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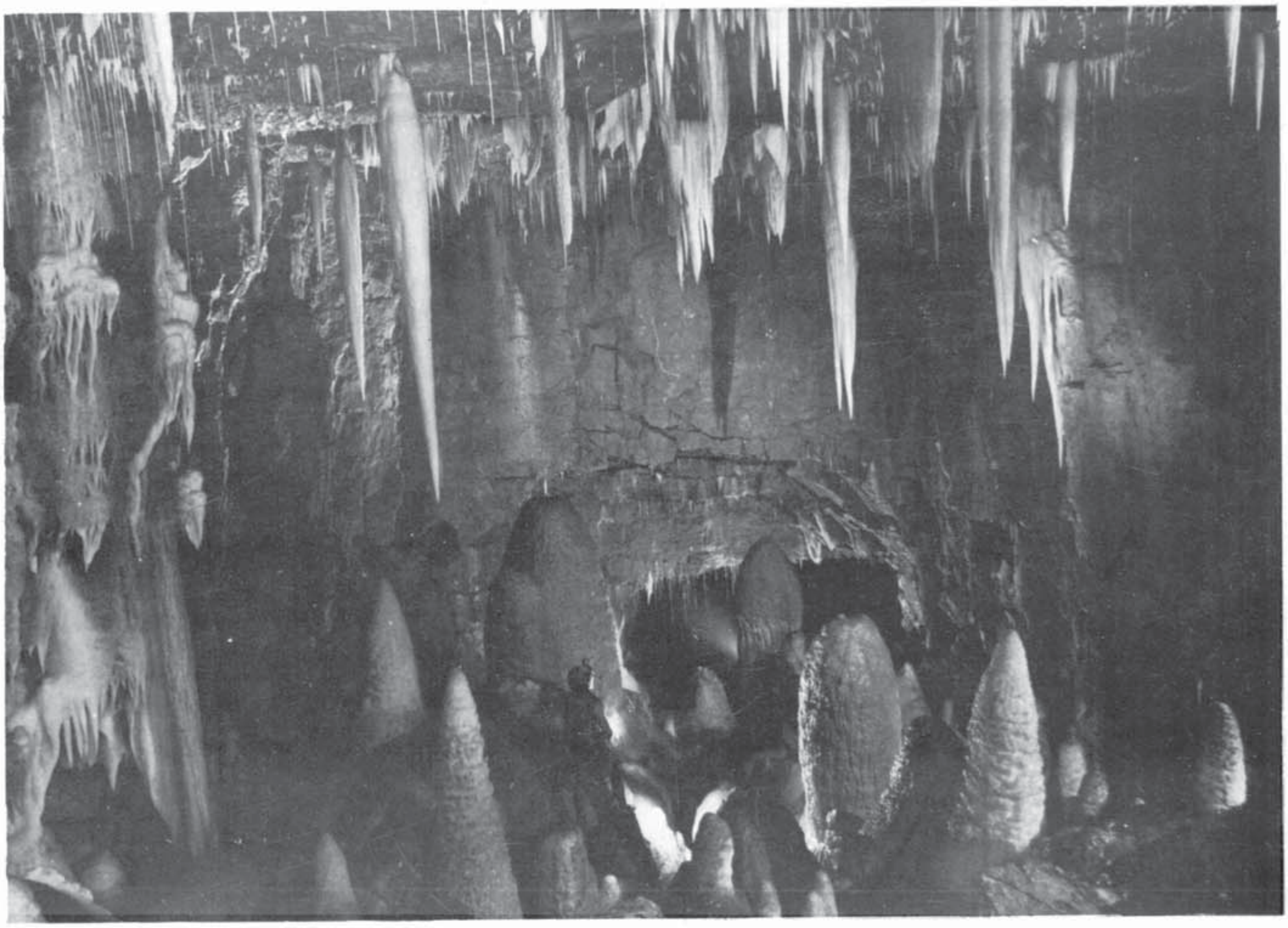

Otter Hole

Derbyshire Sough Hydrogeology

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by Clive Westlake

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OTTER HOLE, near Chepstow, Wales

by J. V. Elliott, C. D. Westlake & M. E. Tringham

Abstract

Discovered in 1974, Otter Hole was explored up to a final length of 3.2 km during the following 2 years. Some of the most impressive speleothems in Britain were found. Dye-tests have established a catchment area of swallets draining from the Old Red Sandstone into the Carboniferous Limestone north of Chepstow. The cave is contained within the Lower Dolomite of the Carboniferous Limestone succession and trends along the strike of the beds round the northern end of the Mounton syncline, with subsidiary effects from the Chepstow anticline. Several passages are aligned along faults and joints. An upper abandoned series of phreatic passages, and the lower streamway can be related to the two lowest terraces of the Wye Valley, while the Tidal Sump in the entrance series is the result of a post-glacial rise of sea-level.

Otter Hole is the only major cave system found so far in the Carboniferous Limestone of the Severn estuary region. It is located at National Grid Reference ST 52539626 on the west bank of the River Wye at 13m O.D. It is best reached from the Forestry Commission car park beside the A.466 Chepstow-Monmouth road 1km. northeast of St. Arvans. A good track leads towards Giant's Cave; then a less well-defined path descends to the river bank which is followed southwards to the entrance.

DISCOVERY AND EXPLORATION

by J. V. Elliott

The first serious recording of the many sink holes northwest of Chepstow was published by the University of Bristol Spelæological Society in 1970. (Drew, Newson and Smith 1970). They were trying to trace the water which rises in the Severn Tunnel.

Some cavers had dug a few sites and some certainly seemed promising. David Parker, a member of the Gloucester Speleological Society and the Royal Forest of Dean Caving Club, called in for a drink in St. Arvans and made contact with George Gardiner and his friends who promised to show him some caves. The results of this visit were two lead mine levels and a promising cave entrance beside the River Wye. However the cave's secrets refused to yield to Dave's hammer and chisel so he tried to call in help. Why it took four years for the help to arrive must remain a mystery but it was tales of a 330 yard level and ship's ladder down a vein of galena that finally lured the RFDCC from their other projects.

It was obvious that Otter Hole (RFDCC 1974-6), as it was later called, was a good site as a low entrance emitted a powerful draught. The Bailey brothers took charge of operations and work commenced blasting a tunnel below the existing bedding plane. 100m down river was a sizeable resurgence situated in the bank rather below mid-tide level. One feature quickly noted was that after this resurgence had been covered by the rising tide the draught in the cave abruptly ceased. Work progressed steadily below the bedding plane, but at the same time someone started blasting their way across the top. This continued and the phantom digger remained anonymous. When the breakthrough came on 14th September, 1974, a couple of items of the phantom's equipment were taken through to help clear the route. In two days exploration 270 metres of cave were open and this terminated in a very strange lake.

The following Tuesday saw three RFDCC members on a photography trip. Realising that the tides were very high they wisely waited for high tide to pass then proceeded to crawl inwards. After 100 metres the unpleasant crawls end, but as they stood up rushing water could be heard. Fear caused a speedy retreat but water surged in from the bedding planes, all but drowning the frightened trio. The first lesson had been learnt: always add one hour to the time of high tide to allow for the delay in its effects on the sump.

The next evening Dave Parker and a strong G.S.S. team arrived at the cave only to be confronted by a livid phantom digger who had just recovered his bucket from the new cave. It also appeared that the entrance passages were still sumped. Over the next few weeks telephone wires burned from Bristol to the Forest as Roy Bennett of the Bristol Exploration Club gave vent to his feelings. It appeared that he had found the cave himself and had not realised it was being dug. Firm friendship was established and all subsequent exploration was a joint effort.

