. Strike and dip of the bedrock. Swallets S_1, S_2 and S_3 have subterranean connection with karst spring U_1.
1) engorged esker,
2) peat-moss,
3) tree-limit,
4) limestone border,
5) "Devil's Crater".
6) intermittent stream with swallet,
7) permanent stream with swallet,
8) karst spring,
9) fossil karst spring.
(Helldén 1974 b).

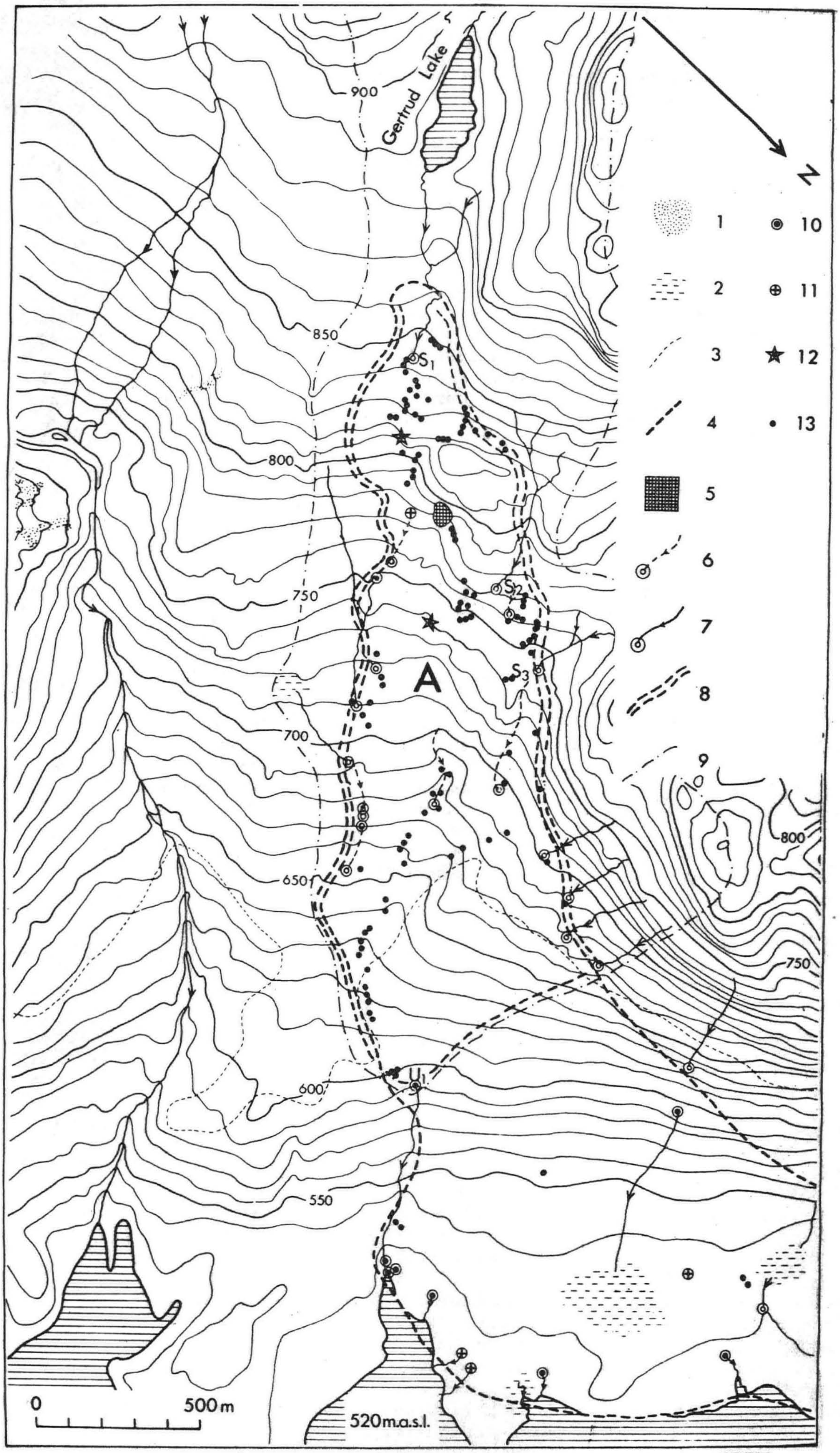


Fig. 3.

Artfjället karst area.
1. engorged esker,
2. peat-moss,
3. tree-limit,
4. limestone border,
5. Devil's Crater",
6. intermittent stream with swallet,
7. permanent stream with swallet,
8. limestone area A,
9. the drainage area of A,
10. karst spring,
11. intermittent karst spring,
12. fossil karst spring,
13. karst depression

(Helldén 1973)

HYDROLOGY

The hydrological data of the area have been presented by Helldén (1973, 1974a, 1974b). Only a short summary is given here.

None of the allochthonous streams that reach the karst belt flow over more than about 100 m limestone before they disappear in a swallet (Fig. 3). The whole drainage pattern is subterranean except during the snow melt period at the end of May and beginning of June, when autochthonous meltwater can give rise to small streams. Of the swallets marked on the map (Fig. 2), S_1, S_2 and S_3 absorb at least 95% of the allochthonous water discharge. The rest of the swallets are more or less intermittent and mainly function during the snow melt period. S_1 takes the largest stream that reaches the limestone area.

In order to find the connection between different swallets and springs and to obtain an idea of the characteristics of the underground drainage system, tracing experiments were carried out with Rhodamin B. The experiments showed that S_1, S_2 and S_3 were connected to the karst spring U_1 (Plate 1, fig. 2).

U_1 has a calculated annual mean water discharge of 105 l/s and supplies water all the year round. During a one week measuring period in December 1971, after more than one month's frost an average water discharge of 50 l/s was recorded. The average during the period September-April has been roughly estimated at 25 l/s, which is thought to be a minimum value. During the period June-August 1971 an average of 275 l/s was recorded. Most of the winter flow originates from snow and ice melting in the contact zone between a relatively warm cave atmosphere and the zero isotherm. During snow melt at the end of May and the beginning of June up to 60% of the outflow at U_1 may consist of percolation water. This value decreases rapidly and at the beginning of August it is only 1-2%. The water swallowed by swallets S_1, S_2 and S_3 constitutes the rest.

LIMESTONE SOLUTION INTENSITY

Methods and results of the investigations regarding chemical processes and limestone solution intensity have been presented by Helldén (1973, 1974b). A short summary of the results is given here.

Water samples were collected from different parts of the drainage area once or twice a day during the period May-August and during one week in December 1971 and analysed within an hour for total hardness, alkalinity and pH. Total hardness was found to vary between about 10 and 30 mg $CaCO_3$/litre at the swallets and 20-55 mg $CaCO_3$ at the karst spring U_1. It was also found that total hardness and carbonate hardness, in mg $CaCO_3$/l, are inversely dependent on water discharge. The relationship can be expressed by the function $y=ax^b$. Its graphic manifestation seems in the first place to be dependent on water temperature and the characteristics of the drainage system. This relationship must be used when calculating the limestone solution intensity.

The $CaCO_3$ transport from limestone area A (1.09 km^2) was calculated on the basis of water discharge measurements and the above mentioned relationship (Table 1). It was found that no less than 67% of the annual $CaCO_3$ transport takes place during the period May-July when the amount of percolation water in the subterranean drainage system is greatest. The chemical denudation is relatively high (28 mm/ 1000 years) compared with results from other arctic regions and also compared with some other results from warmer latitudes. Further, the analyses indicate that the water reaching the outlets is still aggressive.

Table 1. $CaCO_3$ transport from limestone area A (1.09 km^2) (Helldén 1973)

Period	water discharge at U_1 (l/s)	water temp. °C	transp. m^3	% of annual transp.
May	225	+ 0.9	7.2	23.7
June	425	+ 3.0	10.0	32.9
July	155	+ 8.8	3.2	10.5
August	75	+ 8.3	2.0	6.6
Sept.-April	25	+ 2.0	8.0	26.3
Total			30.4	100.0

30.4 m^3/year = 27.9 mm/1000 years.

SOTSBÄCK CAVE

Within the karst area there are about 30 caves varying considerably in size. The smallest are so minute that there is only room for a grown-up man with difficulty, while the largest are penetrable for 20-30 m. The major part, with two exceptions, has been formed in connection with collapse dolines. The two exceptions are the passages that lead into the limestone massif from the fossil outlets marked on the map (Fig. 3).

A conspicuous exception to the above mentioned small caves is the Sotsbäck Cave, which by its size and richness in form constitutes something unique in Sweden. The cave, which is an integral part of the subterranean drainage system of the karst area, was discovered in 1966 by two members of the Swedish Speleological Society (SSF), Yngve Freij and Ebbe Johansson, and since then has been subjected to intensive investigation under the auspices of the SSF. A provisional map was completed in 1969 by Freij and Johansson (Sjöberg 1970) and the total length of the cave passages was measured to 1650 m by the SSF, which makes this cave the largest known in Sweden, even larger than the Lummelunda Cave in Gotland

(1350 m) and the Lullihatjårro Cave (1110 m) to the north or Torne Träsk in Lapland (Freij et al. 1971). When new passage systems were discovered after 1969, the entire cave was surveyed by the author in the summer of 1971. At the same time all the passage systems and the ground surface above the cave were levelled (Figs. 4-5). Given below is an overall description of the extent, morphology and climate of the cave and its genesis and age are discussed.

Methods of measurement

The plan has been constructed from measurements with tape and compass and the map was drawn on drawing plastic in the cave. In order to check that the tape was held horizontally during the measurements a spirit level was used. The distance between the entrance (S_1) and the innermost part of the cave below the collapse doline "Devil's Crater" (520 m) (Plate 1, fig. 1), was measured twice and a difference of 2.5 m was obtained.

The levelling in the cave was made with the help of a meridian mirror and levelling staff. After levelling the main passage between S_1 and the innermost part of the cave twice a difference of 2.0 m was obtained for a vertical difference of 110 m. The obtained values agree very well with those presented on Freij and Johansson's map. Climatic data were collected during the summers of 1970 and 1971 and during a week in December of 1970; first and foremost they cover temperature and air humidity, which were recorded by means of seven thermohydrographs stationed in different parts of the cave system. The levelling took place on the basis of a barometer-fixed point at the cave entrance. The orientation of the s-surfaces was measured with a compass with clinometer needle about every ten metres.

The Cave Pattern

The Sotsbäck Cave can be divided into two complexes which are (1) the large main passage A-AE, which is drained by the stream swalled at S_1 with its outlet at U_1, and (2) the complexes of passages situated above the main passage and marked on the map with dotted lines (Figs. 4-5). The latter complexes of passages are named "fossil" and differ from the main passage because of disparate morphology, temperature and air humidity and because of the absence of concentrated water flows.

The main passage A-AE begins at the collapse swallet S_1, which is more or less snow-covered right up to the beginning of August, and then, it roughly follows the strike of the limestone in a curve as far as the collapse doline "Devil's Crater" to which it is connected (Plate 1, fig. 4). For a distance of about 90 m between the entrance and the 12.5 m waterfall at D the main passage runs along a fissure widened by erosion, then it intersects the limestone layers almost at right angles and runs parallel to their strike. The passage is 1-2 m wide and between 2.5 and 7.5 m high (Plate 1, fig.3). At the waterfalls D-F it widens forming two large chambers and then it continues almost horizontal. For afull 115m long distance between the entrance and F the main passage sinks via rapids and waterfalls about 60 m of the total fall of 110 m. Along the same distance the dip of the s-surfaces in the strike direction of the fold axes varies between 0° and 50°, the mean value being 11° and at F it becomes almost horizontal.

The roughly 230 m long stretch F-T is characterized by the fact that the passage runs almost horizontal and is chiefly excavated along the bedding planes of the limestone. The strata are slightly and irregularly folded but, nevertheless, they display a trend towards gently dipping in the direction of the passage and fold axis, but contrary to the inclination of the floor profile, this time in the direction towards the entrance A. Thus, it has proved impossible to find any reference surface in the stratification of the limestone that can be followed for more than about 100 m. The cross section of the passage varies in form, but unless it has been affected by fissures or downfalls, it often assumes the form of a circle or ellipse. The form is usually modified by fissures and thereby becomes elongated in their direction. At certain places the present subterranean brook has eroded a groove 0.5-2.0 m deep in the floor of the circular passage.

Between T and X the dip of the s-surfaces in the direction of the fold axes again shows higher values and the passage is lowered via three rapids some 13 m over a distance of 25 m. At U and V there are two ponds not quite two metres deep and with a diameter of some 5 metres. The two chambers with the ponds assume the shape of potholes. For the last 25 m before the first pond the passage zigzags which to a certain extent reminds one of a meandering system.

Between X and A the passage has resumed its almost horizontal direction but is interrupted between Y and Z by a collapse. At A, 45 m below the ground surface and about 85 m lower than the point A, the underlying bedrock consisting of phyllitic greenschist is laid bare for the first time. It is on this surface that the water runs when it finally disappears into the collapse accumulation from the collapse doline "Devil's Crater" about 10 m past AE. The passage broadens at Ä simultaneously as the height of the roof gradually decreases until it becomes so low that it is impossible to follow the main passage any longer. Immediately below AE its width is 7 m and its height slightly less than one metre. At AE the cave is connected to the 35 m "Devil's Crater", which is covered with snow during the major part of the year.

As mentioned earlier, the fossil systems differ from the main passage chiefly because of absence of running water. They consist of the so called "Lergrottan" (j-k-l) which is isolated but probably connected to the Sotsbäck Cave, to the passage system that is connected to the main passage at S and K, the chamber above T and also the system that is connected to the main passage at Ö. In addition, there are minor passages at the entrances C, E, F, H, I, P, Q and S. They all have one thing in common, they once functioned as drainage channels, but have since become dry. The appearance of the passages varies. If they have been developed in connection with fissures, which is very often the case with the passage system a-h, the passages are narrow and high. When they have mainly been created along bedding planes, they are often ellipse-shaped and elongated in the dip direction. They may, however, have been modified by small

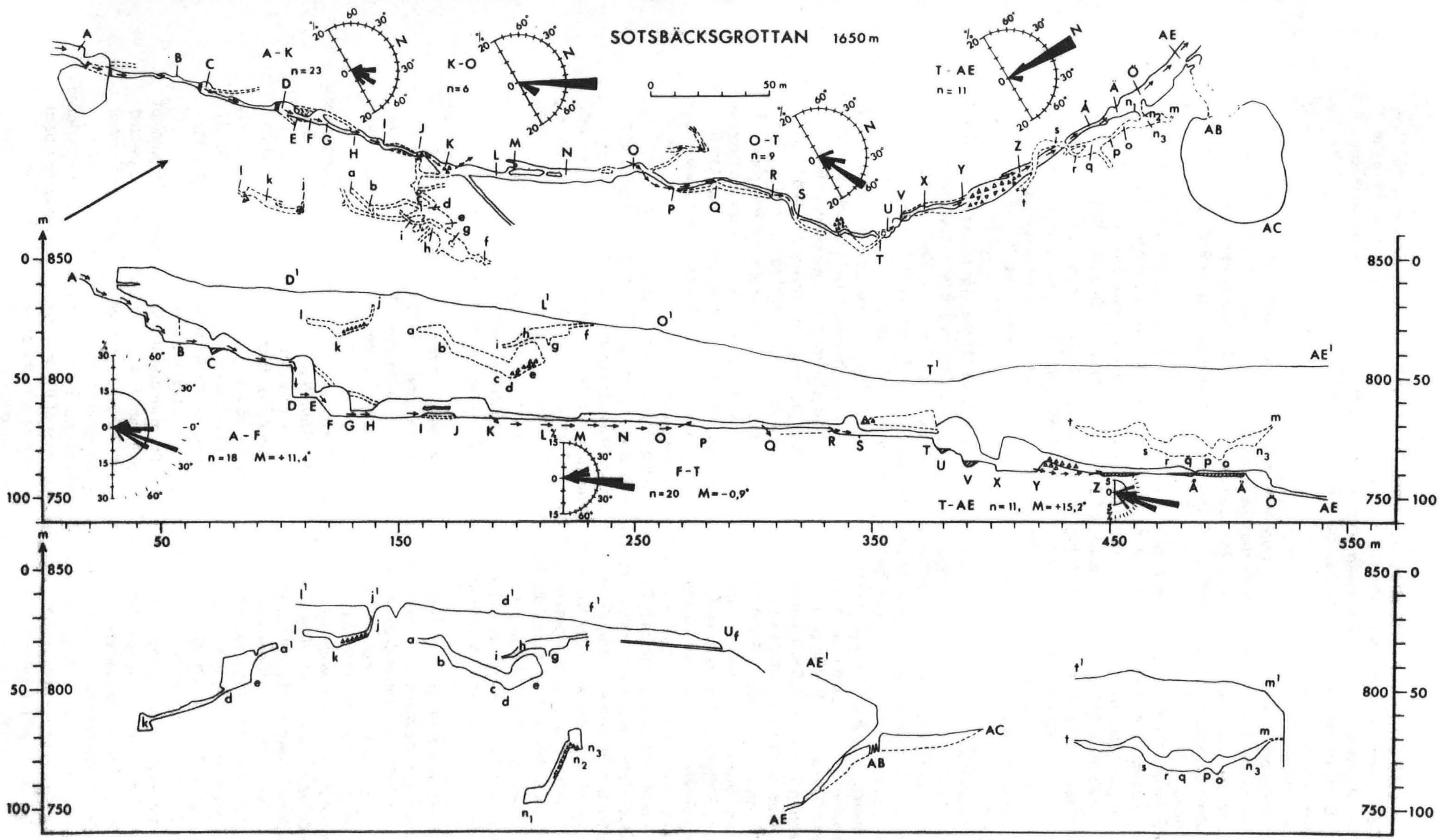


Fig. 4. Sotsbäcks Cave. Dotted lines indicate passages in a different orientation to the master passage A-AE. The rose diagrams above indicate the strike of the beds for the distances A-K, K-O, O-T and T-AE. The rose diagrams below indicate the dip of the bedrock in the direction of the fold axes for the distances A-F, F-T and T-AE. n denotes for the number of measurements and M the mean values of the dip. The arrows indicate water streams and the triangles collapse accumulations (Helldén 1974 b).