The mystery lake was passed to an overhanging choke. This was passed by lassoing some loose and rather muddy boulders. A proper stream passage was reached, but to explore this our lake had to be understood for manifestly it was a Tidal Sump. For a start it rose after heavy rainfall and cut off the way through to the stream beyond. But, most important, it flooded with the rising tide and it was found to shut for 6 hours in every 12 without exception, with a rise and fall of over 6 metres. So to explore the stream passage both tide and rainfall had to be considered and neither were very kind. By 3rd November the Second Choke was reached 600m from the entrance. The entrance series was artificially enlarged in one place and a fixed ladder put up into the First Choke: then, with some rapidly reactive chemical help, the Second Choke was passed. Frustratingly a ladder was needed. Again, owing to the weather it was several weeks before the pitch was descended. The streamway was regained and followed for 100 m to a sump (Sump two). This was free-dived but only was followed by a further deeper sump. The past few months had been plagued by bad weather causing the entrance to remain flooded for weeks. This was a final disappointment.

Two divers from the RFDCC made tentative exploration but it fell to Martyn Farr (South Wales Caving Club and Cave Diving Group) to pass two short but awkward sumps. These are about 12m and 6m and are not free divable. He explored 180m of large stream passage to further sumps not yet passed.

While this was going on the draught had been re-located and some upper chambers dug into. Religiously the draught was followed by blasting and digging a low tunnel. Slowly progress was made, cavers racing in as the Tidal Sump dropped and racing out as it relentlessly rose again some six hours later.

On December 27th 1975 Roger and Laurence Bailey, Rollo Gillespie and Phil Scwarze broke through into the Extension just as time and energy were running out. They followed a large passage with superb stalactite formations for 200m. Here it turned right and grew in size and splendour. Dazed by the discovery they still had to move out at speed!

The weather has always had a say in exploration and this time it really excelled, causing widespread flooding throughout the country. Nevertheless on 10th January, 1976, the same party were joined by Roy Bennett, Jim Hay and John Elliott. Exploration commenced, quickly reaching the fantastic Hall of Thirty. The passage appeared to end but a continuation was followed through more splendour. After some 400m a rest was needed and this set the site for Camp 1. Exploration still continued but the character of the cave changed with many slippery loose boulders. Then Fault Chamber was reached and with it appeared about six ways off. This was too much and the tide was rising so a hasty retreat was made. The next weekend the two Baileys with Roy Bennett pressed in as usual. The second party joined by Colin Graham of SWCC (a resident in the Forest who had refused to believe such a cave existed) went into the cave at low tide intent on the first over-tide trip.

At Fault Chamber the first team was met returning. They were red-faced and incoherent and only gasped words like 'fantastic chamber', 'tunnels' and 'a cairn'. The second team continued onwards and sampled the delights especially at Long Straw Chamber. Eventually their cairn was found showing where they turned back. Over 500m of new cave had been explored with some of the best stalactite formations yet.

The large phreatic tunnel descended gently into the darkness and following it gave a strange feeling that there might be no end to it and it was decided to go to the end no matter how long it took. After a further 500m reality returned with a large boulder choke halting progress in Tunnels Left. This trip lasted 13 hours which is now quite normal in the cave.

Further passage of significance was found on 6th March, 1976. Tunnels Right was increased in length by carefully breaking a way through stalagmite. It was well worth it for in its 200m length was found an amazing green crystal bath. The passage is, however, a nightmare of delicate stalactites. On the way out Rollo Gillespie investigated a small tube at the start of The Extension and backed up by a reluctant John Elliott, climbed high into a nasty choke. A small hole led down into blackness and Gillespie pulled a large rock out of the way causing the whole choke to shudder. Elliott, not quite having passed out with shock, carefully followed Gillespie into the void and a 15m boulder ruckle led to the floor of a huge passage found to be 200m long and containing some beautiful calcite and the magnificent hanging Crystal Balls.

In May, 1976, Martyn Farr dived the sump at the end of the cave but no dry passage was reached. The long process of surveying was taken on by Dave Underhill of Birmingham University Speleological Society. Clive Westlake took many photographs and also supervised the dye-testing. Both Gloucester Speleological Society and Hades Caving Club helped with taping formations and from the latter club Graham Crisp produced the superb sound-slide sequence which does this beautiful cave full justice.

CAVE DESCRIPTION

by C. D. Westlake

ENTRANCE SERIES

The entrance series is fairly arduous and extremely muddy. A few metres inside is the gate and immediately beyond is a 3m drop. The way on is through a muddy crawl indicated by the black PVC pipe leading to the lowest point in the entrance bedding planes. This region becomes impassableduring wet weather or on a high tide of more than 14.7m. Beyond the passage enlarges to stooping height and the none too obvious way on is to the right; ahead are hideously muddy bedding planes trending towards the resurgence. By negotiating various mud-plastered clinbs and grovels more commodious passages are encountered, the general trend now being westwards. The cave is decorated with formations which would be quite attractive without their coating of mud which rapidly increases in filthiness and all-pervasiveness as the Tidal Sump (Sump 1) is approached.

The hydraulics of this notorious obstacle, which is found some 300m from the entrance, are explained below in Hydrology, but cavers will presumably visit it at low water. Then the approach is down a steep slope of usually knee-deep mud to a 6m diameter pool with about half a metre of water over half a metre of liquid mud. Care should be taken to avoid loosing boots, ammunition boxes or cavers. On the far side of the pool is an arch of stooping height with the main stream of Otter Hole flowing outwards. Above is a tight crawl through an eye-hole which provides an alternative route open a few minutes longer than the lower tunnel. The way on is over grotesquely muddy boulders to the foot of a 5m fixed iron ladder. This leads to the First Boulder Choke where the squeezes are quite straightforward. There is an emergency food dump in a small chamber at the highest point in the choke. Beyond, a sordid scramble leads to the stream and the cave takes an abrupt turn to the northwest, progress becoming easier in the almost attractive rift streamway. Despite a short traverse and several boulder obstacles the next 200m can be covered quickly and there is one quite impressive boulder hall. Where the stream is confined to a bouldery trench to the left, dry bedding planes to the right can be followed to the Second Boulder Choke.

The way through is an awkwardly tight chimney which is not easily found at the right of the choke. At the top is a boulder-strewn rift ascending to a 7m ladder pitch down to the stream which is followed for 120m to Sump 2. Though this is only 60cm long and free-diveable, Sump 3 is encountered after only 20m. It is 13m to an airbell followed by the tight 7m Sump 4. A large streamway leads for 150m to Sump 5 which is 30m to an airbell, followed by Sump 6 penetrated for 12m to date.

Rather less than half-way from the 7m pitch to Sump 2 is the turn off to the Extension. This begins as an ascending rift to the north-east, continues as a series of climbs, squeezes and rifts, all very muddy, and ends 20m above the streamway in the Extension. The draught is usually the best aid to navigation in this confusing region. The Extension is reached in a 4m x 2m passage with Crystal Balls Passage going to the right and the main route to the left.

THE EXTENSION

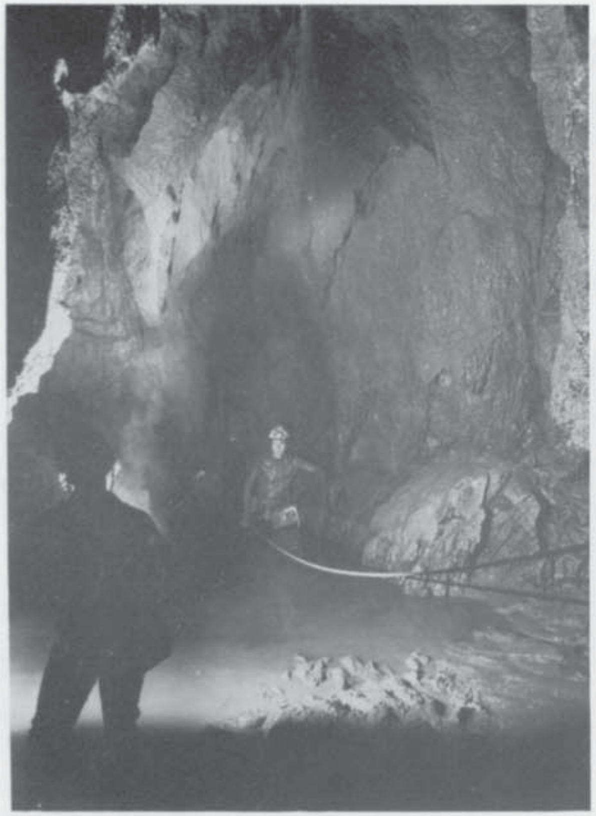
Whereas the caving so far has been ugly and punishing, the remainder passes quite easily through scenery of unimagined splendour, the only problems being the length and remoteness of the cave. First, the route to the end of the cave is described then the only two significant side passages.

MAIN ROUTE

Having turned left (west) in the Extension the caver will not be struck dumb by the very ordinary 4m x 2m passage but after 70m a delicate crystal pool on the right heralds things to come. Quite abruptly the passage enlarges then massive, colourful bosses and stalctites loom ahead. Next comes the Hall of the Thirty, a place better seen than described. The route throughout the Extension is fairly easily followed because of the extensive taping of the formations but the way out of the Hall of the Thirty is a slightly obscure downward slot. Notable formations in the next 50m include a bent straw above a bent stalagmite, spectacular black and white bosses and curtains and exotically coloured flowstone. Camp 1, about 300m into the Extension, is reached through a hands and knees crawl amid pristine white curtains. An aven here provides a steady flow which is collected in various polythene containers and is one of the few sources of clean water in the far reaches of Otter Hole. By ascending a large boulder slope beyond this aven the way on can be found to the right.

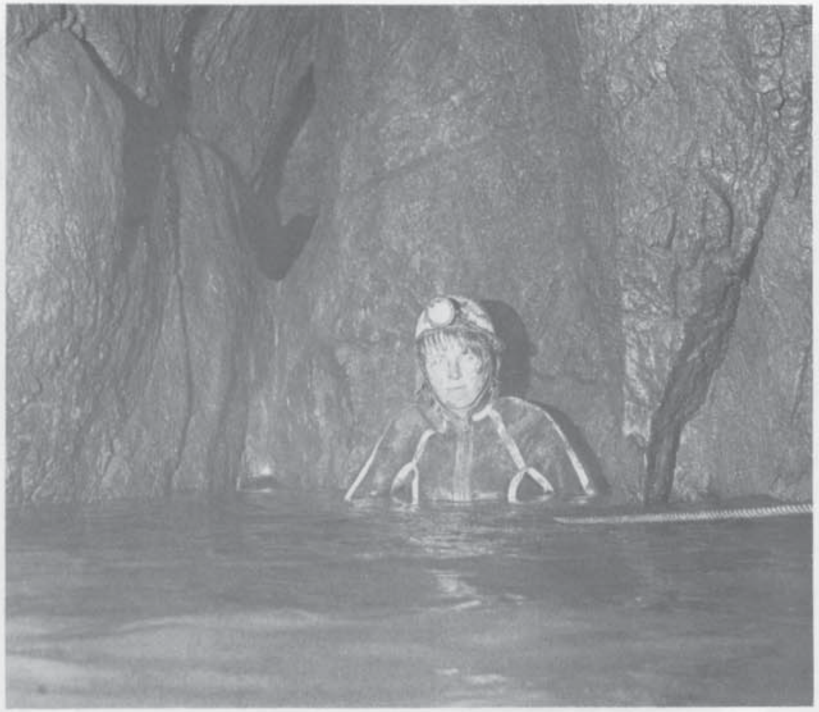
Although the general trend of the Extension has so far been west, the next section runs roughly north west. For 200m the cave is largely devoid of calcite but there are extensive mud formations. Where the passage meets Vicarage Fault there are turnings left, where confused rifts eventually choke, and right through an unstable boulder choke to a flowstoned rift where the draught is lost. The main route reverts to its westerly direction again becoming full of stupendous speleothems. Massive sheets of flowstone decorate the walls of the rifts leading to Long Straw Chamber where the caver may well pause amid the awesome display of crystal pools, flowstone and straws as much as 4m long. 30m of rift lead to a 3m climb with a short and finely decorated side passage on the left. The next section of passage is notable for myriads of translucent straws and exceptionally white flowstone banks, but these abruptly give way to a gently ascending tunnel 4m wide and 1.5m high, floored with red gour pools. Varied caving for 100m leads to Tunnels Junction.

Tunnels Left is the route to the end of the cave. The character of the system changes abruptly to a phreatic tunnel, usually about 4m in diameter and trending south-southwest. At first it is boulder-floored and throughout the formations are of no more than ordinary magnificence. The passage descends gently, especially towards the end of its 500m length where progress is through sand-floored hands and knees crawls linking blind avens on cross-joints. At the end of these crawls a boulder choke is encountered and by climbing up it a large high-level chamber can be reached. By going on straight past the base of the choke and over a mud bank a sizeable stream is met at the point where its downstream course sumps. Upstream is a duck and the majority of the water emerges from a constricted bedding plane to the left. Straight on a tiny trickle can be pursued through 30m of sordid passage to a roomy sump pool. Diving (Farr 1976) revealed an airbell with an aven after 15m, followed by further 30m sump reaching a depth of 12m and emerging in another big aven. The third sump was penetrated for 12m to a depth of 10m.



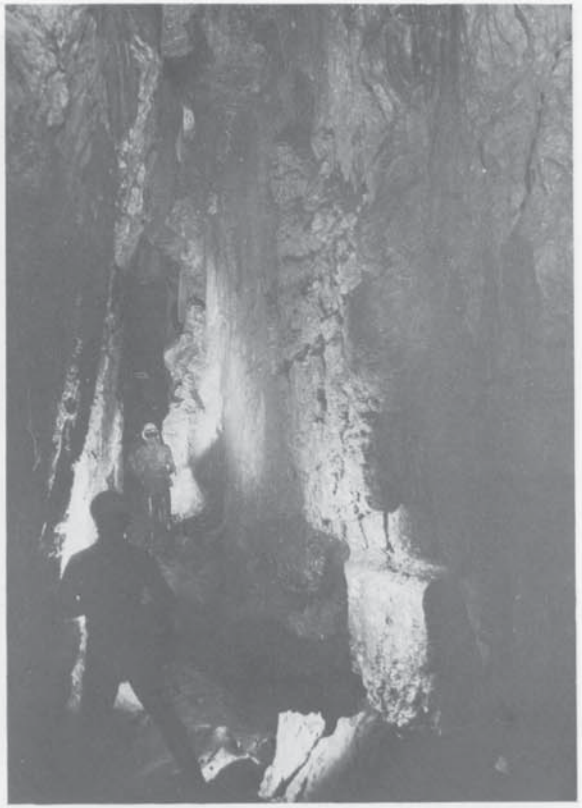
Tidal Sump at low water

(photo Clive Westlake)



Tidal Sump about to close;
only eyehole accessible.