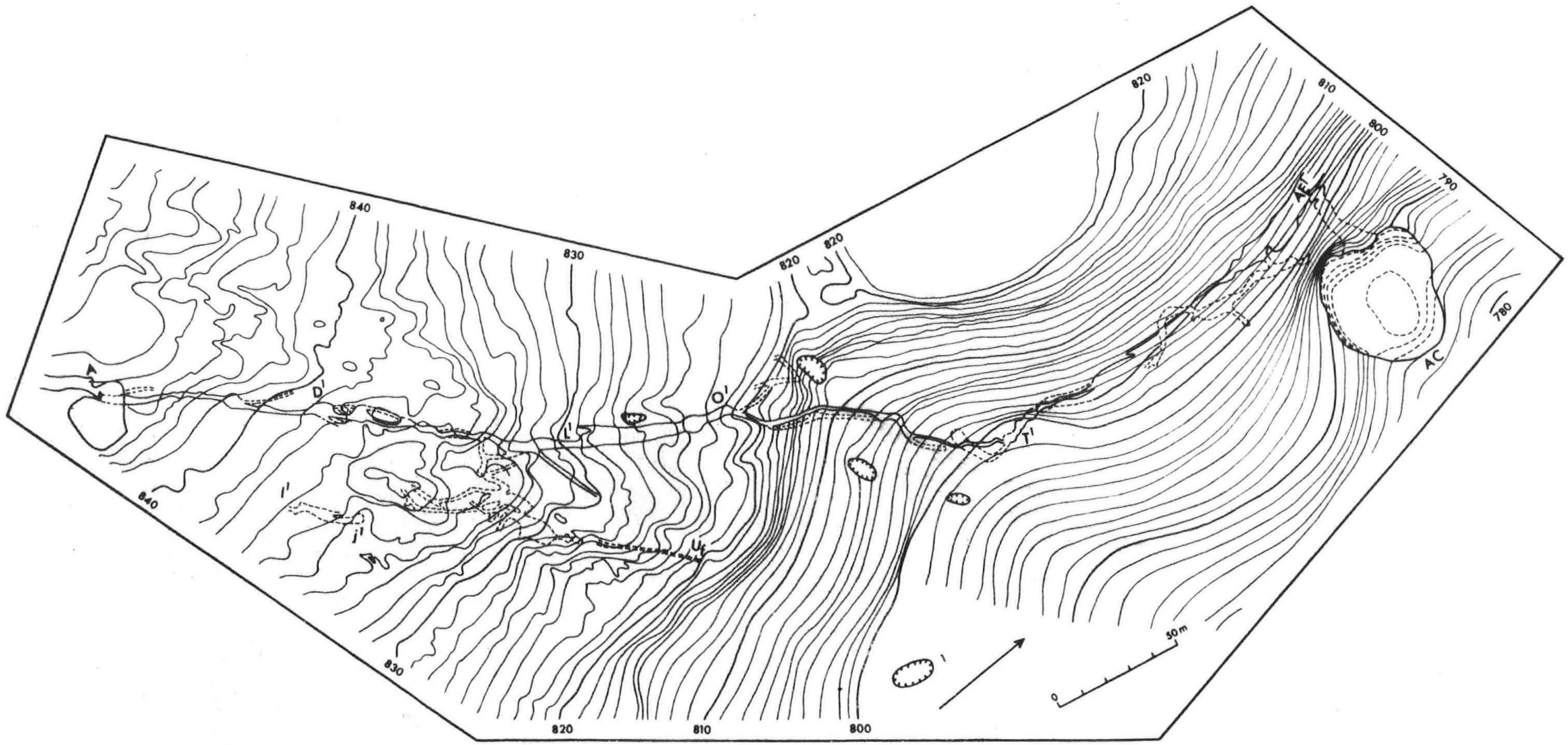


Fig. 5. The extension of the Sotsbäcks Cave system between inlet A and the "Devil's Crater" at AC. U_f= fossil karst spring; (1) very large karst depressions.

Fig. 1. The collapse doline Devil's Crater, July 1971.

Plate 1.

SOTSBÄCK CAVE

Fig. 2. Karst spring U_1 in the beginning of May.

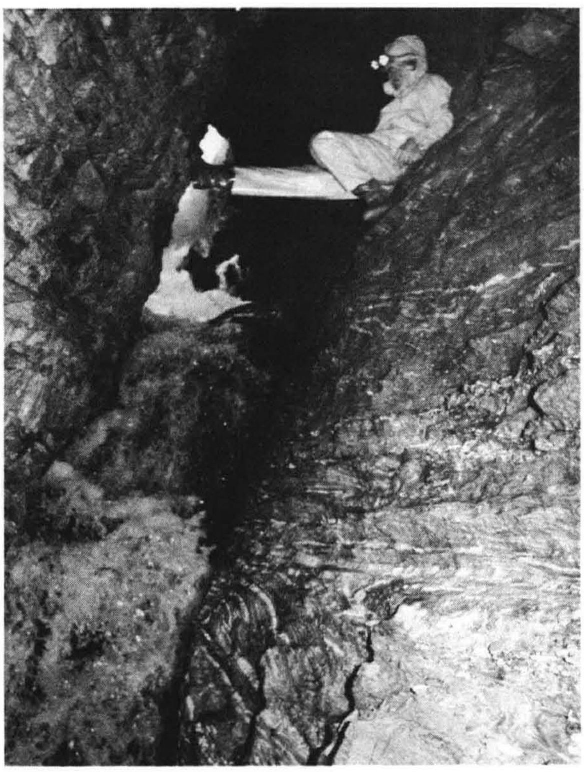


Fig. 3. Traversing just inside Sotsbäck Cave. Entrance visible in background.

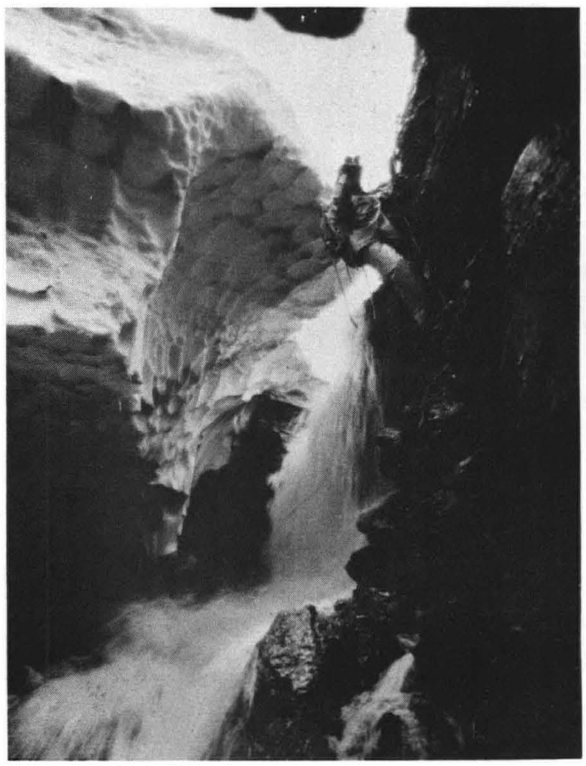


Fig. 4. The swallet entrance seen in early June.

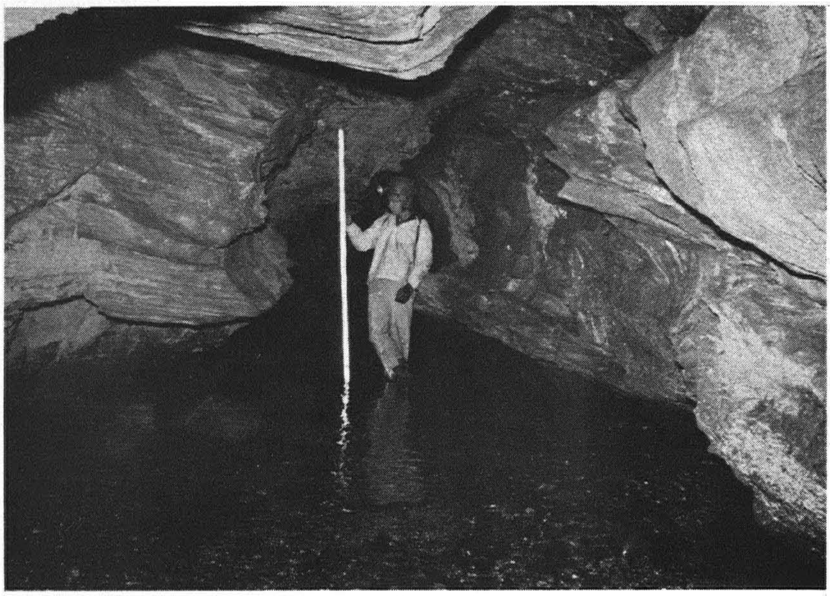


Fig. 1. A passage with both vadose and phreatic features.

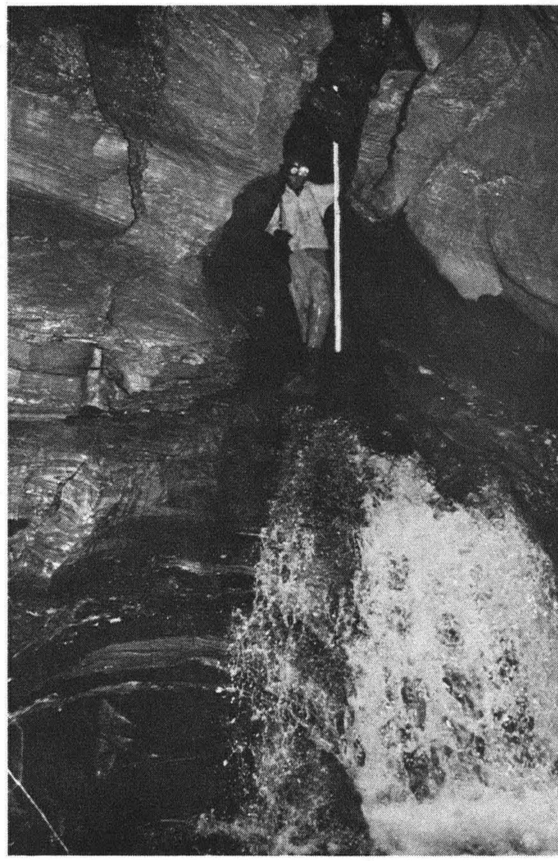


Fig. 2. A small cascade at point V on the plan.

Plate 2.

SOTSBÄCK CAVE

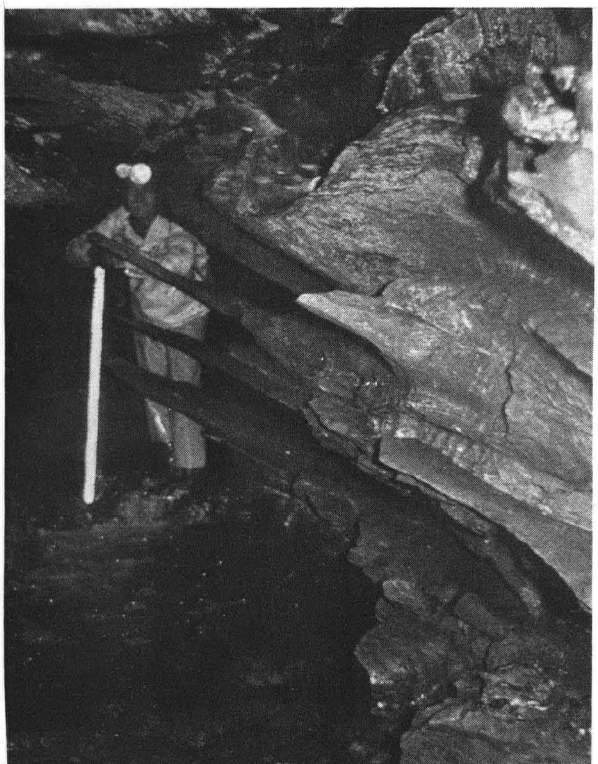


Fig. 3. Selective corrosion of limestone and schist.

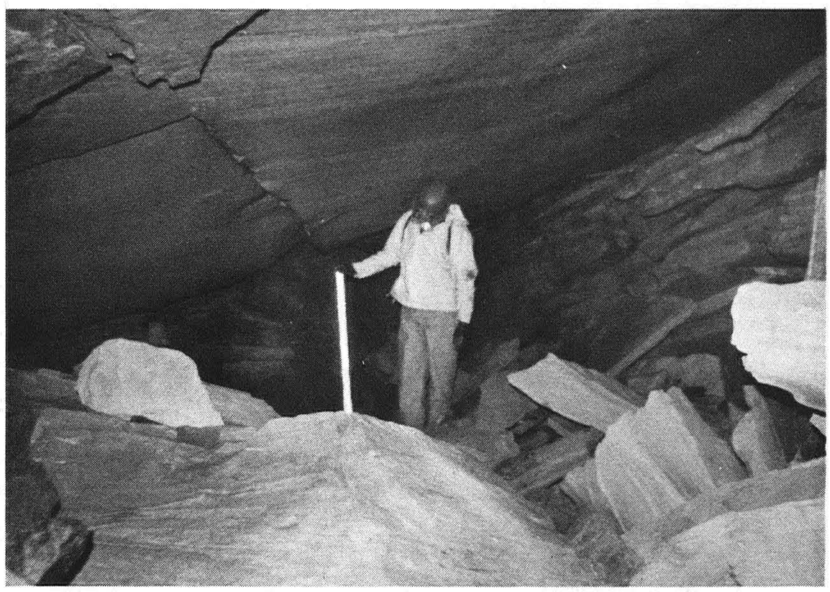


Fig. 4. Slab breakdown from the bedding at point AE.

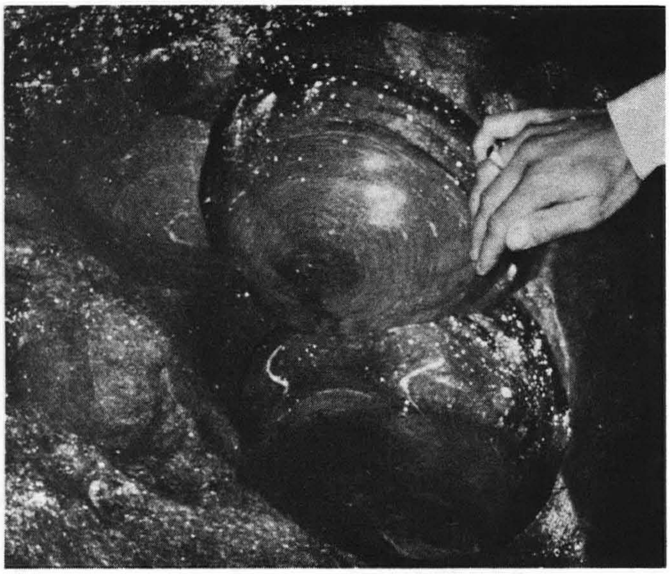


Fig. 1. Potholes developed in banded limestone.

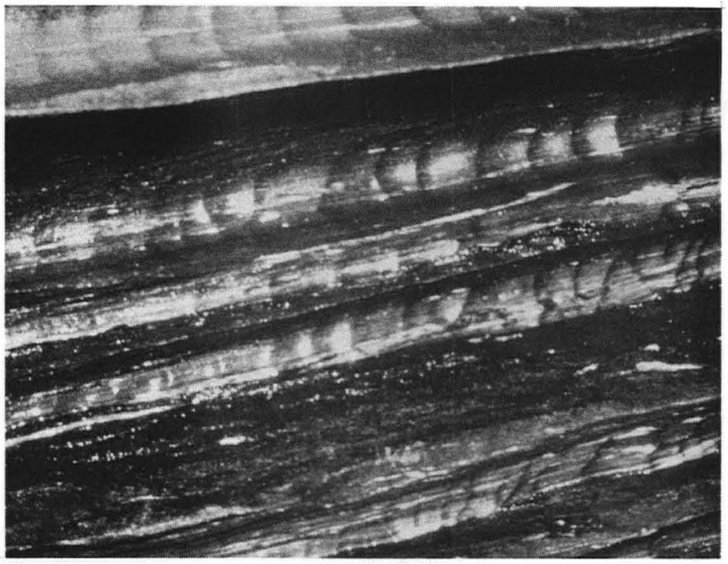


Fig. 2. Scalloped flutes developed in limestone with schist bands.

Plate 3.

SCTSBÄCK CAVE

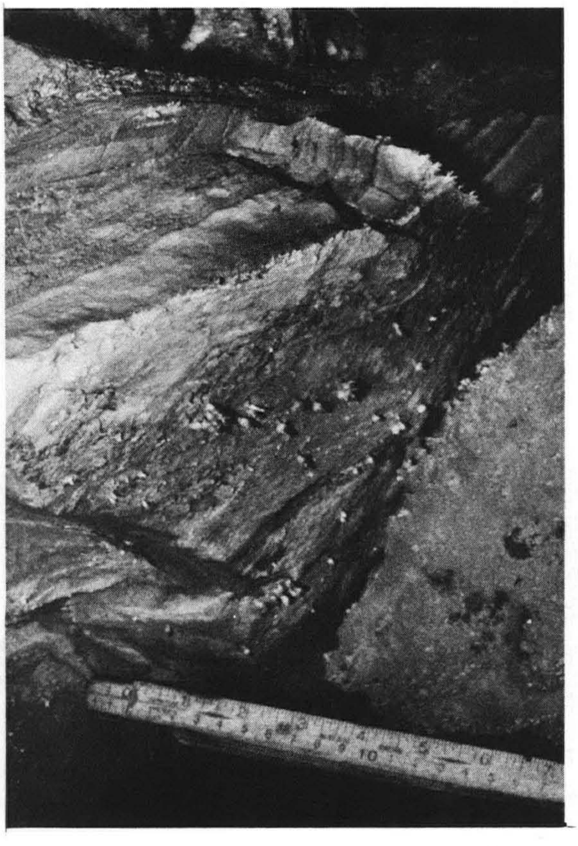


Fig. 3. "Popcorn" or cave coral on fallen blocks.

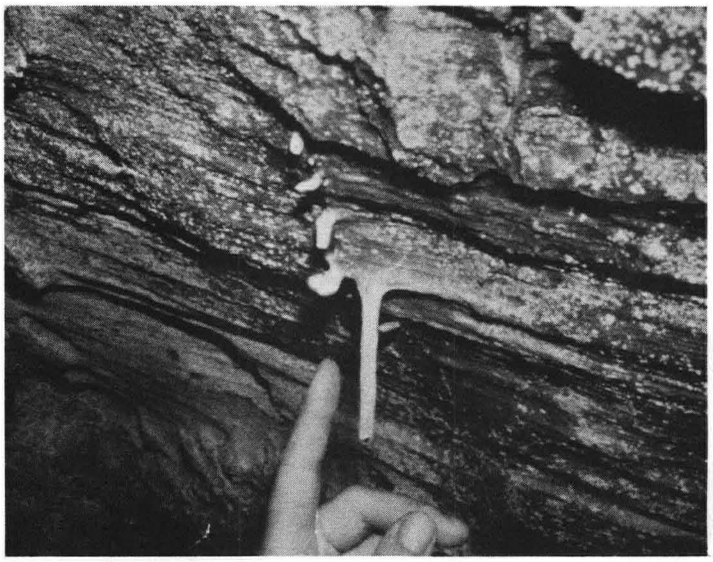


Fig. 4. Straw stalactite and small helictites.

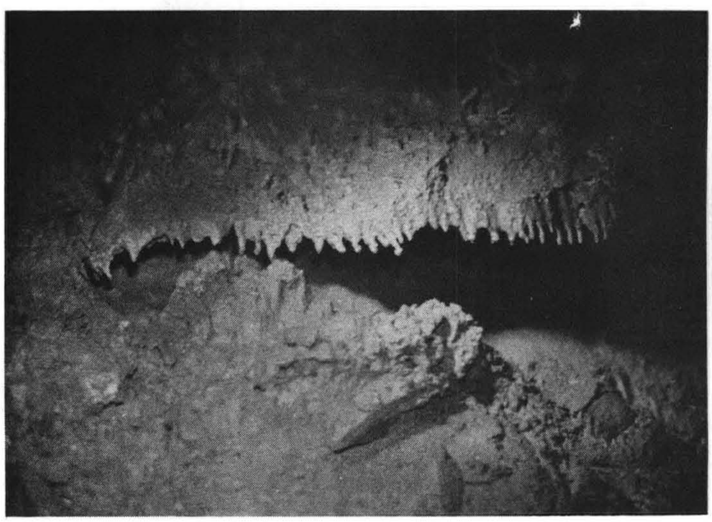


Fig. 5. Calcite deposits on an eroded mud bank.

collapses and then they have assumed a rectangular cross section. "Lergrottan" and the passages that probably connect the fossil outlet U_f with the inner fossil passage system, are mainly of the two latter passage types. Heavy collapses give rise to vaulted roofs since the effect of these is that as great a resistance as possible is obtained. The majority of the large chambers of the cave have some time or other been subjected to collapses, and therefore their roofs usually assume a more or less vaulted form. T may be cited as an example of the fossil system above. The passage system at Ö is a hybrid product and, accordingly, it has been affected by both joint cracks, bedding planes and collapses in the course of its formation. Large parts of the fossil systems are characterized by weathered walls with a coating of weathering residue 1-3 cm thick.

Erosional forms

The relative significance of corrasion and corrosion in the formation of caves and the erosional forms within caves has been discussed since the end of the 19th century (Davis 1930; Malott 1937; Jennings 1971). After measurements of transported sediments and corrosion in England, Newson (1971) arrived at the conclusion that mechanical erosion is of great importance when the main passages of a cavern are forming. This primarily applies to extremely high water discharges when the content of insoluble transported material in the water may exceed the chemical transport. The ample occurrence of circular passages and erosional phenomena of the same size and form on walls, floors and roofs in most caves, however, is interpreted as proof that chemical erosion far exceeds mechanical. The erosional forms found in the Sotsbäck Cave also speak in favour of the predominance of chemical erosion. Yet, certain phenomena suggest that the importance of corrasion must not be neglected. Although the water both at the inlet S_1 and outlet U_1 has been crystal-clear at every water discharge, large parts of the subterranean stream channel are covered by sand, gravel and well rounded stones and blocks. Most of this cover is made up of collapse material, which has been reworked by the water and consists of limestone, quartzite and schist.

The so-called cavitation process is probably of some importance when the morphology of the subterranean systems is developed both in phreatic and vadose circumstances. This process is based on the fact that when the water pressure falls below the vapour pressure, gas bubbles appear which could not develop under excess water pressure. Condensation of bubbles, which takes place by implosion, gives rise to a push wave with an eroding effect. Changes in pressure may be caused by fluctuations in the water velocity. Increased velocity results in decreased water pressure, while decreased water velocity gives higher pressure (Alonso et al. 1972). According to Hjulström's (1935) calculations the critical velocity value that the water has to reach to force the water pressure below its vapour pressure can be fixed at 12 m/s for zero degree water at 760 mm atmospheric pressure. Such high water velocities are very rare in nature but can be exceeded in rapids and waterfalls. According to Hjulström, water reaches a velocity of 15 m/s at a free fall of 11.5 m. Under high hydrostatic pressure the subglacial melt water may also, according to Hjulström, be expected to reach velocities faster than the critical cavitation velocity. In an underground drainage system there exist many possibilities of velocity and pressure changes in the water. The results of the cavitation process may therefore be expected to occur in connection with waterfalls and rapids, where narrow passages broaden or where fairly narrow water-bearing systems lead into passages of greater dimensions, provided that the changes in water velocity are sufficient. Therefore, the process may be complementary to the mixture corrosion introduced by Bögli (1964) and may probably give rise to the same kind of passage modifications as those described by him.

Apart from the passages themselves, the erosive forms comprise waterfalls, rapids, pot holes, scallops, solution pockets and cave karren.

Passages

Circular or elliptical passages have been developed under hydrostatic pressure. Owing to their form they offer the least possible resistance to water and have arisen when an original water-bearing fissure was widen symmetrically, mainly by corrosion. This type of passage is also named a phreatic passage (Lehmann 1932, Thrailkill 1968). According to Bögli (1965) the development of elliptical passages largely takes place when water of different hardness, partly from the main passage, partly from a fissure or bedding plane that intersects the main passage, is mixed resulting in the mixture corrosion (Mischungskorrosion). A fissure or bedding plane that intersects a circular passage, causes zones of weakness in the passage and therefore it is natural that the circle owing to selective erosion is transformed into an ellipse elongated in the direction of the fissure or bedding plane. Examples of circular and first and foremost elliptical passages are found between O and S and in the fossil system that joins the main passage at Ö.

At the moment the water level in a passage system is lowered and air can circulate above the water surface, the phreatic passage is transformed. Free running vadose water deepens the circular passages by both corrosion and corrasion. These gradually become more or less triangular, the apex of the triangle upwards, depending on how rapidly the water level is changed. Under certain circumstances a passage may retain its circular or elliptical form in its top portions, while the lower part is modified by erosion along fissures and/or bedding planes (Plate 2, fig. 1).

Waterfalls and rapids

Waterfalls and rapids are to be found at A-F, T-X and Ä-Ö in connection with the fact that the s-surfaces of the bedrock dip more steeply than usual in the direction of the fold axes. The erosion is both mechanical and chemical (Plate 2, fig. 2).

Potholes

Potholes have arisen in association with waterfalls and rapids. Among the largest ones the ponds U and V can be noted. In the inner parts of the fossil passage at C a number of potholes with a diameter of

0.4-0.8 m and a depth of about 1 m can be found, on the bottom where gravel, stones and blocks of greenschist and quartzite have been left. Therefore, mechanical erosion can have been of certain significance in their genesis. To which extent pebbles have contributed to the formation of the potholes is, however, very difficult to judge taking into account that there are features of almost corresponding size and form both on walls and roofs in certain sections of the cave (cf solution pockets) (Plate 3, fig.1).

Scallops

Scallops, usually 2-10 cm long and 2-3 cm deep, may occur in large groups on walls, floors and roofs in the Sotsbäck Cave. They are seen in both phreatic and vadose passages. Much has been written about the origin and varying size of the scallops. One author has, among other things, maintained the great importance of abrasion and that there is probably a connection between the size and age of the scallops (Maxon 1940; Davis 1963; Glennie 1963). However, after laboratory experiments it is possible to state that the distance between the ridges of the scallops is inversely related to water velocity (Curl 1966, 1973; Goodchild et al. 1971). It has also been shown that they can be developed without any influence of abrasion. In the Sotsbäck Cave the fact that one can find scallops on the roof of certain passages which, where form or size are concerned, do not differ from those developed on walls or floors, indicates that corrosive power is sufficient for their formation.

Scallop patterns developed in limestone strata and interrupted by more than half a metre of projecting thin layers of phyllitic greenschist, point to the same conclusion of solutional development (Plate 2, fig. 3; Plate 3, fig. 2).

Solution pockets

Solution pockets are small cavities, which in most cases occur in association with narrow cracks both on walls, floors and roofs. The diameter and depth vary between 5 cm and 50 cm. According to Bögli (1960) they have been formed by mixture corrosion under phreatic conditions. Vortices in connection with fissures and rough surroundings together with corrasive influence (very small) of suspended material may have been significant.

Cave Karren

By cave karren the author means karren grooves developed along some of the cave walls due to water trickling out of cracks, which is still aggressive enough to dissolve $CaCO_3$. They appear in great numbers between G and I.

Accumulative deposits

The accumulative deposits consist of allochthonous material, i.e. sediments that have been brought into the cave by vadose or phreatic water, and autochthonous material. Autochthonous material is material that originates in the limestone massif itself but has been redeposited in the cave. Among those are different types of limestone deposits, collapse accumulations and insoluble residual material left after the limestone has been dissolved.

Allochthonous material

The largest accumulation of allochthonous sediments is found in the fossil system connected to the main passage at Ö. Vast areas of the chamber more than 15 m long and 10-15 m wide at p-r are covered by 2-4 m sandbanks. The banks are neatly stratified and have also discordant layers. The soil particle size varies in the different layers between fine sand/very fine sand and coarse gravel. The major component, however, is coarse sand. The vertical walls in the blind side passage between p and q are covered from floor to roof by a sand layer of 3 cm to 50 cm thickness. The layer is neatly stratified and entirely intact, although the space between the walls of the narrow passage, which must have previously been filled with sand, can only have been eroded by running water or have been laid bare by some kind of collapse of the underlying strata. The strength of the sand layer is explained by the sand grains being cemented together by precipitated $CaCO_3$. The sediments have been transported to their position during an earlier phase of the history of the cave before the running water left the fossil systems and developed its recent drainage channels.

Clay material which has been brought into the cave by percolation water from the ground surface is something between allochthonous and autochthonous material. Clay material can be mixed with soil from the ground surface, fissures and weathered residuum left by solution of the limestone. This type of sediment is formed mainly in the parts of the cave that are situated nearest the ground surface, e.g. "Lergrottan" (Clay Cave) and parts of the fossil systems.

Weathering residuum

Weathering residuum is to be found in portions of the fossil systems occurring as 0.5-3 cm thick layers of varying colours and composition. In the fossil side-passage entering the main passage at C walls, floors and roofs are covered by a 2-3 cm thick yellow-brown layer of porous, water-bearing material. Below this the limestone assumes its normal appearance. The calcium content of the material is low (Table 2). The weathering matter is probably made up of residium developed when condensing water has dissolved the limestone. To a certain extent very slowly down-trickling percolation water have contributed to the solution and transport of $CaCO_3$. The whole weathering process has to take place extremely slowly so that the weathering matter may be left more or less in situ.

At the big collapse accumulation Y-Z, heaps up to one metre thick of an apparently grey, clayey and hydrated material can be seen. It has no sedimentary character but is rather granular and has in all probability developed in situ. Big blocks, stones and fragments of limestone and schist are embedded in the material. Blocks, stones and fragments of limestone are often covered with a 0.1-1.0 cm layer of phyllitic schist on the side facing towards the roof. After soil texture analyses of the "clayey" matter it proved to be sand-fine gravel. The weight percentage of material finer than fine sand amounted to nearly 40%, while the portion of coarse sand/fine gravel was more than 45%. The chemical composition is evident from Table 2.

Table 2. Chemical composition of weathering residium. (1) weathering residuum from the fossil side-passage at C; (2) weathering residuum from the collapse accumulation Y-Z.

Sample	% CaO	% MgO	%Fe_2O_3+ FeO	%CO_2	Misc. (inc. SiO_2,Na_2O,Al_2O_3)
1.	3.5	6.3	4.2	12.8	73.2
2.	6.3	3.9	4.7	6.6	77.5

Collapse accumulations

Collapse accumulations occur almost everywhere in the cave (Plate 2, fig. 4). They comprise everything from small stones and blocks fallen from walls and roofs to the collapse of huge roof sections.

The largest accumulations of collapse material can be found at Y-Z, the collapse funnel at Ö, which connects the main passage with the above fossil passage systems, and also at the connection between the "Devil's Crater" and the main passage. In these zones enormous limestone layers have loosened along the bedding planes, fallen onto the floor and broken into pieces. When parts of the collapsed matter have been dissolved and transported away, the result has been enlarged chambers often with vaulted roofs. Collapses at the cave entrance A and the collapse zone at Ö and the "Devil's Crater" are caused by corrosion and to a high degree by frost weathering. The temperature in these collapse zones is about 0°C during long spells in the six winter months.

Calcium carbonate precipitations

The most frequent calcium carbonate precipitation in the Sotsbäck Cave is the straw stalactite whose length ranges from 3 cm to 10 cm and diameter between 5 and 10 mm; there are also some helictites, or so called eccentric dripstones, to be seen (Plate 3, fig. 4). According to Moore (1954) helictites are created by water that trickles out of microscopic cracks under hydrostatic pressure. The flow velocity is so low that water drops are not formed, and therefore the force of gravity does not affect the precipitation of the calcium carbonate.

One more type of formation that is independent of gravity is represented by blocks and walls in parts of the fossil system connected to the main passage at Ö. In these places $CaCO_3$ precipitations, 2-3 cm high, consisting of red-yellow spheres with a diameter of 3-7 mm have been formed. The spheres are fastened to the bedrock with tapering stalks. The stalks are only about one mm thick at their base. Similar formations have been described under the name of "cave coral" or "popcorn" by among others Thrailkill (1965) and they are supposed to be genetically closely related to helictites (Plate 3, fig. 3). $CaCO_3$ precipitations on clay and sand in the shape of cm-long stalactite formations are not uncommon (Plate 3, fig. 5).

The majority of the $CaCO_3$ precipitations found in the cave occur between Y and Å and in the fossil system situated above Ö. The total number of stalactites has been estimated at over 200, with an average length of about 10 cm. Only one stalagmite, between s and t, has been found and its height is about 10 cm.

The climate of the cave

During the summer months the temperature along the main passage A-AE ranges from 5 to 10°C with a mean value of ca +8°C just before the waterfall D. Then, the temperature drops slowly and at Ä it varies between 4-5°C. The inner parts of the cave are strongly affected by cold air, which makes its way down from the snow covered "Devil's Crater". The air humidity along the main passage shows values between 90 and 100%. During measurements in the winter of 1970 the temperature was almost stabilized at +2°C apart from the entrance and the innermost parts, where it fluctuated around zero. During the same period the air humidity was ca 90%. During the winter and summer the fossil system had temperatures of 0-3°C and an air humidity of 80-90%.

When visiting the cave at the beginning of December 1970 and 1971 it was almost filled with snow up to the roof for a distance of ca 30 m from the entrance. Between the snow surface and the roof there was a narrow warm-air channel which conveyed warm air towards the entrance.

Discussion and comparisons

There is no reason for assuming that the different levels of the cave, represented by the older fossil systems and the younger main passage, are the result of two different phases in the development of the cave. Owing to the position and morphology of the passages and the strike and dip of the bedrock one may presume that the water, when erosion had continued by stages, eroded deeper down in the dip direction of the layers along fissures and bedding planes and eventually rendered the upper passage systems quite dry. At the moment when the passages with phreatic origin became so wide that their water-bearing capacity exceeded the water supply, their form were modified by vadose water and the erosion was concentrated on their floors, which has contributed further to the fact that the higher passage systems were left without water. It has been impossible to relate the levels of the passage systems to fluctuations in the erosion base level, as has been the case in karst areas, e.g. in England and in Czechoslovakia (Warwick 1960; Waltham 1971; Stelcl 1963).

Comparing Sotsbäck Cave with the caves on Torne Träsk described by Rasmusson (1957) there is conformity regarding morphology and the dependence of the caves on fissures and bedding planes. Rasmusson thinks that the main phase of the development of the Lullihatjårro Cave in all probability dates from the recession period of the latest inland ice.

The Norwegian karst caves are considered to have arisen during or after the latest glaciation (Oxaal 1914, 1918; Horn 1935, 1947; Hjorthen 1968). The presence of ground water circulation in limestone in a permafrost environment has been proved on West Spitsbergen by among others Orvin (1944) and Baranowski (1973). The large sedimentary accumulations in the Sotsbäck Cave indicate that parts of the fossil passage systems took on their recent dimensions during or before the end phase of the recession of the inland ice from the area, when sediment-bearing water was abundant.