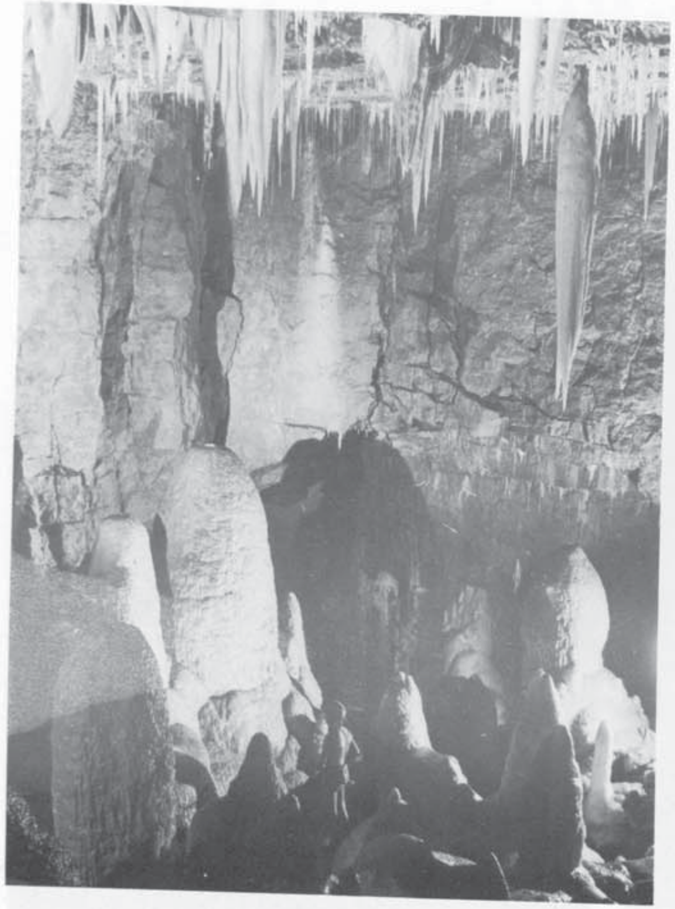
(photo Ian Davinson)



Streamway aligned along a fault
in the Entrance Series.

(photo Clive Westlake)

OTTER HOLE, Chepstow, Wales



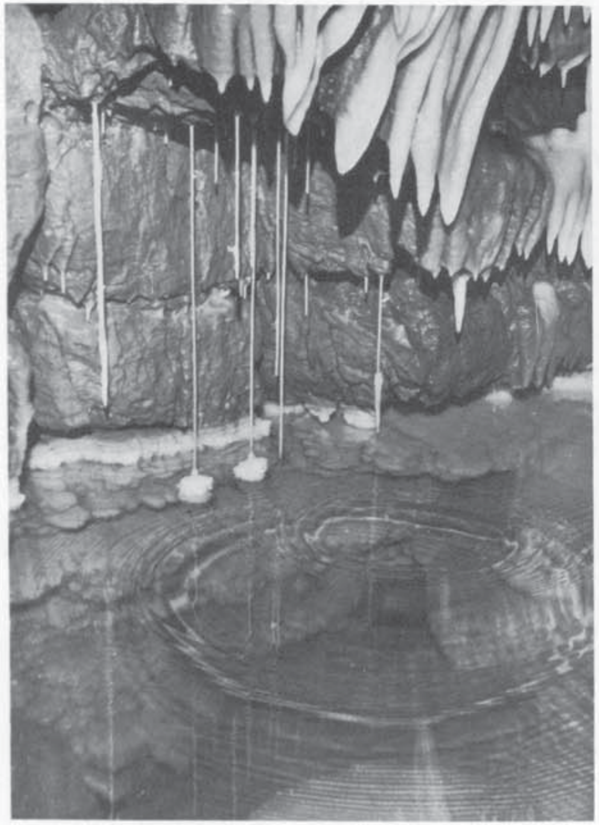
Hall of Thirty

Near Long Straw Chamber

Long Straw Chamber

OTTER HOLE Chepstow Wales

(photos by Clive Westlake)

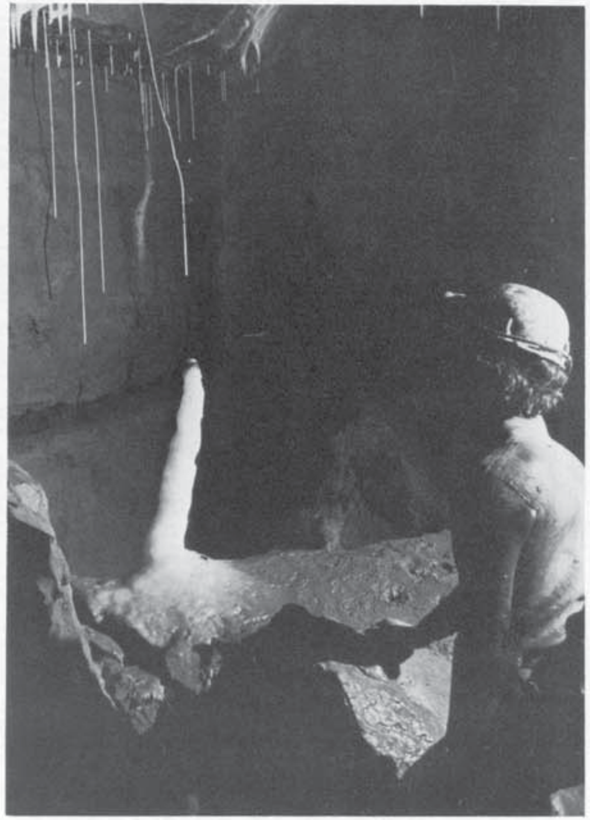


The Crystal Balls

Phreatic tube in
Tunnels Left

OTTER HOLE Chepstow Wales

(photos by Clive Westlake)



The Bent Pair of
Stalactite and stalagmite

TUNNELS RIGHT:

This passage, which is rather more than 200m long, is entered by turning right at Tunnels Junction. It is considerably smaller than Tunnels Left and in several places extreme care is needed to avoid the fine straw stalactites which decorate the passage. Half way along is a splendid green crystal pool (the cause of the green colour is unknown) and the passage ends in a pool choked with a curiously flakey type of calcite.

CRYSTAL BALLS PASSAGE:

At the start of the Extension is a short tight crawl on the right. A confusing route up unstable boulders leads to the top of a choke where the roof seems in imminent danger of becoming the floor along with any caver foolish enough to linger in the vicinity. An alarming, though not particularly hard climb down, followed by a steep boulder slope leads down to safer going in a passage 5m wide x 10m high. Gour pools and dramatically coloured curtains lead to a short crawl and the last section of the passage which is renowned for its crystal balls. These roughly spherical calcite growths cluster round the ends of straw stalactites where they meet the water in gour pools. Altogether an awesome place!

HYDROLOGY

by C. D. Westlake

Otter Hole drains a large area to the west of the tidal reaches of the River Wye (see fig. 1). Its mean discharge is hard to estimate when the cave is inaccessible in wet weather, but a figure of 200 litres per second is probably not too inaccurate; thus by British standards Otter Hole is a large resurgence. The stream resurges between high and low water marks on the west of the Wye about 100m SSW of the entrance. Its course between the Tidal Sump and the resurgence is not negotiable and is unlikely to be attractive. From the Tidal Sump it is followed upstream for about 500m to Sump 2 and divers have proceeded 200m further.

The only other significant stream in the cave is encountered at the very end of Tunnels Left. It cannot be followed any distance up or down-stream and its volume is about half that of the main stream.

The mainstream water has been noted to smell strongly of diesel, manure or both on various occasions and it cannot be recommended for personal use in the cave.