A rough estimation of the maximum age of the cave can be obtained in the following way. The total length of the passages between A and AE is ca 1500 m. The average width has been estimated at 5 m and the height at 4 m, which results in a cubic content of ca 30 000 m^3. If the cave is supposed to have the same proportions all the way to the outlet U_1 and the underground drainage distance between the swallet S_1 and the outlet U_1 is supposed to be 5000 m (the horizontal distance S_1-U_1 is 2200 m), i.e. 10 times longer than the distance A-AE, the total volume of the cave between inlet and outlet will be 300 000 m^3. If one takes the monthly chemical transport from the area in August (Table 1), when the content of percolation water in the drainage system is exceedingly small and, accordingly, the major part of the $CaCO_3$ that has been transported out at U_1, has been dissolved along the main passage, the transport per annum can be estimated at 10 m^3.

On these assumptions the water would need 30 000 years to excavate the cavern. This figure is highly exaggerated, since measurement of the cave volume is probably exaggerated, the chemical transport is rather on the small side and since the significance of the mechanical erosion has not been taken into consideration. The main phase of the development of the cave can, therefore, be assigned to the late and post-glacial time in all probability. However, the initial phase of the origin of the cave can be put at a considerably earlier date.

It is very difficult to form an opinion of the duration of this phase, when extremely small quantities of water could penetrate through hydrographically active cavities in the bedrock. The above mentioned estimation of the maximum age of the Sotsbäck Cave presuppose that this initial phase has already been passed.

M.S. Received December 1974.

Ulf Helldén,
Naturgeografiska Institutionen,
Lunds Universitet,
Sölvegatan 13, S-223 62,
Lund, Sweden.

REFERENCES

Alonso, M., Finn, E.J. 1972. *Fundamental University Physics.* Part I, Mechanics. Addison Wesley Publ. Corp. pp.271-275.

Baranowski, S. 1973. Verbal communication.

Bögli, A. 1960. Kalklösung und Karrenbilding. *Zeit. f. Geomorph.* N.F. Supp.2, pp.4-21.

1964. Mischungskorrosion- ein Beitrag zur Verkarstungsproblem. *Erdkunde,* 18, pp.83-92.

1965. *The role of corrosion by mixed water in cave forming.* In: *Problems of the speleological research.* Proc. Int. Speleol. Conf., Brno 1964 (Ed. O. Stelcl). pp.201-208.

Corbel, J. 1957. *Les Karsts du nord-oest de l'Europe.* Mem. Institute Etudes Rhodaniennes de l'Université de Lyon. Nr 12, 544 pages.

1960. Nouvelles recherches sur les karsts arctiques Scandinaves. *Zeit. f. Geomorph.* N.F. Supp.2, pp.74-78.

Curl, R.L. 1966. Scallops and flutes. *Trans. Cave Res. Group G.B.,* Vol. 7, No. 2, pp.121-160.

1973. *Deducing flow velocity from scallops.* In: Int. Speleol. 1973, Abstracts of papers (Ed. V. Panos). Palacky University, Olomouc, page 98.

Davies, R.E. 1963. Flow markings. *Cave Res. Grp. of G.B., Newsletter* 87, pp.8-9.

Davis, W.M. 1930. Origin of limestone caverns. *Bull. Geol. Soc. Am.,* 41, pp.475-628.

Freij, Y., Linden, A., & Sjöberg, R. 1971. Sveriges 20 längsta grottor 1970. *Grottan. Org. f. SSF.* Nr 3 page 8.

Glennie, E.A. 1963. Flow markings. *Cave Res. Grp. of G.B. Newsletter* 87, pp.8-9.

Goodchild, M.F., Ford, D.C. 1971. Analyses of scallop patterns by simulation under controlled conditions. *Jour. Geol.* 79, pp.22-37.

Helldén, U. 1973. Limestone solution intensity in a karst area in Lapland, northern Sweden. *Geografiska Annaler,* Vol. 55A, Nr. 3-4, pp.185-196.

1974 a. The hydrology and morphology of a karst area in Swedish Lapland. *Trans. British Cave Research Association.* Vol. 1. No. 1, pp.43-53.

1974 b. Karst. En studie av Artfjällets karstomrade samt jämförande korrosionsanalyser fran Västspetsbergen och Tjeckoslovakien. *Med. fran Lunds Universitets Geografiska Institution. Avhandlingar* LXXII, 192 pages.

Hjorthen, P.G. 1968. Grotter och grotteforskning i Rana. *Norges Geol. Unders.* Smaskrift nr 9. 40 pages.

Hjulström, F. 1935. *Studies of the morphological activity of rivers as illustrated by the river Fyris.* Almqvist & Wiksell. Uppsala. pp.305-320.

Horn, G. 1935. Uber die Bildung von Karsthöhlen unter einem Gletscher. *Norsk Geogr. Tiddskrift,* 5, pp.494-498.

1947. Karsthuler i Nordland. *Norges Geol. Unders.* Nr 165, 77 pages.

Jennings, J.N. 1971. *Karst. An Introduction to Systematic Geomorphology.* M.I.T. Press. 252 pages.

Kulling, O. 1955. Beskrivning till berggrundskarta över Västerbottens län. Sveriges Geol. Unders. Ser. Ca, No 37, del 2 pp.105-287.

Köppen, W. 1936. *Das geographische System der Klimate.* 44 pages in: Köppen-Geiger, *Handbuch der Kilmatologie.* Bd. 1, teil C, Berlin.

Lehmann, O. 1932. *Die Hydrografie des Karstes.* Franz Deuticke. Leipzig und Wien. 212 pages.

Malott, C.A. 1937. Invasion theory of cavern development. *Proc. Geol. Soc. Am.* for 1937, page 323.
Maxson, J.H. 1940. Fluting and facetting of rock fragments. *Jour. Geol.* 48, pp.717-751.
Moore, G.W. 1954. The origin of helictites. *Nat. Speleol. Soc.* Occ. Papers 1.
Newson, M.D. 1971. The role of abrasion in cavern development. *Trans. Cave Res. Grp. of G.B.*, Vol. 13, No. 2, pp.101-107.
Orvin, A.K. 1944. Litt om kilder pa Svalbard. *Norges Svalbardog Ishavsundersökelser* 57, 24 pages.
Oxaal, J. 1914. Kalkstenshuler i Ranen. *Norsk Geol. Unders.* 69, 46 pages.
1918. Huler av Grönlitypen. *Norsk Geol. Tidskr.* 5, pp.1-5.
Rasmusson, G. 1957. Formproblem i nagra karstgrottor inom Torneträskomradet. Lic. avh. Naturgeografiska Inst. Lunds Universitet. Unpublished. 224 pages.
Sjöberg, R. 1970. Ovre Altsvattenexpeditionen 1970. S.S.F. (Swedish Speleological Society) Komp.
Stelcl, O. 1963. Höhlenniveaus des "Suchy zleb" im Mährischen Karst. *Die Höhle,* 14, Heft 1, pp.1-10.
Sweeting, M.M. 1972. *Karst landforms.* Macmillan Press, London and Basingstoke. 362 pages.
Thrailkill, J.V. 1965. Origin of cave popcorn. *Bull. Nat. Speleol. Soc.* 27, 2, page 59.
1968. Chemical and hydrological factors in the excavation of limestone caves. *Bull. Geol. Soc. Am.*, 79, pp.19-45.
Waltham, A.C. 1971. Controlling factors in the development of caves. *Trans. Cave Res. Grp. of G.B.* vol 13, No.2, pp.73-80.
Warwick, G.T. 1960. The effect of knick-point recession on the watertable and associated features in limestone regions, with special reference to England and Wales. *Zeit. f. Geomorph.* N.F. Supp.2, pp.92-97.

Trans. British Cave Research Association. Vol. 2. No. 1. pp.29-34. April 1975.

THE USE OF SATURATION INDEX AND POTASSIUM-SODIUM RATIO AS INDICATORS OF SPELEOLOGICAL POTENTIAL WITH SPECIAL REFERENCE TO DERBYSHIRE.

by Noel Christopher

Summary

The fundamental basis of the saturation index and potassium-sodium ratio are examined to discover if they will serve as hydrogeochemical indicators for speleological reconnaissance.

It is found that both parameters have considerable potential in this respect, and an indication is given of how to interpret the results obtained from field work.

INTRODUCTION

1. Saturation Index

A saturation index was first proposed by Langelier (1936) to relate the degree of saturation of a natural water with respect to calcium carbonate, to its tendency to be scale forming or corrosion.

The index is defined as:

$$SI = pH - pH_s$$

where pH = the pH of the water under examination

and pH_s = the pH of the water when just fully saturated with respect to Calcium Carbonate.

pH_s was defined as

$$pH_s = pK_2 - pK_s + p(Ca) + p(Alk)$$

where p = an operator indicating the logarithm of a reciprocal.

K_2 = the second dissociation constant of carbonic acid.

K_s = the solubility production of calcium carbonate.

(Ca) = the molar concentration of calcium in the water.

(Alk) = the titratable alkalinity of the water.

The initial index as proposed suffered from two drawbacks: (a) inaccurate values of K_2 and K_s, and (b) no allowance was made for the effect of variations in ionic strength of the solution, as K_2 and K_s, were defined in terms of molarity not activity.

Several papers have recently been published which correct these deficiencies (Jacobson 1972; Picknett 1973; Christopher 1974), and the values of K_2 and K_s are now accurately known for the temperature ranges encountered in karst studies, and variations in ionic strength can be taken into account.

Jacobson and Langmuir (1972) have used a computer program to calculate values of the saturation index. Picknett (1973) has criticised the constants used by Jacobson and Langmuir as being inaccurate. However, Christopher (1974) has shown that the effect of using Picknett's constants instead of Jacobson & Langmuir's is to increase the saturation index by a maximum of 0.04 units at 10°C. Picknett (1973) has given a table of saturation pH values for a range of calcium concentrations and temperatures and it is easy from these to plot graphs of pH_s against calcium concentration and to read off pH_s for a particular water under consideration. Picknett's values are accurate for pure calcium bicarbonate solutions, but natural waters often contain other ions which will effect the ionic strength of the solution and thus pH_s. Normally the total dissolved solids of karst waters will be principally calcium bicarbonate, and the effect of other ions on its ionic strength will be small and usually less than 0.002 units, increasing pH_s by approximately 0.02 units; therefore, the error introduced into pH_s determinations by assuming the total dissolved solid content to be wholly calcium bicarbonate is also small.

Picknett (1972) has also shown that the presence of small amounts of magnesium can have an effect on pH_s. He found that at low percentages of magnesium relative to calcium, pH_s was depressed reaching a maximum depression of 0.05 pH units at 5% magnesium, and from this value as the percentage of magnesium increased pH_s was also increased. At 13.2% magnesium the suppression was annulled, and the enhancement had reached 0.10 pH units at 30% magnesium.

In Derbyshire waters a magnesium percentage of 5-10% is usual and from above figures it can be seen that the effect on pH_s will therefore be slight and less than 0.05 units. The effect of a depression of pH_s on the saturation index will be to increase the index, and the converse is obviously true for an enhancement of pH_s. A negative index means that the water is under-saturated with respect to calcium carbonate, due to the presence of free carbon dioxide in the water. If the water is in a totally enclosed conduit then this free carbon dioxide cannot escape and dissolution of the limestone occurs until the equilibrium pH is achieved. Because of the high soil air carbon dioxide content percolation water is usually very rich in dissolved carbon dioxide which cannot escape until it reaches a void with a free air surface, and the air in contact with the water has a lower partial pressure of carbon dioxide than the water. When this occurs the pH rises and the saturation index also increases and eventually becomes positive. These conditions occur when karst water flows along an open passage and results given in table 1 taken from Jacobson and Langmuir (Jacobson 1972) illustrate this.

Table 1 (after Jacobson & Langmuir 1972)

Reference of Resurgence	Saturation Index	Type of Resurgence
NYSP1	+ 0.381	Open
NYSP3	+ 0.263	Open
NYSP6	+ 0.323	Open
NYSP2	– 0.498	Flooded
NYSP4	– 0.057	Flooded
NYSP5	– 0.169	Flooded

The implications of these results for speleological reconnaissance are discussed later.

2. Potassium—Sodium Ratio

It is well established that the alkali metals in aqueous solution are subject to selective ion exchange reactions, when the solution is in contact with clay minerals. The tendency for absorption increases with increasing atomic number and also depends upon the type of clay mineral (Edmunds, 1971, p.22). The order of absorption intensity is usually given as

$$Li^+ < Na^+ < K^+ < Rb^+ < Cs^+$$

that is: lithium is the least absorbed ion and caesium the most strongly absorbed.

Lithium, rubidium and caesium are present only in very small amounts in natural, non-thermal, waters. The average concentrations found by Edmunds (1971, p.22) varied from 17 μg/l for lithium to 0.1 μg/l for caesium. It is just about feasible to measure these levels of lithium by flame emission spectrometry but one has to resort to neutron activation analysis to determine rubidium and caesium at these levels. This obviously renders these latter elements useless for the purpose of routine study; also the low levels of lithium render it less than ideal for this purpose.

Sodium and potassium occur in natural waters to a much greater extent; sodium values of up to 20 mg/l are common and can be much higher, especially in thermal waters. Potassium occurs to a smaller extent than sodium, but concentrations of 1-5 mg/l are common, and up to 10 mg/l are not unknown. Holden stated (1970, p.5) that in natural waters the sodium concentration does not usually exceed 30 mg/l and the potassium concentration usually does not exceed 10-15 mg/l. These concentrations are easily determined by flame emission spectrometry to a good degree of accuracy.

Goldschmitt (1950, p.51) has pointed out that, whereas the amount of sodium and potassium brought into circulation by weathering is roughly equal, the amount of sodium still in circulation, as represented by the average composition of sea water, is much g reater than the amount of potassium (Table 2). This is due to the selective absorption of potassium from solution on to clay minerals.

Table 2 (after Goldschmitt, 1950, p.51)

	Brought into circulation	Still present in sea water	% remaining of original
	gm/kg Sea Water		
Sodium	16.9	10.7	64.6
Potassium	15.0	0.37	2.5

The amount of potassium relative to sodium can be expressea as a percentage by weight ratio, and figures given by Goldschmitt (1945, p.159) show that during the process of weathering and transport of the decomposition products of magmatic rocks to the sea, potassium is steadily lost and the ratio of potassium to sodium steadily decreases (Table 3).

Table 3 (after Goldschmitt, 1954, p.159)

	$\frac{K}{Na}$ % by Wt.
Magmatic Rocks	91.9
Rivers and Lake Water	40.7
Sea Water	3.56

The concentration of potassium by ion exchange in clay minerals is illustrated by the analysis figures given in Table 4. These show that the concentration of potassium in shale and mud is 2-3 times the concentration of sodium and that the concentration of potassium remaining in the sea is only one hundreth of that present in the mud.

Table 4 (after Goldschmitt, 1954, p.159)

	% by wt. K	% by wt. Na	Ratio K/Na 1:
Sea Water	0.037	1.07	0.035
Terrigenous Muds (AV.52 samples)	1.87	0.79	2.37
Shales (AV.78 samples)	2.70	0.76	3.55

The average concentration of potassium relative to sodium for inland waters (rivers and lakes) of the world has also been calculated from figures given by Goldschmitt (1954, p.51) and these are presented in Table 5.

Table 5 (after Goldschmitt 1954, p.51)

Continent	Na % by wt.	K % by wt.	K % by wt. Na
North America	7.46	1.77	23.7
South America	5.03	1.95	38.8
Europe	4.32	2.75	63.7
Asia	5.98	1.98	33.1
Africa	4.90	2.35	48.0
Average all continents	5.79	2.12	36.6

As can be seen the percentage ratio of potassium—sodium varies quite widely and is surprisingly high for European inland waters, but the average is 36.6 for world waters.

No mention is made by Goldschmitt of the potassium—sodium radio of underground waters, so the author has carried out a search of the available literature for data and the results are presented in Table 6, together with experimental results obtained by the author for resurgences and surface streams in Derbyshire and North Cheshire. During this search the author found many more water analyses than those used in table 6, but in many cases either potassium or both sodium and potassium concentrations were not given. Additional figures were taken from Holden (1970, p.24).

Table 6

Source	Type of Water	No. of Samples	% K Na Mean	Range of % K values Na
Edmunds 1971	Streams on shale or grit	10	34.1	11.1 – 92.0
	Limestone resurgences	31	19.3	3.1 – 54.4
	Soughs draining mostly limestone	13	10.5	2.3 – 18.0
	Thermal resurgences	14	6.8	2.2 – 20
Author	Surface streams on shale or grit	20	26.9	11.8 – 57.6
	Limestone resurgences	9	13.5	5.2 – 18.8
Holden 1970	Chalk springs and bore holes of South East England	21	12.2	3.8 – 28.6
	Greensand springs and bore holes	13	15.7	3.4 – 27.3
	River Dee at Chester	Average of many	27.0	not known
	River Thames	Average of many	20.4	not known
	River Lee	Average of many	20.3	not known
	New river (contains some chalk water)	Average of many	16.9	not known

Table 7 (after Holden 1970, p.24)

Variation of Potassium to Sodium Ratio with Depth in a Well Sunk in Triassic Sandstone near Bridgnorth.

Depth (Meters)	$\frac{K}{Na}$ % by wt.
70 – 125	25
210	4.8
245	8.0
270	2.4
330	0.7

3. Discussion of Potassium–Sodium Ratio

The results given in Tables 6 and 7 show very clearly that the ion exchange process continues when the water passes underground, and that the longer the water remains underground, and the greater the depth the water reaches the lower the potassium–sodium ratio becomes. This conclusion is most clearly shown by Edmunds' results and is fully supported by the author's own results.

Edmunds' results show that the ten surface streams he sampled (Table 6) had an average potassium–sodium ratio of 34.1% which is very close to the world average whereas the limestone resurgences have a lower ratio of 19.3%. Soughs which will contain a higher amount of percolation water have an even lower potassium to sodium ratio of 10.5% and thermal waters which will have spent many years below ground have the lowest potassium–sodium ratio of 6.8%. Tritium analysis of some of the resurgences show the water to be at least 20 years old.

The potassium content of water in chalk aquifers relative to sodium is 12.2% and that in greensand aquifers 15.7%; this probably reflects the higher porosity and therefore lower retention time in the latter aquifer, and these are lower than the Thames and Lee rivers which rise and flow on chalk or greensand.

The author's results, whilst showing the same trend as those discussed above, differ in absolute values quite considerably from those of Edmunds, and show a lower variability, especially those from the limestone resurgences. This is probably because the author's samples were all taken in conditions of comparable flow, and at a different level of flow to those of Edmunds. Edmunds' samples were taken at three different times of the year, and presumably under very different flow conditions. Unfortunately, Edmunds does not state clearly when his samples were taken or at what stage of flow.

The results for the surface streams show that a ratio of potassium–sodium of between 20 and 35% can be expected for surface streams in the southern part of Britain, whilst in Derbyshire a value of between 26.9 and 34.1% is to be expected. It is interesting to note that these values are very much lower than the percentage ratio of potassium to sodium present in the rocks over which the streams flow (Table 4). Further it is interesting to note that the highest value recorded of potassium to sodium ratio (92.0%) is very close to the maximum one would expect from the composition of magmatic rocks of 91.9% potassium to sodium ratio. To illustrate the grouping of the results, it would have been possible to calculate standard deviations and hence 68 or 95% confidence limits. However, it was considered that, because of the heterogenous nature of the results, these confidence limits would be largely meaningless. Instead a histogram analysis of the results has been carried out and these are illustrated in figures 1 to 8.

These results show that for surface streams and resurgences of Derbyshire the majority of results fall within a narrow range of potassium to sodium ratio. Fig. 1 shows that, of Edmunds' results for Millstone Grit and Shale, 70% of the results fall between 20 and 35% potassium to sodium ratio, and, but for a single result at 92%, the mean value would be 27.6% much closer to the result obtained by the author.

Fig. 2 shows that, of Edmunds' results for limestone resurgences, 61% lie between 0 and 15% potassium–sodium ratio, and a further 22.5% lie in the range 25-35%. This probably reflects the existance of two classes of resurgences, one class with relatively long flow-through times, giving low potassium–sodium ratios, and the other class with rapid flow-through times, giving potassium–sodium ratios close to those values found in surface streams. The existance of two classes of resurgences is supported by the results from soughs and thermal resurgences, where all the results are within the band, 0-20%. The results from the soughs, which are already stated, one would expect to be carrying largely percolation water, are fairly evenly spread with some concentrations in the range 5-10%. The thermal waters which will have been underground for a very long period 86% of the results are in the range 0-10% potassium to sodium ratio.

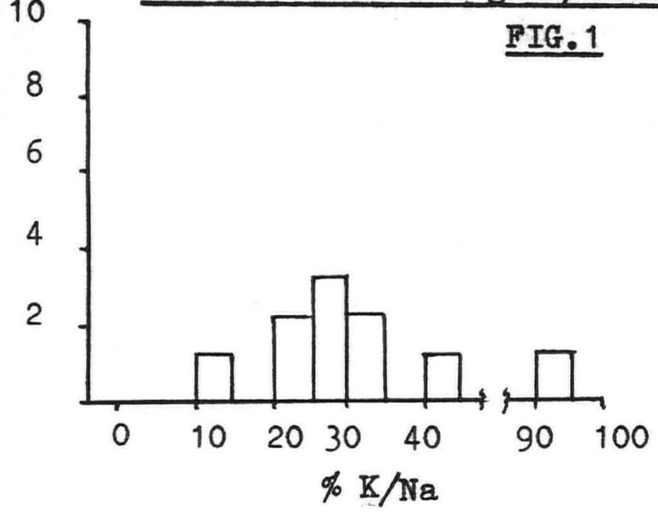
The results shown by Figures 5 and 6 are fully consistent with those conclusions; 75% of surface streams lie between 10 and 30%, and 88% of the results from limestone resurgences are between 5 and 20% potassium–sodium ratio.

The results from the chalk springs and boreholes are also consistent with these conclusions (Fig. 7), 71% falling between 0 and 15% potassium–sodium ratio, and a further 24% in the range 20-30%. Although the absolute values have decreased somewhat this is only to be expected with a material with higher primary porosity such as chalk, and a lower potassium to sodium ratio for surface rivers. The results for a greensand aquifer are more evenly spread, (Fig. 8), with some preference for the range 15-30% potassium–sodium ratio.

It can be seen from the histograms that the number of samples in some groups are small because of the size of the sample population, and so it would be unwise to be dogmatic in interpretation at this stage. However, the results of three separate authors for several types of geological strata conform to the overall

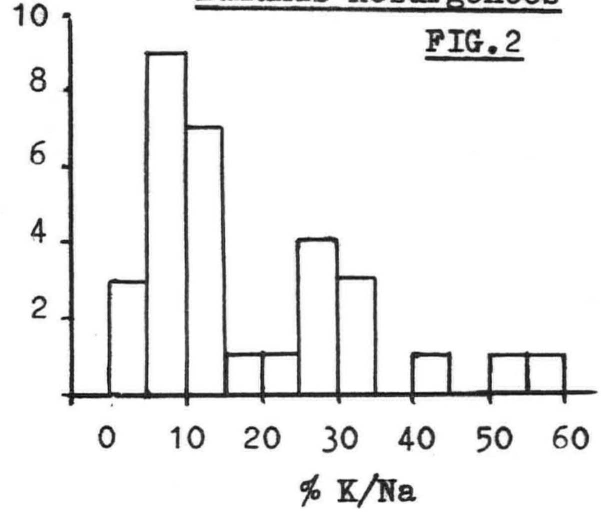
Edmunds Millstone grit/shale

FIG.1



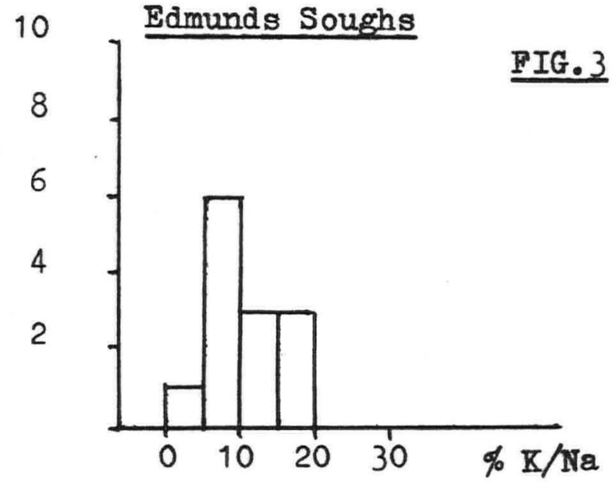
Edmunds Resurgences

FIG.2



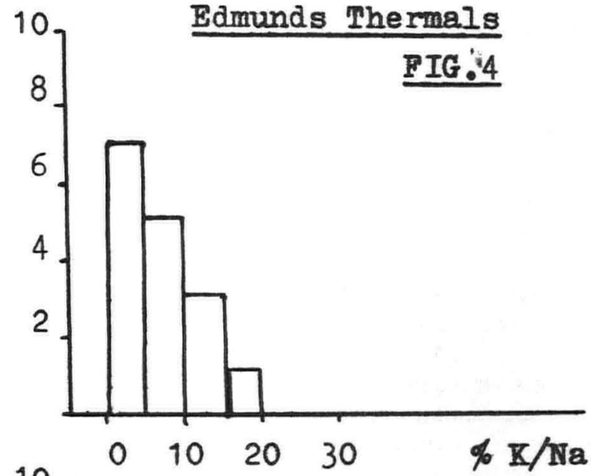
Edmunds Soughs

FIG.3



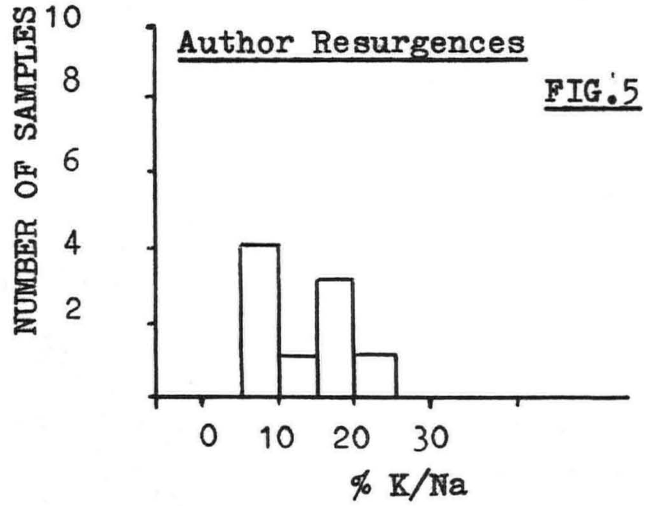
Edmunds Thermals

FIG.4



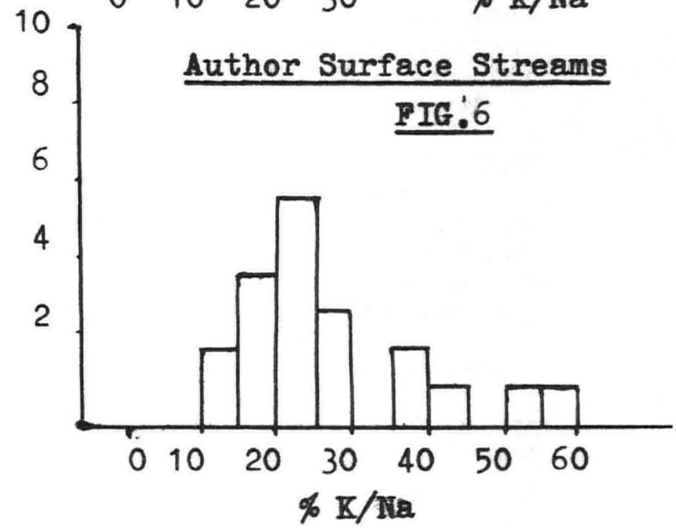
Author Resurgences

FIG.5



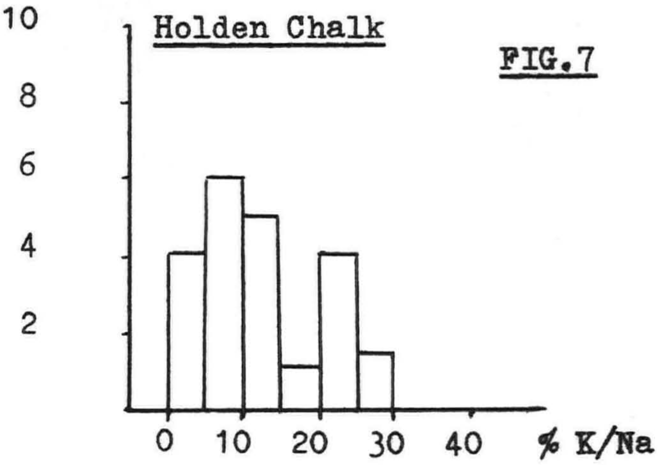
Author Surface Streams

FIG.6



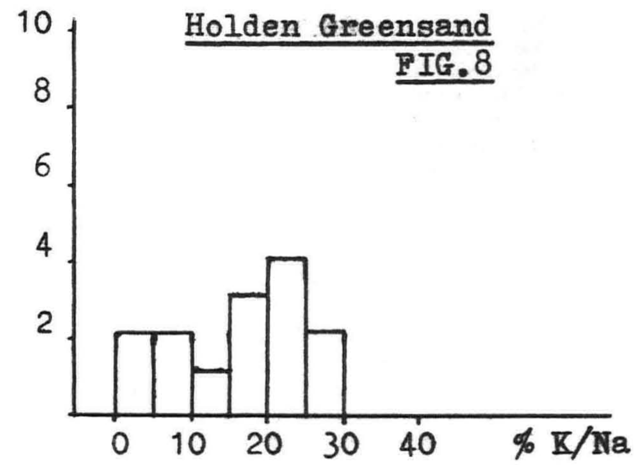
Holden Chalk

FIG.7



Holden Greensand

FIG.8



picture which can be predicted from an appreciation of the chemistry of potassium—sodium in aqueous solutions. Neither Edmunds nor Holden have drawn attention to the variation in concentration of potassium relative to sodium of ground waters, but when these results are compared with the limited results of this author the overall interpretation of all results is consistent with the percentage potassium—sodium ratio being a function of the flow through time, and this has important implications when assessing the speleological potential of a resurgence.

4. Implications for Speleological Reconnaissance

A preliminary programme of chemical investigations, has indicated the usefulness of these two principles, and a technique of speleological reconnaissance based on the analysis of resurgence water is being developed. The ultimate weapon in the hydrologists' and chemists' armory for this type of study is the flood pulse analysis technique (Ashton 1967) but the logistics involved in a widespread use of this technique are daunting, and so it was felt necessary to investigate the basic chemistry of ground waters to see if it would be possible to deduce any information on the nature of the system behind a resurgence from a single or small number of analyses. It is believed that the elucidation of the fundamental background of the saturation index and the potassium—sodium ratio allow an important beginning to be made.

A resurgence should be sampled; preferably twice, once during low flow, but not drought, conditions, and once during flood. The sample should be analysed for: calcium, magnesium, sodium, potassium and these together with temperature, pH and conductivity measurements made on site, will give sufficient information to make a reasonable assessment of the resurgence's speleological potential.

If, during conditions of low flow, the resurgence has a positive or slightly negative saturation index, then it is highly likely that the flooded zone behind the resurgence is small and that open passage exists; if coupled with this it has a potassium—sodium ratio close to that of rivers and surface streams in the same drainage basin, the the water will have spent no great length of time underground, and has probably flowed directly to the resurgence, along an open passage. Conversely, if the saturation index is negative by 0.5 units or more and the potassium—sodium ratio low, one would expect the water to have originated mainly from percolation.

If the saturation index is negative and the potassium—sodium ratio high, this would indicate a resurgence under artesian conditions, but with open passage before the artesian section, and one should look away from the immediate area of the resurgence to gain entry into the system.

When sampled, during flood conditions, one would expect the first type of resurgence to have an even more positive index and the potassium—sodium ratio to increase over the value obtained under low flow conditions, ultimately approaching that of surface streams.

The results for the second type of resurgence would not be expected to change greatly from the low flow values; whilst in the third case where artesian conditions prevail in the resurgence area, one would expect some change, especially in the potassium—sodium ratio, but not a very large change in the saturation index. However, in this case one would expect the absolute value of the saturation index to be lower than in the second case.

CONCLUSIONS

It has been possible, now that the physical chemistry of calcium bicarbonate solutions is better understood, and by realising that the ratio of potassium—sodium is a function of ground contact time, to apply the saturation index and potassium—sodium ratio to the problem of speleological reconnaissance of resurgences. The evidence gathered from these parameters can be used in conjunction with geological, hydrological and geophysical evidence fully to assess the nature of the system feeding a resurgence.

Work is in hand applying these principles to the drainage basins of Derbyshire and also other ionic ratios are being examined for further indications of speleological potential.

REFERENCE

Ashton, K. 1967. The Analysis of flow data from Karst drainage systems. *Trans. Cave Res. Grp.G.B.* Vol. 7, No. 2, pp.161-203.

Christopher, N.S.J. 1974. An improved method of calculating saturation indices, in press.

Edmunds, W.M. 1971. The Hydrogeochemistry of the Derbyshire Dome with special reference to trace elements. *Inst. Geol. Sci – Report No. 71/7.*

Goldschmitt, V.M. 1954. *Geochemistry* – Clarendon press, Oxford.

Holden, W.S. 1970. *Water treatment and examination.* Churchill Press.

Jacobson, R.L. and D. Langmuir 1972. An accurate method of calculating saturation levels of ground waters with respect to calcite and dolomite. *Trans. Cave Res. Grp. G.B.,* Vol. 14, No. 2, pp.104-108.

Langelier, F.W. 1936. *Jnl. American Water Works Ass.,* Vol. 28, pp.1500.

Picknett, R.G. 1972. The pH of calcite solutions with and without magnesium carbonate present, and the implications concerning rejuvenated aggressiveness. *Trans. Cave Res. Grp. G.B.* Vol. 14, No. 2, pp.141-150.

1973. Saturated calcite solutions from 10 to 40°C. A theoretical study evaluating the solubility product and other constants. *Trans. Cave Res. Grp. G.B.,* Vol. 15, No. 2, pp.67-80.

Received 21st Nov. 1974

Noel S. J. Christopher,
22 Deva Close,
Poynton,
Cheshire.

Trans. British Cave Research Association. Vol. 2. No. 1. pp.35-40. April 1975.

BIRDSEYE STRUCTURES IN CAVES

Peter A. Bull

Abstract

Aerated, post-depositional structures found in a number of caves are described and existing theories of formation in surface examples are reviewed in the light of observations from the cavern environment.

Sequential development theories concerning the formation of the structure are discussed and their significance as palaeoenvironmental indicators are considered.

Introduction

The development of aerated structures within sedimentary deposits is a well known phenomenon in many differing environments. Structures analagous to those found in surface sediments are now noted from the cavern environment in South Wales and the Mendips although it is thought that they represent a fairly common feature in caves containing sediments.

Birdseye Structures in Surface Environments

It is necessary to define the following terms to prevent any confusion.

1. Postdepositional — Any feature that forms after a sediment has been laid down can loosely be termed postdepositional.
2. Birdseye Structures are "sedimentary structures that represent open spaces exceeding the average particle size, each having a maximum size in the range of a few decimetres" (Deelman, 1972, p.584).

Various authors have, however, coined different names for birdseye structures of apparently similar features; "Cavernous Sands", (Kindle 1936); "Fenestra", (Tebutt et al. 1965); "Spongy Textures", (Conybeare and Crook 1968) and "Vesicular Structures", (Springer 1958; Miller 1971; Evenari et al. 1974) but for the purpose of this paper the original term "Birdseye Structures", (Ham 1952) is used.