WATER TRACING:

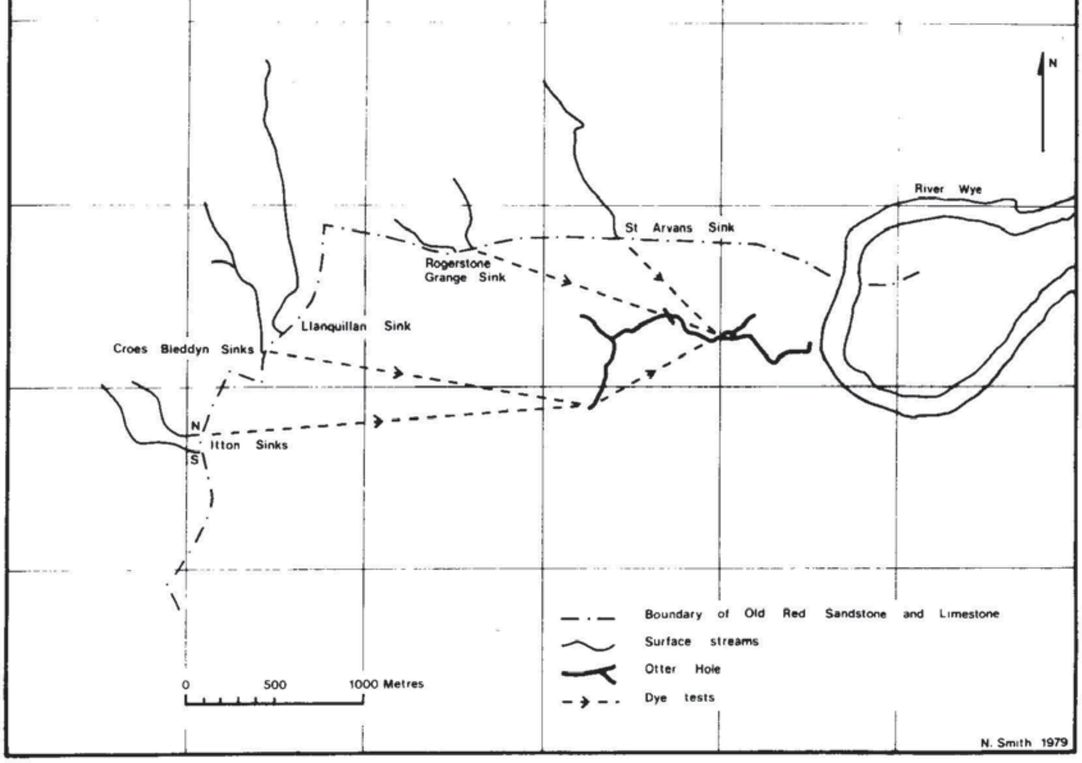
The only relevant hydrological work done in the region before the discovery of Otter Hole had been the UBSS's reasonably convincing demonstration that Cas Troggy (ST459928) feeds the Severn Tunnel Great Spring (Drew, Newson and Smith 1970) but little was known of the area further east towards Otter Hole. In 1977-8 a series of dye tests involving numerous cavers from several clubs established the catchment area of Otter Hole.

The first test proved the water at the far end of Tunnels Left flows to the main stream re-appearing at Sump Two. As already noted there is a discrepancy between these two flows which was elucidated when the next two tests from St. Arvans Sink, otherwise known as the Rookery (ST513968), and Rogerstone Grange East Sink (ST506967) were positive at Sump Two but negative at the end of Tunnels Left. It now remained to establish the origins of this latter stream and tests from Croes Bleddyn (ST494962) and Itton North Sink (ST490957) were positive. In the meantime the water sinking at Camp 1 was proved to reappear at Sump Two.

It is reasonable to assume that the intervening, untested, swallets such as Llanquillan Quarry Sink (ST494963) and Itton South Sink (ST491956) also flow to Otter Hole. The combined catchment areas of these swallets and the limestone between them and the Otter Hole resurgence total approximately 8 sq. km. which is an area appropriate for the 200 litres per second in the cave. The total area of the limestone outcrop to the west of the Wye is in the order of 40 sq. km.

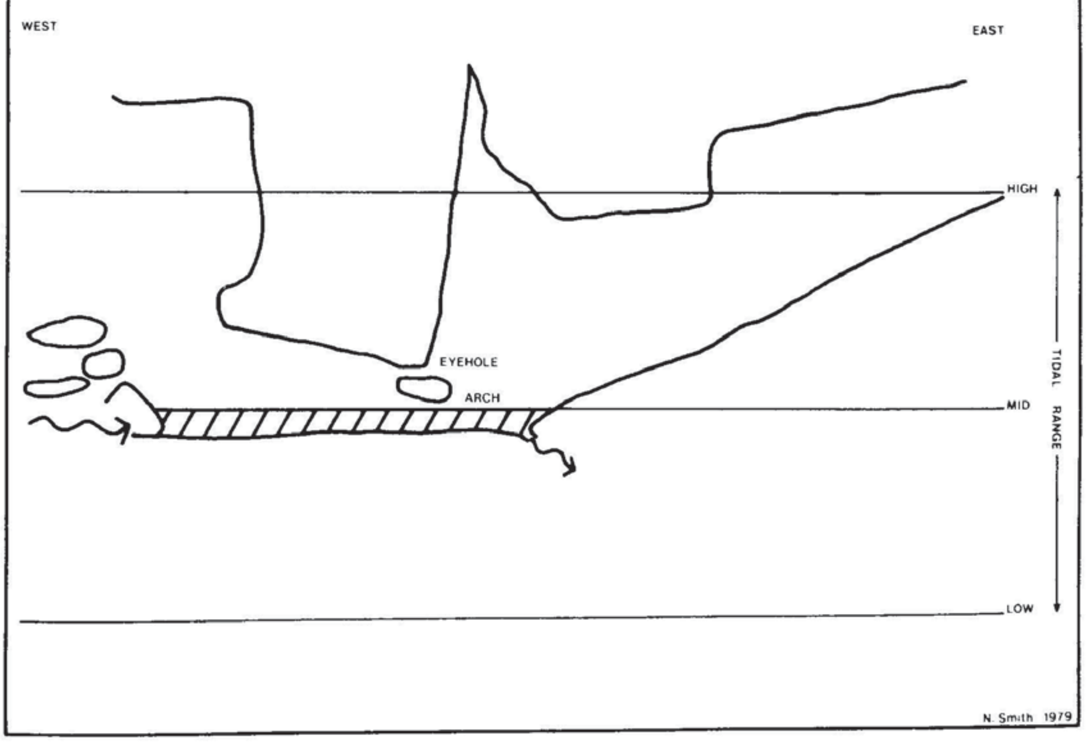
THE HYDROLOGY OF THE OTTER HOLE AREA

Fig. 1.



DIAGRAMMATIC SECTION OF OTTER HOLE TIDAL SUMP

Fig. 2.



so it is not unreasonable to suggest that the drainage beyond the limits of the Otter Hole catchment is to the Severn Tunnel Great Spring which is known to have a mean discharge in excess of 500 litres per second.

THE TIDAL SUMP:

Although some caves in County Clare end in sumps at sea level, the Tidal Sump in Otter Hole is a unique feature. Its operation is not fully understood, but the following description (see fig. 2) is intended to explain what happens during the drier periods when it is accessible.