As postdepositional features, birdseye structures occur as modifications of previously deposited sediment and have been described as palaeoenvironmental indicators for a number of different environments. The numerous workers who have reported these structures mostly agree that the features result from the entrapment or generation of gases in the sediment. The actual mechanisms of formation have been summarised by Deelman (1972) who distinguished seven modes of formation largely to cover the environments from which these structures had been reported.

1. Birdseye structures can result from the decay of algae that often cover sediment and also the subsequent collection of the gases produced by photosynthesis within an algal mound.
2. Burrowing by animals, into soft sediment, can cause structures analagous to those formed by algal decay.
3. Decomposition of organic matter that has been buried within a sediment bank can produce gases, which if trapped, may result in the preservation of bubble shaped vugs or voids forming birdseye structures.
4. Those structures caused by diagenesis as proposed by Illing (1959) result from lithification and subsequent solution or replacement of a sediment bank causing voids to form similar to birdseye structures. Deelman (1972 p.589) however, suggests that the forms resulting from diagenesis should not be termed birdseye structures since "birdseye structures should be considered to be sedimentary structures sensu largo (sic), so that they possess significance for the analysis of the palaeoenvironment".
5. The mechanism of syneresis or droplet separation has been proposed, again by Illing (1959). Syneresis is due to the spontaneous separation of a liquid from or by a gel at the hypothetical gel-air contact surface during ageing resulting in shrinkage and formation of cracks or vesicles. As Deelman comments, (1972 p.587) "Illing only suggests this mode of origin and his paper does not cite any experiment or observation in relation to its theories on birdseye origin in carbonate sediments".
6. Horizontal movement during dessication shrinkage is advocated by Deelman as being a viable mechanism for the formation of birdseye structures since dessication of a sediment bank causes shrinkage of individual interstitial voids between particles because of the lack of water. This results in horizontal and vertical shrinkage causing voids to be formed akin to birdseye structures. Features formed by this process are reported by Deelman (1972) from a paper by Fischer (1964 pp.117 and 118, figs. 11 and 12).
7. A mechanism of formation is cited by Deelman (1972) which results from the action of capillary and non-capillary interstitial particle spaces and is simply termed the capillary/non-capillary mechanism. Capillary pores differ from non-capillary pores in behaviour, since the former are responsible for storing water and the latter hold air. When a dry sediment is flooded, water passes quickly through the capillary pores and whilst the non-capillary pores remain filled with air, water circulates around the surrounding capillaries. Figure 1 shows the process diagrammatically modified from Deelman (1972 p.590) and similar to Miller (1971 p.637). Stage 1 shows the dry sediment with capillary and non-capillary pores. Stage 2 shows that after water incursion (shaded area) air is trapped. The surface tension of the water contracts the outer surface of the trapped air bubble (Stage 3) into a convex surface since it is then the smallest air-water contact. Since the volume of the air has to remain constant (Boyle-Gay Lussac's Law), the contraction is followed by expansion until the air bubble becomes larger than the original pore when, according to observations during experimentation

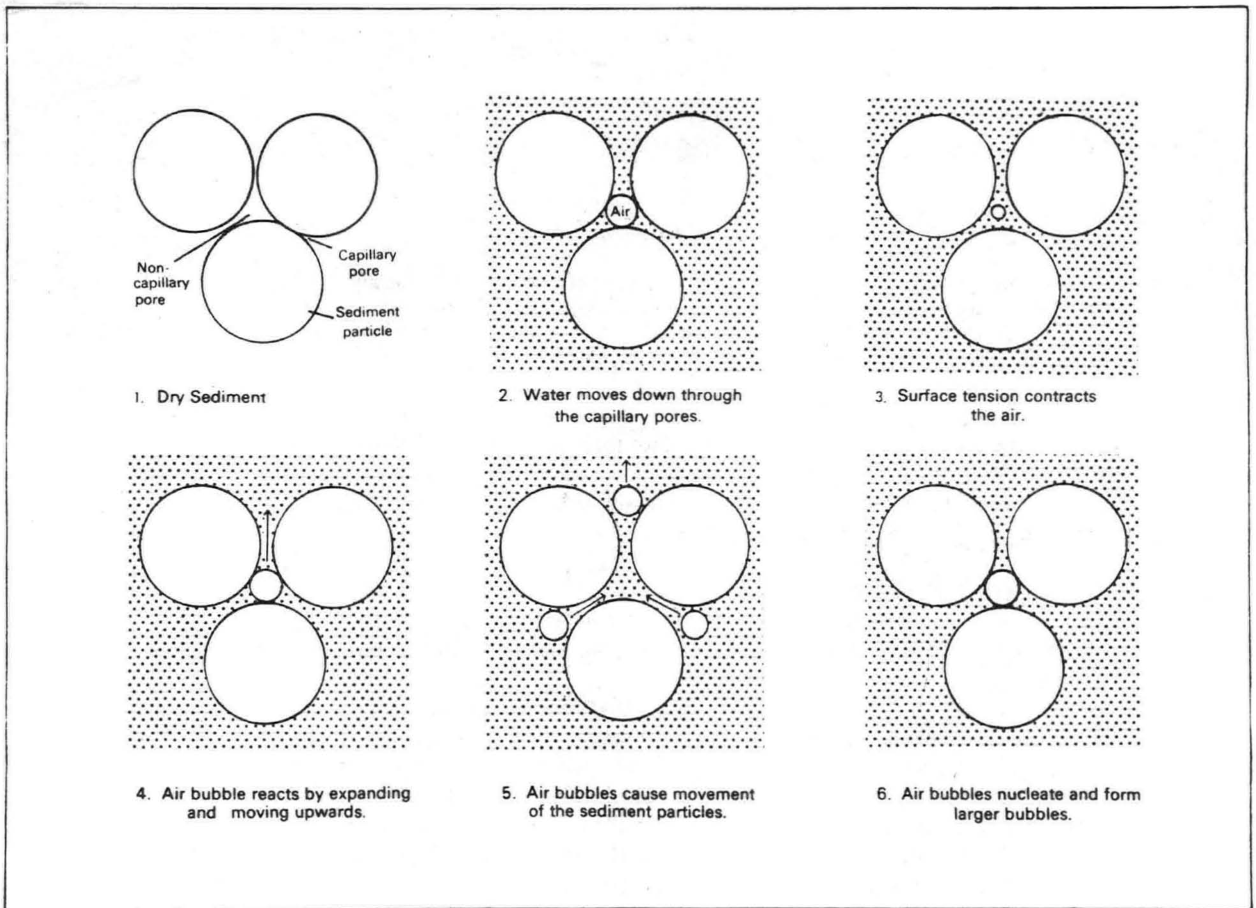


FIGURE I

Diagram showing the stages of formation of air bubbles by capillary/non-capillary action. The shaded area indicates water. (modified Deelman 1972)

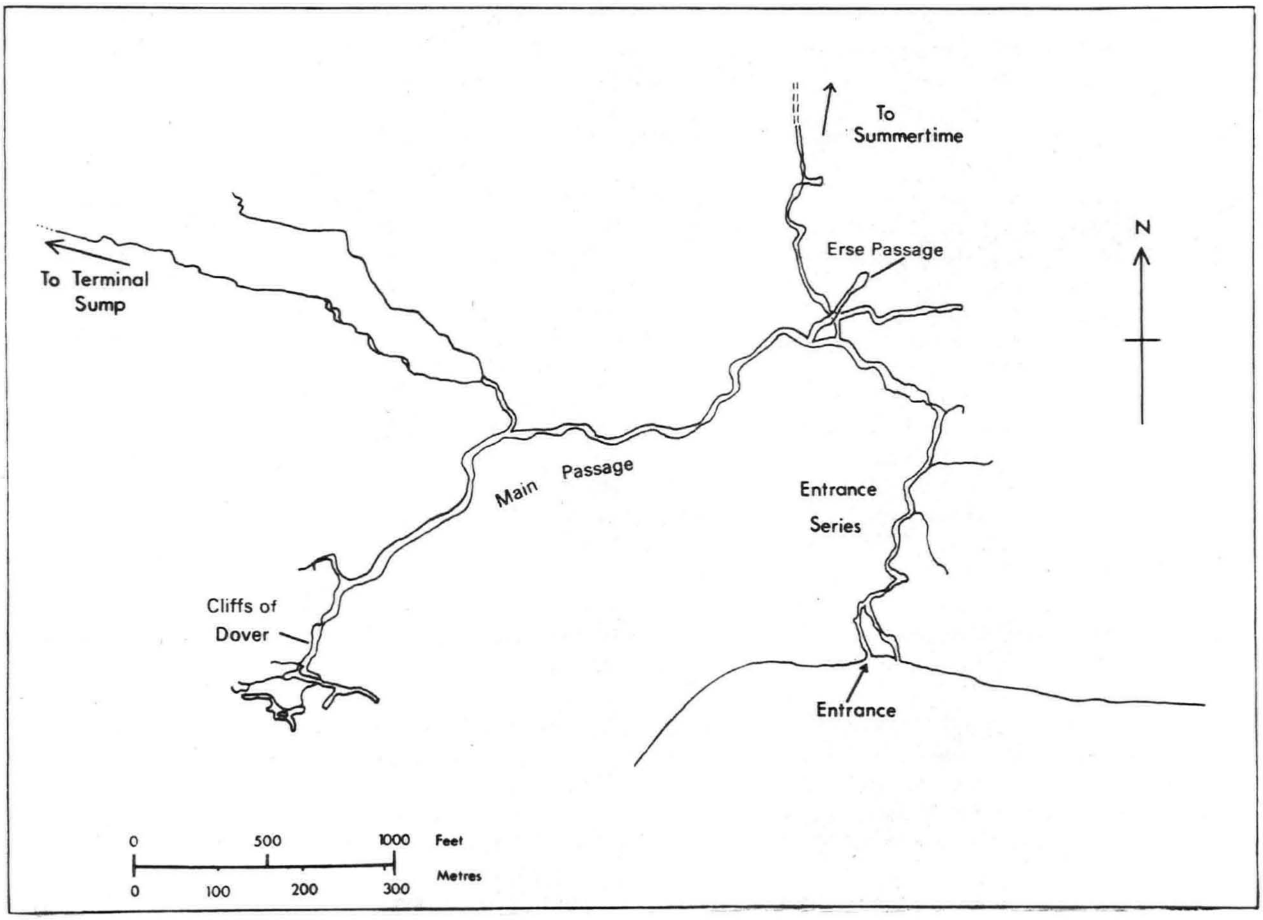


FIGURE 2

Diagram showing selected locations in Agen Allwedd, Powys. (Modified from Lord 1961 survey)

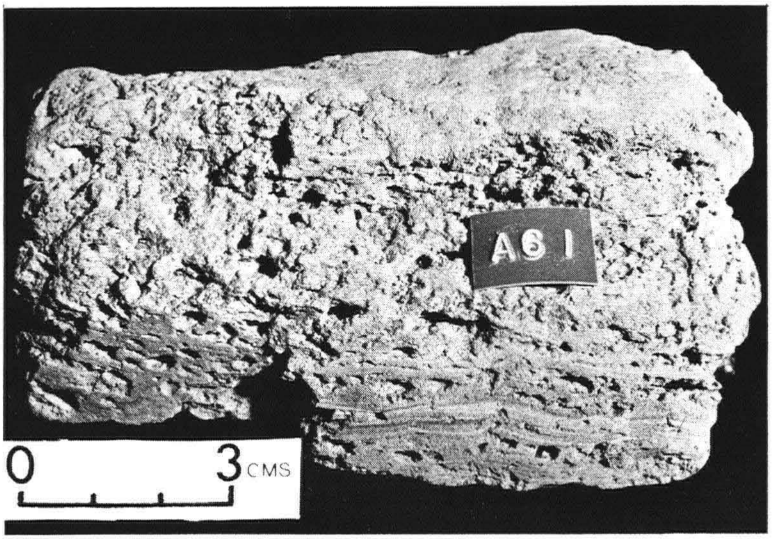
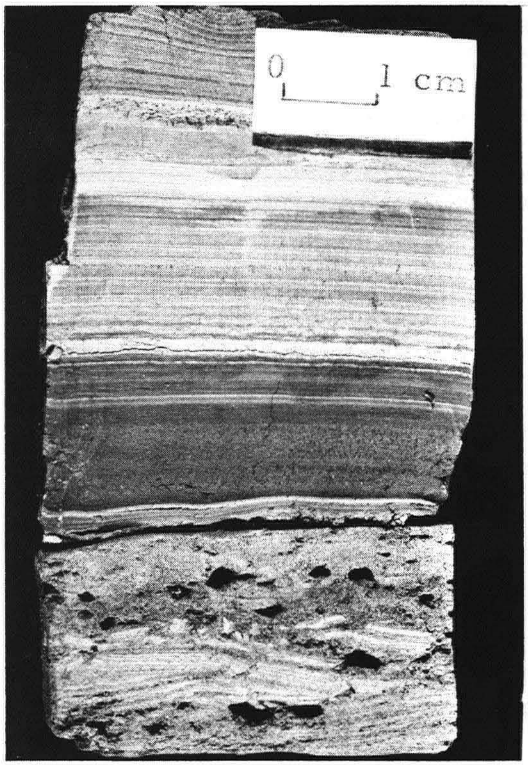


Fig. 1.

Oblique view of Birdseye structuring from Cliffs of Dover showing cavities between silt laminae.

Fig. 3.

Birdseye Structures between silt and clay laminae and below a thick cap mud.



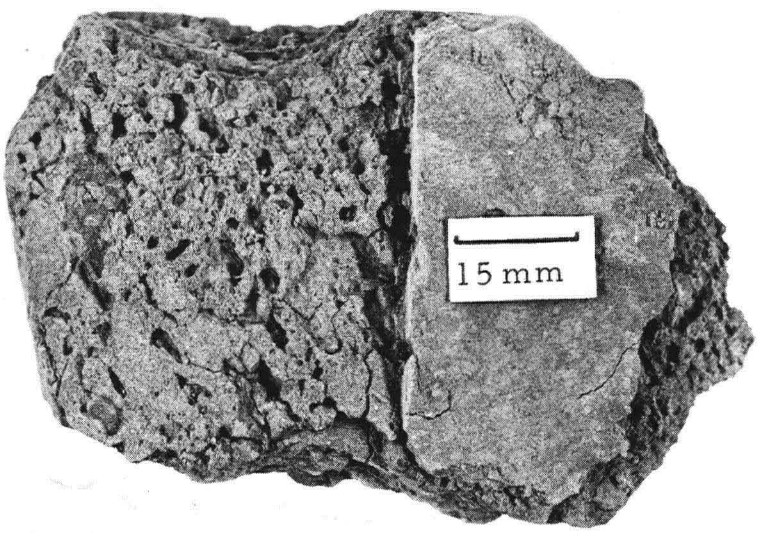


Fig. 2.

Birdseye Structures from Cliffs of Dover showing cavities below the cut away cap mud.

(Deelman 1972 p.591) the grains begin to move due to the very unstable state. With all the grains adjusting to the new state, large bubbles form. (Stages 4, 5 and 6).

As soon as the bubbles are large enough they rise (Archimedes Law) since they are lighter than both the water and sediment particles and unless hindered, are released at the surface.

The capillary/non-capillary mechanism is not limited only to calcareous sediments since beach sands, largely siliceous, commonly exhibit these features as noted by Kindle (1936); Trefethen (1941); Emery (1945) and Deelman (1972) and indeed massive expulsion of air from beaches causes the effervescence of intra-tidal zones as described by Kindle (1936 p.19).

Miller (1971), however, had postulated the capillary/non-capillary mechanism for formation of birdseye structures which he termed vesicular structures and stated that, after water incursion "the air is sealed and compressed in a cavity under a pressure equal to the sum of the capillary pressure and the pressure of the water...The soils involved are very unstable when nearly saturated and the air pressure is sufficient to form the cavity into a sphere, thus achieving the smallest surface area per unit volume" (Miller 1971 p.637). Furthermore, Miller showed a positive correlation between the increase in vesicles and the number of cycles of water incursion. He also stated (p.636) that as a result of experimentation, "it makes little difference whether the soil was wet by flooding, with air escape prevented or, from the bottom, with air allowed to leave the surface, thus indicating that air entrapment ahead of the wetting front was not important".

Deelman concluded that birdseye structures could form in all types of sediment so long as air or gas was trapped and that "doubts should be expressed as to the general belief among geologists that birdseye structures are reliable indicators of supra or intra-tidal environments", (Deelman 1972 p.594). Indeed, many such palaeoenvironments have been advocated by authors, for example, supra- and intra-tidal conditions have been suggested to be the environmen of formation of sediment containing birdseye structures by Kindle (1936), Trefethen (1941), Emery (1945), Shinn (1968), and Conybeare and Crook (1968). Whereas it cannot be doubted that many authors noted birdseye structures forming in these environments it should not be stated that birdseye structures are palaeoenvironmental indicators of these conditions since similar structures have been reported under different conditions elsewhere by frost action (Parea 1970), capillary action in deserts (Springer 1958; Miller 1971), and now, in this paper, from the cavern environment.

Birdseye Structures in Caves

Birdseye structures have been noted from Penyre (Powys, South Wales) and also in Sidcot Swallet (Burrington, Somerset) and are discussed in more detail from Agen Allwedd (Powys, South Wales) particularly from the Cliffs of Dover and Erse Passage (see fig. 2) although it is thought that these structures form in many caves containing sediment banks.

No previous description or identification of these structures from the cave environment is known to the author and therefore descriptions of specific sites of occurrence are given together with a tentative chronology of the palaeoenvironmental conditions of formation in the immediate vicinity of the structures, although Dr. T.D. Ford, (per. comm.) has observed the presence of entrapped gases (air) in a shallow pool in a then newly discovered part of Peak Cavern and the subsequent expulsion to the surface of the air after being disturbed by footfall.