If the Tidal Sump is approached at low water, the main stream is observed to flow into the sump pool where it sinks to be seen next at the resurgence which is rather above the low tide mark of the Wye. Now the Tidal Sump can be passed by merely wading under the arch at the upstream end. This condition prevails until mid-flood tide, some three hours after low water. At this juncture the water, having risen in the river and the unknown passages upstream of the resurgence, reaches the level of the Tidal Sump which begins to fill, the way through becoming impassable to cavers within about half an hour. The tide and the Tidal Sump continue to rise until high water approximately three hours later. The entire sump chamber and long stretches of passage upstream well beyond the traverse are submerged and remain so until mid-ebb tide. At this point the retreating tide uncovers first the eyehole then the arch beneath it, this process again taking about half an hour and being accompanied by loud gurgling and glooping. The tide continues to ebb for some three hours until low water but this has no visible effect on the Tidal Sump as it is perched at approximately mid-tide level. Thus cavers can pass during a period of about six hours when the Tidal Sump is open, but careful attention to Arrowsmith's tide tables is essential to avoid disappointment and/or discomfort. Some cavers elect to go in as the sump opens and return before it closes, while others wishing to spend longer than the six hours this allows in the further reaches, go in before the sump closes and return after it opens; obviously such parties are temporarily 'trapped' in the cave.

This description applies only during relatively dry conditions and Otter Hole has remained inaccessible during long periods. On these occasions the Tidal Sump has been observed at low tide when the water level has been stationary but far above the arch and eye-hole. This is not caused by excessively high tides which are of course matched by correspondingly low tides and are not confined to winter when the Tidal Sump is most likely to be impassable. High stage in the River Wye may have some influence but the most likely explanation is the increased discharge of the main stream. It seems that the input is greater than the capacity of the restricted passages to the resurgence so the Tidal Sump remains at a level above that of the eyehole even at low water. This explanation is supported by accounts of the flood which trapped cavers from Bath University over two high tides in June 1979.

Under wet conditions Otter Hole remains inaccessible for months because the Tidal Sump does not open, although a further hazard exists in the bedding planes en route from the entrance which are flooded by tides higher than 14.7m. They drain only slowly perhaps because of the addition of percolation water. In general Otter Hole is inaccessible between September and April though it does also become impassable in severe summer floods. The fact that exploration continued intermittently through the winter of 1975/76 indicates that no hard and fast rules can be applied.

GEOLOGY AND ORIGIN OF OTTER HOLE

by Mark E. Tringham

Otter Hole provides an excellent example of a major cave system in which a variety of geological and morphological features may be seen. The cave is unusual in that as well as containing an active streamway and abandoned dry passages, it also contains some intertidal sections. A notable feature of the cave is the proliferation of massive calcite formations, especially in the abandoned dry passages. This article presents the results of a recent study made of the geology and morphology of the cave and surrounding countryside.

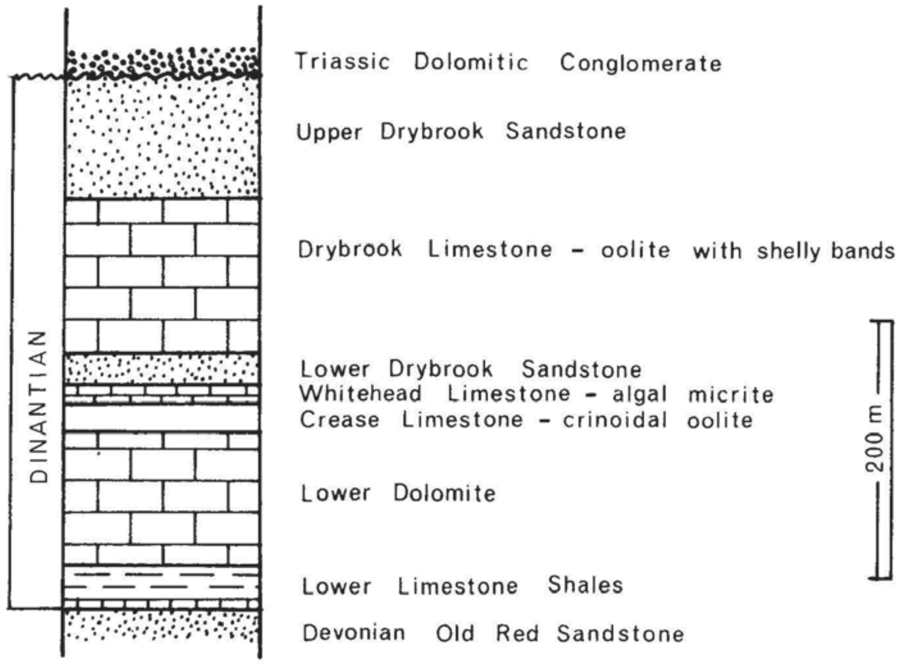


Fig. 3 Dinantian stratigraphy of the Chepstow area. The Dinantian sequence comprises shale, dolomite, limestones and sandstones, which total an approximate thickness of 400 m.

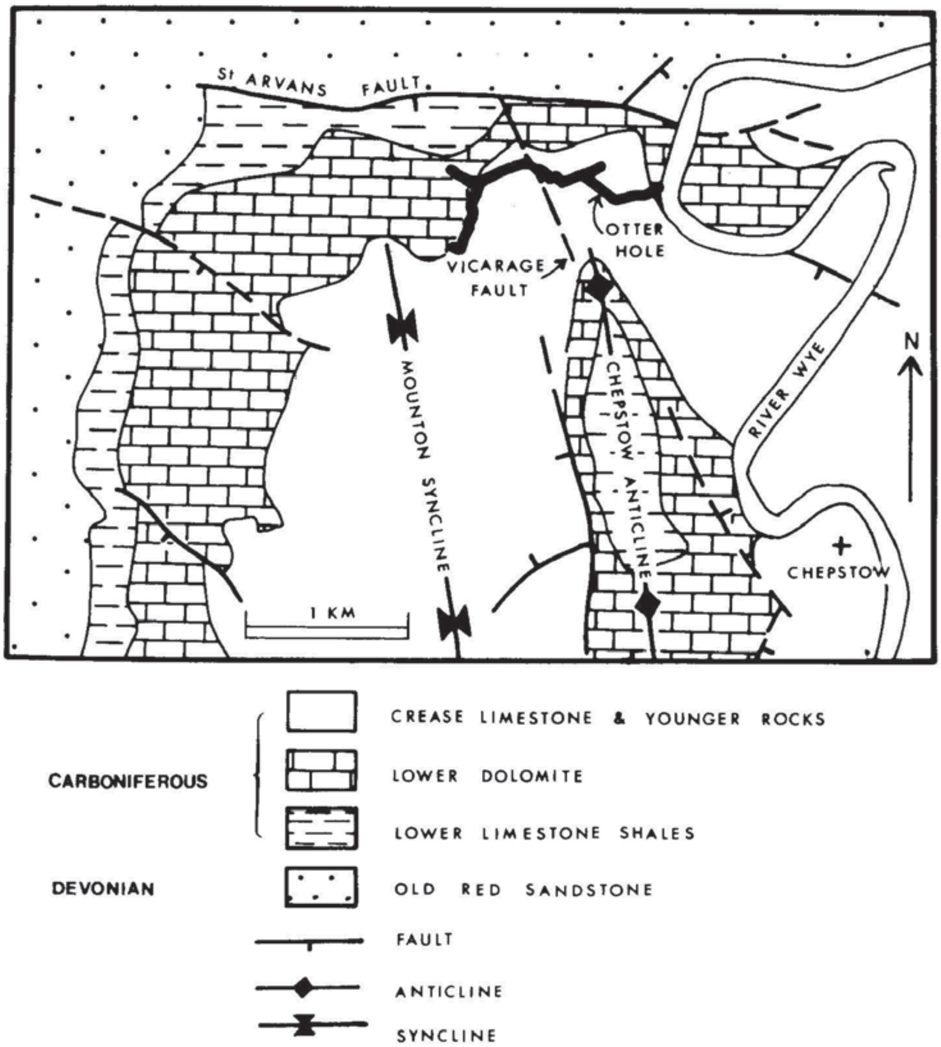


Fig. 4 Geological map of the Chepstow Area showing the relationship between Otter Hole, the River Wye, and surrounding geology.

The geology of Chepstow and surrounding areas has been described in detail by Welch and Trotter (1961) in the Geological Survey memoir for Monmouth and Chepstow. Around Chepstow the Carboniferous Limestone is represented by a succession of limestone and sandstone formations (Fig. 3), which may be correlated with those of the Forest of Dean with only minor thickness changes. However, in contrast to the Forest of Dean, out of the five limestone formations present, only the Lower Dolomite is known to contain a significant cave.

The Lower Dolomite is a monotonous series of well-bedded grey sparry dolomites and dolomitic limestones 100m thick. The original sedimentary features such as ooliths and fossils have mostly been obliterated by dolomitisation. Bedding surfaces are commonly undulating or stylolitic, with thin partings of red or green clay.

Around the edge of the Carboniferous outcrop, surface streams flow off the surrounding Old Red Sandstone and sink into a number of swallow holes in the basal limestone of the Lower Limestone Shales. The basal limestone is a red shelly crinoidal limestone separated from the Lower Dolomite by 30m of shale.

The outcrop pattern of the Carboniferous Limestone is influenced by a number of folds and faults of Hercynian age. In contrast to the rest of South Wales, fold axes in the Chepstow area trend NNW-SSE perpendicular to the regional trend. The folds generally plunge south and are asymmetric, synclines having steeply inclined eastern limbs and more gently inclined western limbs.

Faults affecting the area include one set of E-W trend, such as the St. Arvans Fault which bounds the Carboniferous outcrop to the north of Chepstow, and another set trending NNW-SSE parallel to the folds. The NNW-SSE faults have a reverse throw, and on structures such as the Chepstow Anticline they partially replace the folds along their length.

Of particular importance to the formation of caves is the Pleistocene and Recent geological history of the area. The present day landscape and drainage has evolved by progressive river downcutting during falls in the sea level up to the end of the last ice age, and by a rise in sea level since that time. In the Wye Valley pauses in downcutting are represented by four terraces between 3m and 60m O.D. Of the four, only the second terrace is recorded from the Chepstow area, at a height of 25-30m O.D. (Welch and Trotter 1961). At Chepstow the presence of a river channel buried beneath estuarine alluvium indicates a more recent rise in sea level of at least 15m since the last ice age.

Otter Hole lies within the Lower Dolomite, mostly beneath a cap of Crease Limestone, at a depth of about 80m beneath the surface. The cave occurs in the Mounton Syncline and on the projected extension of the Chepstow Anticline. The Mounton Syncline is a southward-plunging gentle fold, on which dips in excess of 10^{o} are rare, while the Chepstow Anticline is a tight but laterally impersistent structure. In the area of the cave the Chepstow Anticline is replaced by a NNW-SSE trending fault, here named the Vicarage Fault, which downthrows to the ENE. The fault was mapped by the Geological Survey as passing near St. Arvans Vicarage, but is seen within the cave slightly to the east with a steep inclination (Fig.4).

The line of the cave approximately parallels the outcrop of the boundary between the Crease Limestone and the Lower Dolomite. Given a flat land surface and a steady dip, this indicates that the cave occurs at a particular stratigraphic position within the Lower Dolomite. Measurement of bedding orientations in the cave reveals that around St. Arvans the Mounton Syncline forms a continuous gentle fold as far to the east as the Wye, interrupted only by the Vicarage Fault. The plan of the cave forms a curve which generally contours this southward plunging syncline.

The geological features of the cave are summarized in Fig. 5. Many structures such as folds and faults are well displayed underground, and have a significant effect on the plan of the cave. However, many structures are not seen on the surface, either because much of the surface geology is obscured by soil cover, or because the structures do not persist to the surface. In many parts of the cave a close relation occurs between the location and type of cave passage and particular geological structures.

The cave maintains a gentle uphill gradient from 13m O.D. at the entrance to about 40m O.D. at Camp One, but beyond Tunnels Junction along Tunnels Left, the cave is unusual in that it is inclined gently downwards between a height of 42m and 31m O.D. at the end of the cave.

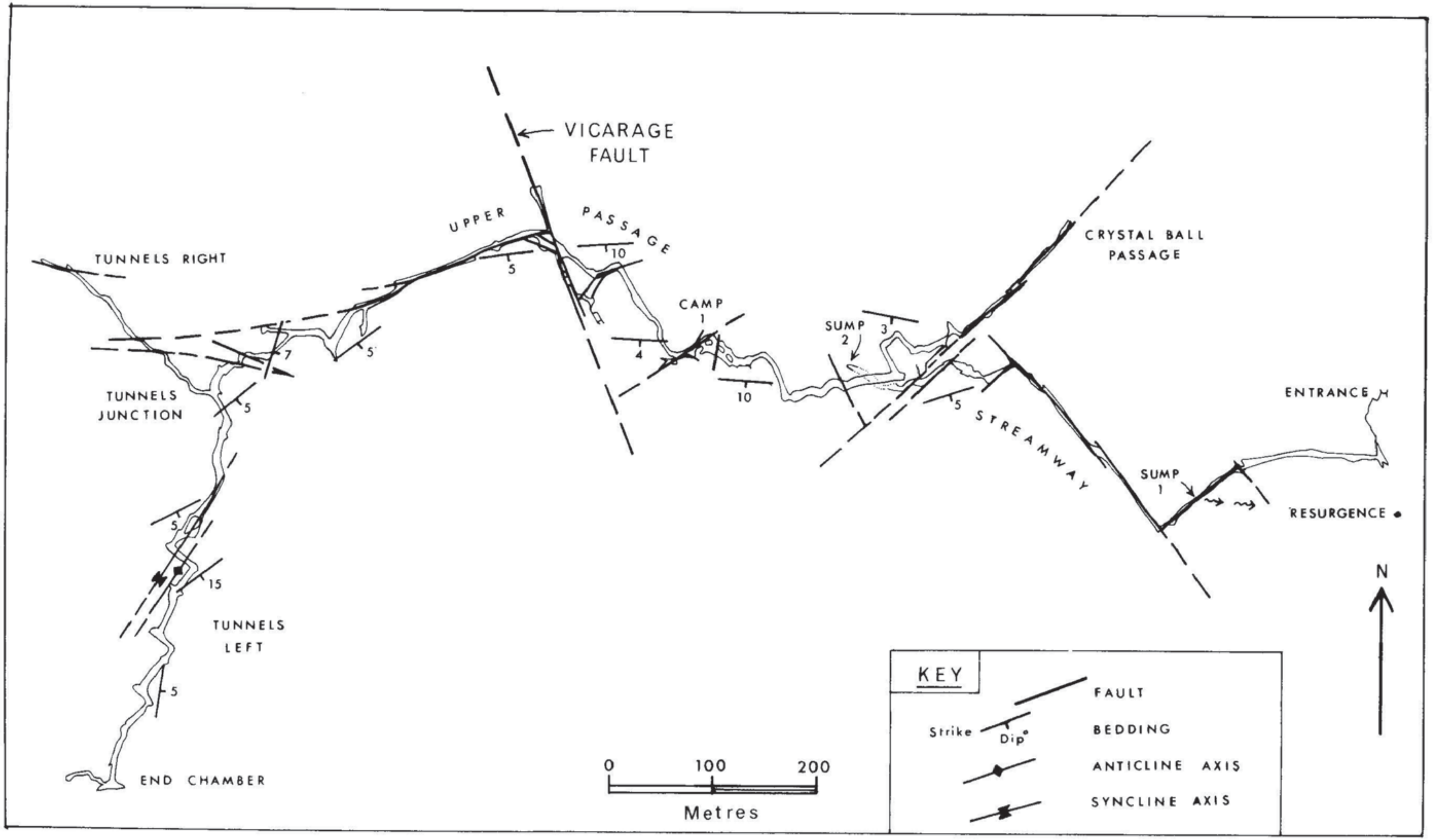


Fig. 5 . A plan of Otter Hole, showing principal geological features in the cave.