Mode of Formation in Caves

Of the mechanisms suggested by Deelman (1972) and others and summarized above, a number of them can be dismissed relatively quickly when discussing formation in the cavern environment. The algal origin is unlikely to be a viable mechanism in caves as algae need light for photosynthesis and so only cave entrances could provide such facilities for growth. Burrowing too, is unlikely in the context of this study as worms and other burrowers rarely live long in the true cavern environment and indeed, in Agen Allwedd the Cliffs of Dover are over 1000 metres from the entrance and about 200 metres from the surface. Furthermore, no casts, a sure sign of burrowing activity, were seen; both the isolated nature of individual birdseyes and the general complexity and selectivity of the structures within the sediment bank rule out the formation of the birdseyes by burrowing.

For the purpose of this study diagenetic origins of birdseyes are dismissed as the sediments studied have undergone very little diagenesis.

Droplet separation too, is unlikely in caves and is dismissed as a viable mechanism by Deelman (1972).

Dessication shrinkage and lateral movement of sediment is possible in the cavern environment and may well cause birdseye structures, however, no structures were seen to be caused by this mechanism in this study.

Gas genesis caused by organic decay is also viable in the cave environment although, this is unlikely as a mechanism of formation of birdseye structures in the case study in Agen Allwedd since, firstly, no significant amount of organic material was present in the direct vicinity of the structures and, secondly, the birdseyes form between sealing silt and mud bands and do not appear to form within them.

Finally, capillary/non-capillary action is thought to be a major mechanism of formation of birdseye structures in caves since the conditions for formation of these features are ideally present in the cavern environment.

Discussion

At the Cliffs of Dover (Fig. 2) extensive birdseye structuring of the uppermost 50 cms. appeared alternating with finely laminated silts. The mean grain size of the laminated silts and the structural birdseye silts were both similar (3.67 and 3.80 phi units), the former indicating periods of stillstand, the latter, periods of water incursion into the dry sediment bank as a result of draining and flooding.

In a number of samples studied from the Cliffs of Dover, a cap mud (which is extensive throughout the Main Passage) acts as the seal preventing air escaping. This finely laminated mud appears distorted around its junction with the silts as a result of localized growth of air bubbles. The significance of this is twofold. Firstly, to be distorted, the cap mud must first be present in situ and already laminated as a result of gently settling out of fine sediments. Secondly, the distortion by the nucleating air bubbles affected a number of the basal laminae and either the nucleation of the air must have taken a sufficiently long time allowing the mud to settle and form a seal or, the formation of the birdseye structures (and hence a flooding of the air filled sediment bank) post-dated even the formation of the cap mud. If the latter case were to apply the sequence of events would follow this;

1. Sediment deposition
2. Periodic influxes of fine sediments under stillstand conditions (i.e. cap mud formation).
3. Relative drying of sediment, allowing air to refill interstitial spaces due to draining.
4. Influx of water, nucleating air under the cap mud, forming birdseye structures.
5. Draining and drying out of sediment.

Samples studied showed alternating laminae and birdseye structures within group 1 of the above sequence and hence, complicate proceedings further, since they indicate formation of the structures during the waning period of original sediment deposition, suggesting a finely fluctuating balance of water level about the upper levels of the sediment bank. Also, since the birdseye structures alternate with a laminated silt, periodic incursions of fine sediment into the flooded level seems indicative.

However, the alternating laminated silts of group 1 appear broken in a number of samples, with the birdseye structuring interspersed amongst the fragments. If the fragmentation occurred in situ, it may be as a response to dessication cracking (i.e. the process of lateral movement during dessication shrinkage). Alternatively, the fragmentation of the laminated layers may represent collapse of the layer containing the birdseye structures.

At one locality in Erse Passage (see fig. 2) the cap mud had been ruptured as a result of the accumulation of too great a volume of air which escaped through its captive layer at this point thinner than the cap mud in the Main Passage. The surface expression of this rupturing was a gas-pit which, in this instance, indicated nucleation of the air after the deposition of the entire laminated cap mud. This may suggest therefore, that the flooding of an air-filled sediment bank does not immediately cause the upward migration of all the air bubbles although total movement of the air will occur in a short period, geologically speaking. However, the laminated silts are not differentially ruptured to separate levels as a result of air escaping during the process of sedimentation, sot it can be concluded that, after initial flooding and subsequent effervescence of the escaping air, isolated air pockets continue to form, rising slowly through the sediment and, in the instance cited, escaping through the sealing cap mud layer.

Conclusions

Birdseye structures are useful environmental indicators in caves, being formed by the rapid and often periodic flooding of dry sediment causing entrapment and nucleation of air. In the context of this study the presence of birdseye structures in Agen Allwedd indicates a period of relatively dry conditions between the main phase of sedimentation and the cap mud deposition and probably post-dates this latter deposit.

As a mechanism for formation of birdseye structures in caves (particularly Agen Allwedd) only capillary/non-capillary action, dessication shrinkage and organic decay can be accepted as viable mechanisms for the cavern environment.

No attempt has been made to classify the individual forms of birdseye structures, although further work is being undertaken to identify the form of these structures in caves so that more detailed environmental sequences may be understood, with an emphasis on the size relationship of void size to repeated incursions of water (Miller 1971).

Acknowledgements

The author wishes to thank Miss G.E. Groom, Dr. G. Kelling and Dr. T.D. Ford for critical review of the script. Thanks are also due to all the members of Chelsea Speleological Society, particularly Mr. I.G. Penney, Mr. R. Musgrove, Mr. A. Millett, Mr. A. Happ, Mr. P. Tarrant and Mr. R. Stroud who helped with the fieldwork, to Mr. S.J. Culver and Mr. P.F. Bent for their valuable discussion, to Mr. C. Edmunds, Mr. M. Hibbart and Mr. S.J. Culver for their portering services, to Mr. J. Ford, Miss I. Parsons, Mr. I. Carpenter, Mr. J.A. Briggs and E.G.O.N.S., for help on the Mendips, to Mr. A. Cutcliffe for his photographic work, to Mr. R. Williams of the Britannia Inn, Crickhowell and to Mrs. L. Bull for typing the script. Fieldwork was carried out whilst the author was a recipient of a Natural Environment Research Council grant. A grant in aid of publication from the University College of Swansea is gratefully acknowledged.

Received February 1975

Peter A. Bull,
Geography Department,
University College of Swansea,
W. Glamorgan.

References

Cloud, P.E. 1960. Gas as a Sedimentary and Diagenetic Agent. *Amer. J. Sci.,* Bradley Volume 258-A pp.35-45.

Conybeare, C.E.B. and Crook, K.A.W. 1968. Manual of Sedimentary Structures. *Bur. Min. Res. Bull.* 102. Canberra, pp.41.

Deelman, J.C. 1972. On Mechanisms causing Birdseye Structures. *N.Jb. Geol. Palaont. Mh.,* 10 pp.582-595.

Emery, K.O. 1945. Entrapment of Air in Beach Sand. *Jour. of Sed. Petrology* 15 (2) pp.39-49.

Evenari, M., Yaalon, D.H., Gutterman, Y. 1974. Note on Soils with Vesicular Structure in Deserts. *Z. Gemorph.* 18(2) pp.162-172.

Fischer, A.G. 1964. The Lofer Cyclothems of the Alpine Triassic. A symposium on Cyclic Sedimentation, Bull. 169 v.1, State Geol. Survey of Kansas, pp.107-149.

Ham, W.E. 1952. Algal Origin of the "Birdseye" Limestone in the Mc-Lish Formation. *Oklahoma Ac. Sci.,* Proc. 33, pp.200-203.

Illing, L.V. 1959. Deposition and Diagenesis of some Upper Palaeozoic Carbonate Sediments in Western Canada – Fifth World Petroleum Congress, Proc. sect. 1 pp.23-50.

Kindle, E.M. 1936. Dominant Factors in the Formation of Firm and Soft Sand Beaches. *Jour. of Sed. Petrology* 6 (1) pp.16-22.

Miller, D.E. 1971. Formation of Vesicular Structure in Soil. *Soil Science Soc. Am. Proc.* 35 pp.635-637.

Parea, G.C. 1970. Strutture simili alle "Birdseye Structures" Prodotte Del Gelo in un Sedimento Fluviale. *Bull. Soc. Geol. It.* 89 pp. pp.353-359.

Shinn, E.A. 1968. Practical Significance of Birdseye Structures in Carbonate Rocks. *Jour. of Sed. Petrology* 39 (1) pp. 215-223.

Springer, M.E. 1958. Desert Pavement and Vesicular Layer of some Soils of the Desert of the Lahontan Basin, Nevada. *Soil Science Soc. Am. Proc.* 22 pp.63-66.

Tebutt, G.E., Conley, C.D., Boyd, D.W. 1965. Lithigenesis of a Distinctive Carbonate Rock Fabric. *Contrib. to Geol.,* 4 (1) pp.1-13

Trefethen, J.M. 1941. Dominant Factors in the Formation of Firm and Soft Sand Beaches – A Discussion. *Jour. of Sed. Petrology* 11(1) pp.42-43.

Trans. British Cave Research Association. Vol. 2. No. 1. pp.41-46. April 1975.

SEDIMENTS IN CAVES

by Trevor D. Ford

(from the lecture presented to the British Cave Research Association conference at Leeds in September 1974)

Summary

A review is presented of the types of sediment which may accumulate in caves, their modes of transport and composition. Some aspects of their use in interpreting the geomorphological history of the cave system are discussed, and some frequent misinterpretations are put in perspective, e.g. "boulder clay in caves".

Introduction

Rock fragments in process of transport from their source to their ultimate resting place in the sea may have a temporary resting place in a cave and may provide us with information not only on their own history but also on that of the cave (Fig. 1). Such sediments may be classified thus (with the provisions that many are of mixed character):—

Endogenetic (or autochthonous) — derived by internal processes, i.e. those operating within the cave.
Exogenetic (or allochthonous) — derived from external sources and carried in to the cave by the agents of transportation such as wind, water and ice.

Endogenetic sediments

Sedimentary materials from endogenetic sources include the insoluble residues from the limestone itself, generally composed of authigenic quartz crystals, chert and flint nodules released from the enclosing limestone by solution, clastic particles deposited with the original lime-sediment including sand grains, silt and mud particles, fragments from shale partings, and scattered pyrite grains. The last two do not survive for long in most cave environments. The reaction of sulphuric acid produced by oxidation of pyrite with the surrounding limestone may result in the growth of gypsum crystals. Together with these non-carbonate materials, there may be contributions from the limestone itself in the form of blocks derived from roof collapse or by permafrost shattering of walls and roof of near-surface passages. Stalactites and stalagmites are strictly endogenetic chemical sediments but they are not discussed herein as they form a subject in their own right.

The deposits produced by endogenetic processes thus include limestone block piles which may be gradually broken down into limestone gravels or carried away in solution, chert gravels, quartz crystal sands or silts, endogenetically derived sand, silt or mud deposits and shale flake breccias. Gravels may also form from minerals released from vein deposits by solution, with galena, fluorite and baryte gravels as examples in caves which traverse ground with mineral veins. Flakes of mica and grains of felspar may be derived from schists interlayered in metamorphic marbles. The oxidation of pyrite may lead to local deposits of iron oxides or hydroxides. Mixtures of endogenetic materials with exogenetic deposits are common.

Exogenetic sediments

Materials derived by processes operating on the surface outside caves, are much more common. Exogenetic sediments may be carried in by wind, water or ice, and occasionally by biological means.

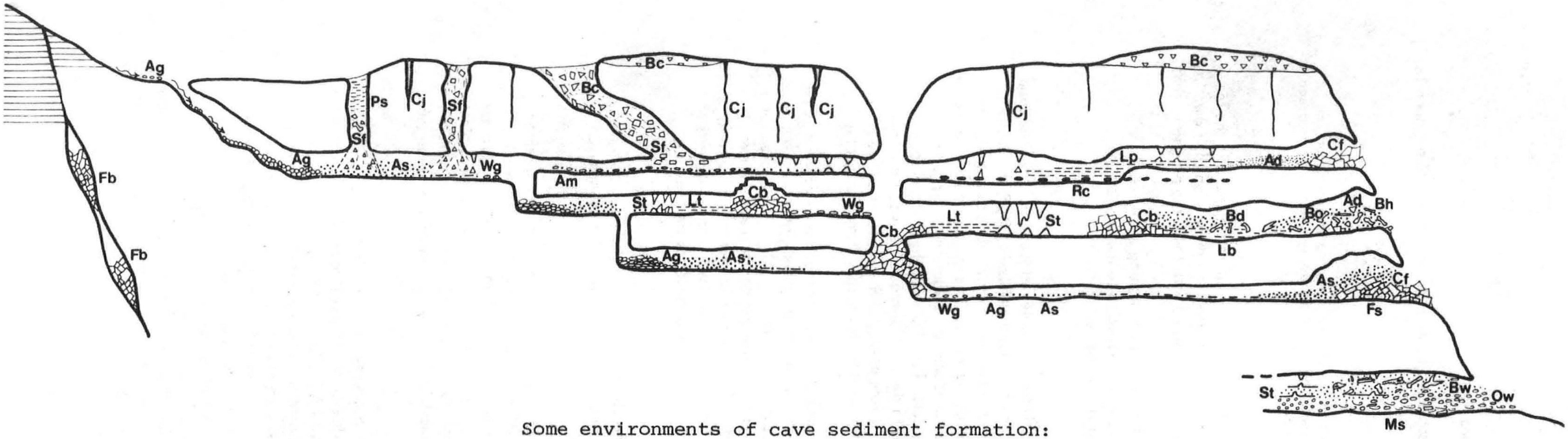
Sediments transported by wind

Wind-borne materials are usually found near entrances as layers of fine dust particles, commonly forming a major component of cave earths. Exceptionally wind-blown dust in a periglacial environment may be more or less identical with loess on the surface. Large cave systems with more than one entrance may have draughts strong enough to transport air-borne dust right through, and relatively sheltered places may become the depository for such air-borne cave earth a long way from the entrances. If the walls are wet at times air-borne dust may adhere to them giving the characteristic "dirty" appearance of some caves.

Sediments transported by water

Water is the main agent by which sediment is brought into a cave system. Running streams carry along pebbles, sand, silt and mud in amounts which vary according to the stage of flow. The dynamics of sediment transport in caves have been discussed by White and White (1968). The bulk of the material is carried under flood conditions, and may, of course, be washed right through the system to reappear at the resurgence as a turbid flow. During its passage through a cave system the flow is in a confined but irregular channel and the exogenetic material in transport may abrade or undermine the walls, so adding endogenetic material. More may be added from solution residues, or, of course, from glacial, solifluction and aeolian deposits. Analytical studies of the composition, size and shape of pebbles, sand and silt may give some clues about the source or sources of the materials but few studies have been reported.

Fluvial sediments are transported either in suspension by saltation, or by rolling along the bottom: the particles collide with each other and are thus mutually abrasive. Angular rock fragments introduced into a cave are rounded during their passage through the system. Owing to a cushioning effect of water the smallest particles receive very little rounding, but pebbles may reach a spheroidal shape. These effects are well-known to sedimentologists and are covered in Blatt et al. (1972) and Hatch, et al. (1971). Few tests of the rate of rounding have been done under cave conditions except by Newson (1971) but it should be



Some environments of cave sediment formation:

Alluvial	Gravel in contemporary stream	Ag	"Cave Earths"	Air-borne dust	Ad
	Sand in contemporary stream	As		Bone gravel due to inwashing	Bw
	Gravel or sand in abandoned meanders	Am		Bone gravel due to animals dens	Bd
	Winnowed gravel below inlets	Wg		Bone gravel due to human occupation	Bo
	Inwashed peat and soil	Ps		Bone gravel with hearths	Bh
Glacial	Boulder Clay fill of old potholes and swallets	Bc	In situ	Residual chert nodules	Rc
	Outwash gravel washed into cave mouths	Ow		Fault or vein breccia	Fb
	Solifluxion sludge via swallets and collapses	Sf	Clay fill	Silts in abandoned phreatic system	Lp
	Frost scree in entrance	Fs		Laminated clays and silts due to backing up of former surface lakes	Lb
Collapse	Boulder piles from roof collapse	Ch		Clays and silts trapped by settling-tank effects of collapses and stalagmite dams	Lt
	Blocks from cliff falls over entrances	Cf		Clay-filled joints	Cj
			Marine Shelly gravels and sands		Ms
			Stalactites and stalagmites		St

possible with the aid of more experimental data to deduce the distance of transport of pebbles or sand grains seen in a cave deposit.

Sedimentary accumulations occur in caves owing to an interruption in transportation. The accumulations within stream cave systems contrast with those in entrances, as the former are chiefly water-borne while those in entrances contain varying amounts from aeolian, glacial, solifluction and other mass-movement effects. The causes of interruptions within stream cave systems are usually "accidents" of erosion of the cave itself: a roof collapse may form a dam with a resultant settling-tank effect on sediments carried in by the stream. Oscillations of flow stage may give a laminated alternating fine and coarse sedimentary deposit, such as that in the Sand Caverns of Gaping Gill. Gradual removal of the dam by solution may allow the stream to cut a channel through the deposit, but then a further roof fall may restore the dam and allow the channel to be re-filled. Abandonment of a passage by a stream taking a lower route may allow flood waters to overflow periodically into the old passage there to deposit sediment, often progressively finer in grain upwards.

Many fluvial sediments are in fact fluvio-glacial having been transported and deposited by melt-water streams from glaciers (Plate 1, fig. 2). The physical characteristics are much the same though the composition may be more varied and the quantities can at times be much greater than "normal". The example in the Sand Caverns of Gaping Gill, cited above, may well be of fluvio-glacial origin.

When a vadose stream becomes laden with sediment and enters phreatic passages its velocity is reduced and the coarsest fraction is dropped. This restricts the channel so that the next smaller grain sizes are carried further inwards and so on. In an ideal phreatic tube system the grain sizes may all be sorted out downstream by this means. If a phreatic passage is drained or abandoned the sediments should reveal the former direction of flow, e.g. if a floor with pebble gravel is so exposed it may mean that the entry point of a vadose stream was not far away. Damming of the resurgence by ice may cause the return of a passage to epi-phreatic conditions with similar sedimentary results.

It is not uncommon to find passages completely choked with fluvial sediments. In Ingleborough Cave, Yorkshire, several passages are completely full of bedded gravel except for the top few centimetres which have sand or silt. This type of deposit probably represents rapidly-flowing streams heavily laden with pebbles, derived from glacial outwash on the plateau above: as the channel became full, perhaps owing to an obstruction downstream, or to epi-phreatic conditions, the flow was diverted and the remaining passage became a backwater suitable for the settlement of fine-grained material. Pebbles frequently show imbricate stacking, i.e. each lying against the previous one, with an upstream dip, thereby indicating the direction of flow.

Lag gravels are sometimes left by the winnowing out of fine to medium grained by moderate stream flows cutting through earlier fluvioglacial fills. An example is the gravels seen on shelves high above the stream in West Kingsdale Master Cave which indicate a probably near-complete fill at one time (Plate 1, fig. 1).

Sediments transported by Ice

A third agent of transport is ice: glaciers moving over an area eventually stagnate and on melting produce an unsorted mixture of stones and clay known as boulder clay or till. Owing to certain aspects of the physics of crystallization of ice under pressure, glaciers can only move through caves of more than average proportions: few examples have been noted and none described in detail. Ice can, however, move into a cave entrance and till deposits can be found in entrance passages. As the till represents the residue from melting ice it will form no more than a layer on the floor of the cave. Melting of ice at the sole of a glacier may release till whence the fine fraction may be washed down joints and bedding, but the resultant deposit will generally be indistinguishable from water-laid mud. As glacier ice will in general not move through a cave of small dimensions, the cave may just fill with ice crystallizing in situ. True till is probably rare except in cave entrances or on the floor of large caves.

Much of what is commonly referred to as boulder clay in caves is probably due to solifluction, where repeated freezing and thawing will allow the sludging of true till or other sediments into the cave. This will generally be found close to entrances though the sludging process may allow a remarkable quantity of material to move through a small hole, sometimes to the extent of filling a cave passage for many metres. The resultant mass of a poorly sorted mixture of boulders, sand and mud is what has often been called boulder clay by cavers. If it can be demonstrated to be a solifluction deposit, it is an indication of the former presence of a cold climate, but unfortunately solifluction deposits can sometimes have much the same characteristics as deposits which have sludged by being overleaded with water. If the latter contain materials derived from earlier till or true solifluction deposits there may well be no recognizable difference between the deposits of fully glacial or cold wet climatic conditions. Sludging of loess into caves may result in ochreous yellow clays. Owing to freeze and thaw action in cave mouths the deposits therein may sometimes sludge outwards, mixing bones and pottery of different ages and causing problems to archeologists! Subglacial or marginal glacial melt-water streams may sometimes flow into caves leaving outwash gravel sheets through much of the cave system. Frost-shattered scree may fall into cave entrances from overhanging cliffs.

Clay-fill

A common cave sediment, often of controversial origin in the past, is clay-fill, first described from Missouri caves by Bretz (1942). In general terms this represents the transition of an active cave to a condition

Plate 1

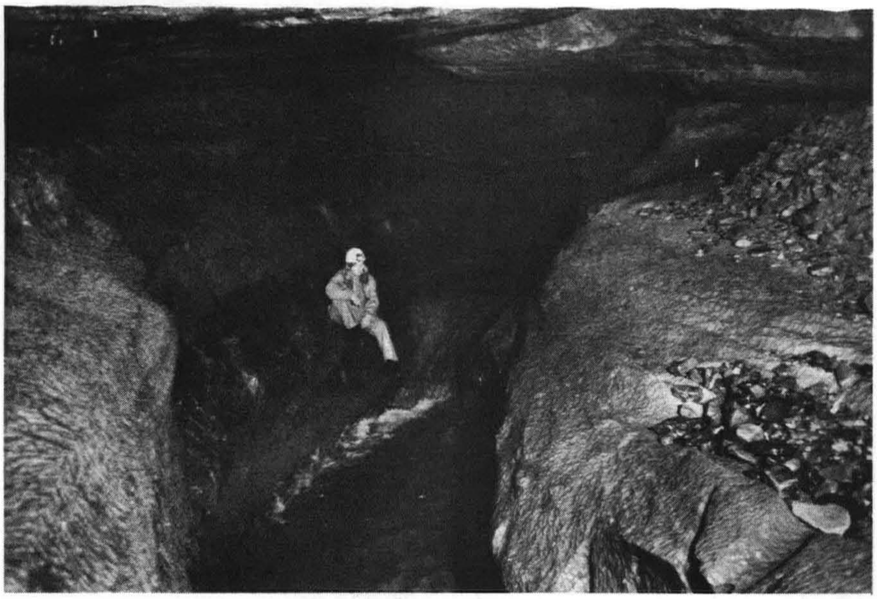
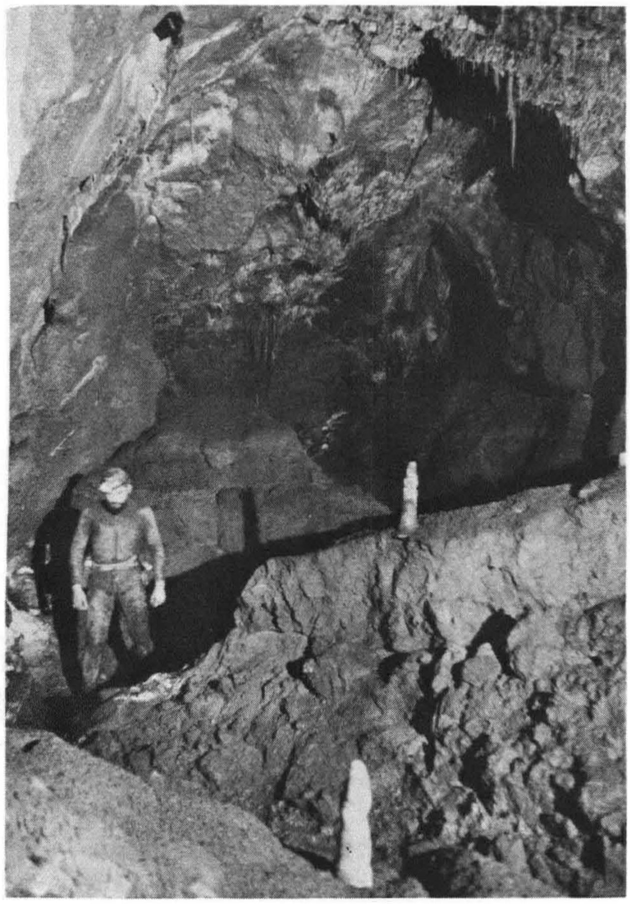
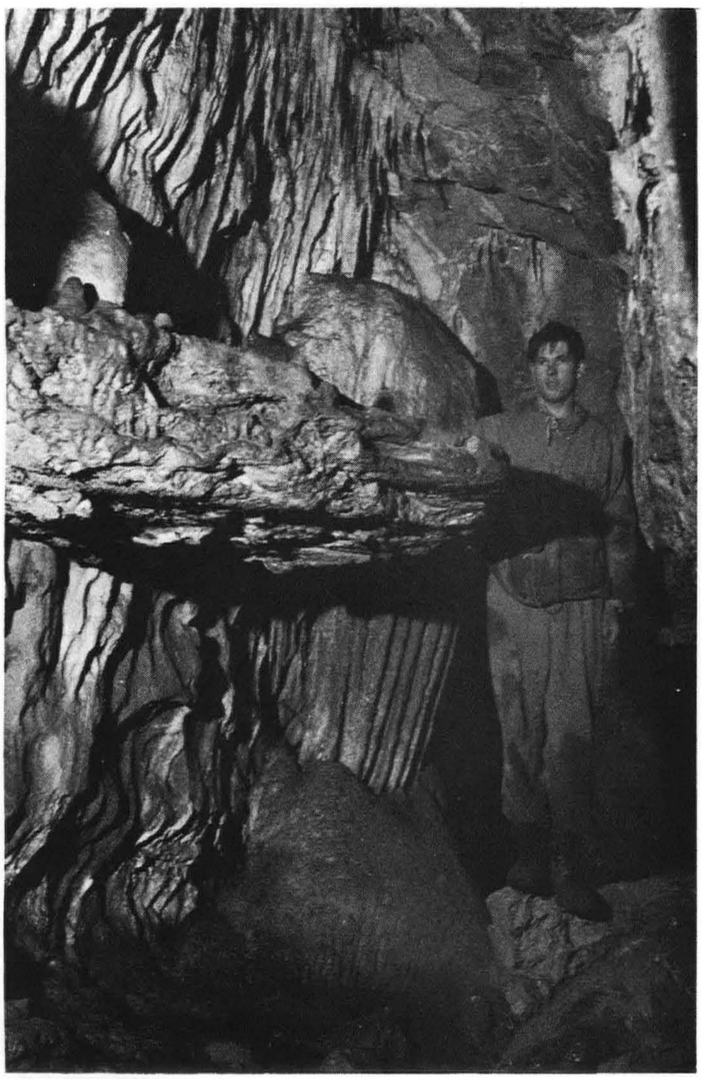


Fig. 1. Lag-gravels in West Kingsdale Master Cave, the coarse fraction left from a former alluvial (fluvio-glacial?) fill stage. (photo by Tony Waltham)

Fig. 2. Stream trench cut through an alluvial (fluvio-glacial) fill in Big Meanie, Leck Fell. Stalagmites from a post-glacial phase rest on the clay cap to more coarse-grained sediment. (photo by Tony Waltham) →





←

Fig. 3. Alternations of stalactite deposition and alluvial fill in the East Passage of Gaping Gill. The projecting shelf is all that remains of a former gravel fill, now cemented by stalagmite. A new stalactite mass has grown behind the shelf. (photo by T.D. Ford)

of relative inactivity when it can become a settling tank for fine-grained sediment. As Bretz argued this may be during the period between the development of a phreatic "first-cycle" cave and a vadose "second-cycle" system. Equally it may be the settling-tank effect of the phreatic part of an integrated drainage system which receives only fine-grained input; or it may be due to outside climatic influences, such as a glacial episode cutting off all but a little undermelt flow beneath the ice so that the only available material is very fine-grained. Alternatively, a fine-grained fill may represent the washing through of a loess cover over the limestone mass. Sometimes, caves close to a limestone-shale contact contain ochreous clay which is no more than the washed-in weathered shale subsoil. A detailed study of clay mineralogy may be necessary to distinguish the various types of clay-fill origin. Cave clays are commonly yellow-brown but may be red if residual iron-rich terra rossa soils are washed in from the surface. Blue-grey clays may result from the reduction of the iron to the ferrous state.

Biogenic sediments

A special type of exogenetic material is of biological origin. Included are such deposits as bat and bird guano, the remains of insects and beetles which feed thereon, bone gravels washed in from the surface, bone-rich talus cones beneath pitfalls, bone accumulations from occupation by man or animals, and peat derived from surface deposits. These may occur as admixtures with other deposits. Peat and guano may take part in chemical reactions within the cave environment and so produce other deposits such as humates or nitrates and phosphates.

Sediments as clues to cave histories

Clues about the history of a fluvial cave may be obtained from the relationship of the sedimentary fill to the passage shape. Three examples will suffice: one, seen deep in Speedwell Cavern, Derbyshire, has passages with a typical vadose-trench beneath phreatic tube T-shaped cross-section filled with yellow clay, with only slight traces of stratification. Such passages are now dead tributaries to an active stream in a similar passage. Clearly this has been a multi-stage development of a vadose stream cave, with a fill stage interposed, owing to external climatic influences probably with a good supply of loessic material. The second example is on Masson Hill at Matlock where fluorspar miners have broken into a series of caves exhibiting phreatic solution features on their walls but which are filled with bedded sands and silts. These are composed of materials derived from the Millstone Grit, the nearest outcrop of which is several miles away at a lower altitude on the other side of a valley 250 metres deep! These caves were apparently breached during a Pleistocene glacial episode and almost immediately filled with outwash material, some probably from englacial streams, bringing material from far distant outcrops of the Millstone Grit. A third example is the alternation of two generations of stalactite deposition with alluvial infill and subsequent undercutting, seen in the East Passage of Gaping Gill (Plate 1, fig. 3).

The sediments of cave entrances are much more varied. Fluvial, aeolian, periglacial or glacial sediments may occur much as described above, but as, entrances are much more susceptible to climatic changes, alternations of these classes of sediments are likely to be much more frequent. Channelling into early deposits by streams intermittently in flood is more common, but perhaps the most important distinction from the dominantly fluvial sediments of stream caves is the presence of layers of frost-shattered talus from the roof. In many archaeological and palaeontological caves the presence of such layers has been taken to indicate former cold climatic phases, though in moderately high latitudes today there is still sufficient frost in winter to produce such talus. Cold climates alternate with warmer and wetter phases and these may often be reflected in the presence of layers of stalagmite or of tufa. Cave earths are common in such sequences and may reflect the blowing in of aeolian dust, of soil formed from vegetation in the cave mouth or the dirt brought in on the feet of animals. The wastes from the feeding activities of mammals may form a contribution, and the activities of man may produce characteristic deposits such as middens or burials. A further factor in the formation of cave entrance sediments is that burrowing animals may cause considerable mixing of the component layers, and if man has used the site for burial of his dead considerable confusion of layers may result.

A special case of cave entrance sediments is the talus cone which may occur beneath a hole in the roof, possibly caused by collapse. A mixture of roof blocks, soil and subsoil may form a heap beneath, which gradually builds up as further debris is washed or blown in, and as animals fall into the pit-fall trap. Temporary habitation by trapped but living animals may cause further mixing of the talus. A fine example is that in Joint Mitnor Cave in Devon, which formed the basis of that so ably described by Sutcliffe (1970).

If a cave mouth opens in the bank of a river the sediments may be affected by pouring in river-borne material, which will decrease in grain size inwards, in contrast to the downstream size-grading seen in phreatic tubes. Channelling and re-sorting of existing sediments may take place if a river breaches an existing cave mouth.

Some caves open directly on the sea shore and may thus contain marine deposits such as shell sands or beach cobbles. Other caves discharge their streams directly from the sea floor and when they become inactive they may be filled with marine sediments of various types.

The deposition of calcium carbonate cement in a cave sediment is an extension of the stalactite formation process and is discussed elsewhere in this book. It may be noted, however, that cemented cave sediments indicate a change in environmental conditions, which may be due to climatic hydrological or chemical factors. Such cementation must be taken into account in studying the history of a cave system.

Conclusions

Sedimentary deposits in caves can thus tell much about the history of a particular cave, such as the possible source areas of the inflowing streams, whether or not the area has been glaciated, submerged beneath the sea and so on. But there are many pitfalls in the study of such cave sediments: the possible modes of formation of the clay-fill have already been discussed. Laminated silts and clays may result from glacial ponding and so compare with the varved clays of proglacial lakes, or they may simply result from a roof fall and settling tank effect on a stream with variation in flow and sediment-carrying power. Boulder clay, periglacial solifluction deposits and aqueous sludge deposits can look very similar and may in fact be indistinguishable at times. The presence of palaeontological material such as scattered bones may help in interpretation but on the other hand, the bones may have been derived from an earlier deposit, transported along the cave and then buried again. Similarly vegetable debris in cave silts may be that of contemporary plants, or it may have been derived from an ancient peat deposit above the cave. Carbon 14 dates are meaningless in such cases.

In practice there has been little description or analysis of cave sediments (except for Sweeting 1972) apart from those bearing archaeological remains. Much more descriptive work is needed before more accurate conclusions can be drawn and diagnostic tables set up. Size ranges of pebbles and sand, roundness tests and variations in stream flow stage need to be related to each other in as many areas as possible, and in turn they must be compared against a background of different source rocks in different climates, past and present.

Rec'd January 1975.

Trevor D. Ford,
Geology Department,
University of Leicester,
LE1 7RH.

References

Blatt, H., Middleton, G. & Murray, R. 1972. *Origin of Sedimentary rocks.* Prentice-Hall, New Jersey. 643p.

Bretz, J.H. 1942. Vadose and phreatic features of Limestone Caverns. *Jour. Geol.* Vol. 50, pp.675-811.

Hatch, F.H., Rastall, R.H. & Greensmith, J.T. 1971. *Petrology of the Sedimentary Rocks.* 5th Edition. Murby. London. 502p.

Newson, M.D. 1971. The role of abrasion in cavern development. *Trans. Cave Res. Grp. G.B.* Vol. 13, (2). pp.101-108.

Sutcliffe, A.J. 1970. A section of an imaginary bone cave. *Studies in Speleology.* Vol. 2, No. 2., pp.79-80.

Sweeting, M.M. 1972. *Karst landforms.* Macmillan, London. 362p.

White, W.B. & White, E.L. 1970. Channel hydraulics of freee surface streams in caves. *Caves and Karst,* Vol. 12, No. 6, pp.41-48.

The TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION covers all aspects of speleological science, including geology, geomorphology, hydrology, chemistry, physics, archaeology, and biology in their application to caves, as well as technological matters such as exploration, equipment, surveying, photography and documentation. Papers may be read at General Meetings held in various parts of Britain, but they may be submitted for publication without being read. Manuscripts should be sent to the Editor, Dr. T. D. Ford, Geology Dept., University of Leicester, Leicester LE1 7RH, who will be pleased to advise in cases of doubt about the preparation of manuscripts. The Transactions is normally issued four times a year to paid-up members of the British Cave Research Association. Subscriptions are due on January 1st annually.

Full Members £3 per annum or U.S. $8.50

Corporate Members Clubs £3 per annum or U.S. $8.50

Institutional Members £4 per annum or U.S. $11.00

Back numbers of the Transactions and other publications can be obtained from Bryan Ellis, 7 School Lane, Combwich, Bridgwater, Somerset TA5 2QS

Printed by Hawthornes of Nottingham Ltd.