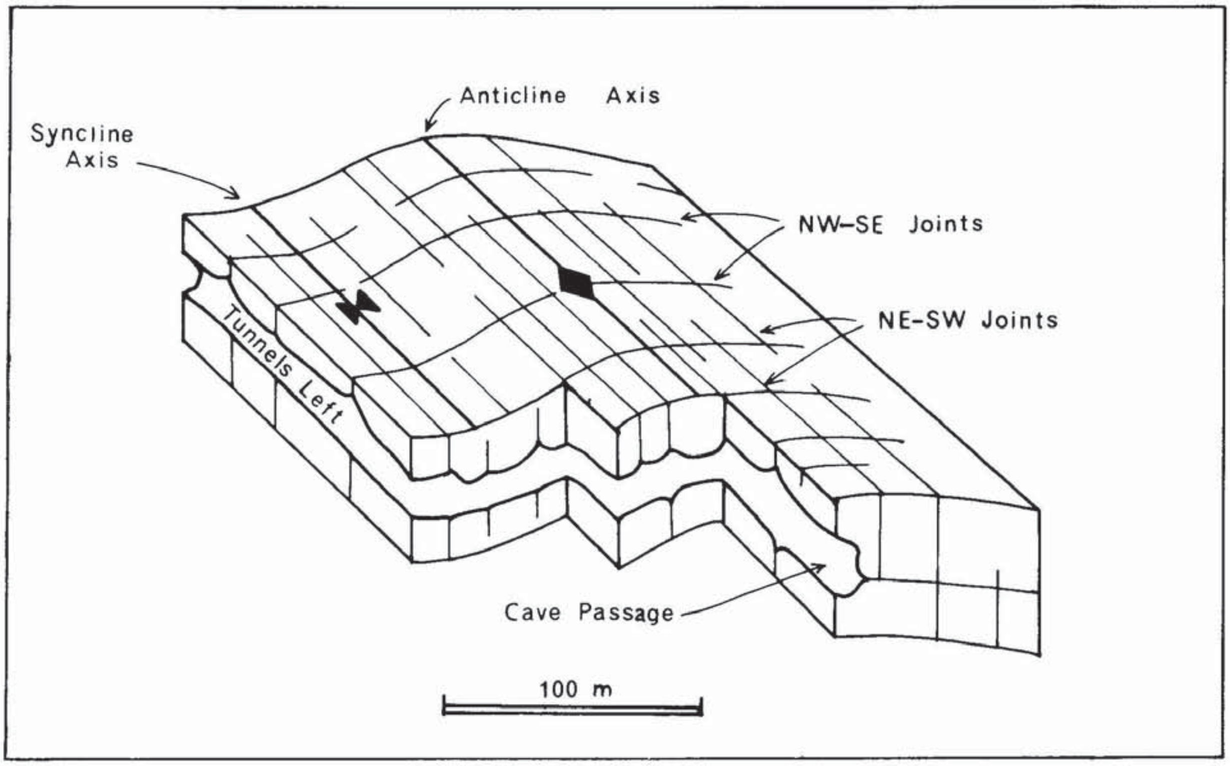


Fig. 6 Tunnels Left, as viewed from the west, illustrating the relationship between the cave passage, folds and joints.

This unusual inclination is explained in that the passage follows the general trend of a pair of minor folds which plunge to the south-west (Fig. 5). In detail, the passage follows two well developed sets of joints which lie parallel and perpendicular to the folds. The geometry of the folds joints and cave passage is illustrated in Fig. 6. It is thought that an increased frequency of jointing around the folds has localised the passage at this slightly deeper position in the Lower Dolomite.

Of particular interest are a number of passages which follow faults; in many places these are visible for distances exceeding 200m. The faults are all either vertical or steeply inclined, and form two sets which trend approximately NNW-SSE and NE-SW. In some places zones of fractures occur rather than single fault surfaces. For example, the Vicarage Fault forms a zone of vertical or steeply inclined fractures, which have formed a rift complex of passages.

The faults may be recognized by the spectacular occurrence of breccias up to 5m or more in thickness, where crushed fragments of Lower Dolomite are cemented in calcite, dolomite and clay. The rock adjacent to the faults is in some places strongly veined by calcite, which when eroded has formed a distinctive 'box work' surface. Fault surfaces show slickenside scratches and crystal fibres, produced by movement between rock surfaces on each side of the faults. The orientation of slickensides, when used as a guide to the direction of fault movement, indicates that on many faults this was in a horizontal direction, the faults being of wrench type.

The inherent mechanical weakness of the fault breccias has in some places caused roof collapse, and large boulder piles. Where two or more faults meet, this collapse is particularly evident, and near Camp One an aven which marks the highest point in the cave has formed at such a position. Where faults are traced along their length they are frequently seen to branch, or to form an en-echelon arrangement, where one fault replaces another at a slightly offset position. In some cases this has yielded slightly offset cave passages which are joined by chambers.

The permeable and soluble nature of the fault rocks is attested to not only because the cave has formed along so many faults, but also because many fine formations have formed along the same structures. The water percolating down through the faults has in some places produced spectacular red and black formations of iron-rich calcite.

GEOMORPHOLOGY

The cave development has been deduced from the character of individual cave passages, and the interrelation between different passages. In Otter Hole, passages have been extensively modified by collapse of walls and roof, and by the growth of speleothems, so that in many places original passage morphology is no longer visible. For this reason detailed estimates of cave development are difficult to make for some passages, however a generalised synthesis is possible. Features used to distinguish phreatic and vadose development include passage shapes, altitudes and gradients, and water flow direction indicators such as scallops and ripple marks.

The cave is divided into two main parts, a lower active streamway, and an upper dry passage. The upper passage forms the larger part of the cave, and consists of one main route, and one tributary, Tunnels Right. The main passage maintains a remarkably gentle downward gradient between 42m O.D. at Tunnels Junction, to 32m O.D. at the end of Crystal Ball Passage. The downward gradient in the opposite direction along Tunnels Left has previously been mentioned in connection with the geological features of the cave. Passage cross-sections, where preserved without breakdown, such as at Tunnels Junction, are either elliptical or circular, and large roof domes and rifts occur on some faults and joints. Where present, scallops and rippled sand banks all indicate an original water flow direction from the end of the cave towards Crystal Ball Passage. These features indicate that the upper passage developed under phreatic conditions without significant vadose modification. This phreatic cave, with its contributary Tunnels Right, acted as a route for water draining towards the Wye, when the water table was well above its present level. The height of the upper passage at 32-42m O.D. may be correlated with the second terrace of the Wye at 25-30m O.D. It is proposed that the passage formed below a water table which sloped gently down towards the Wye. Enhanced solution at such a position probably occurred by mixing of stream and percolation water, in the manner proposed by Bögli (1971). After the upper passage was drained speleothem infilling began, faults and joints providing suitable conduits for percolation water. However, in Tunnels Left a thin veneer of clay coats walls and formations up to a height of about 33m O.D., proving a relatively recent flooding subsequent to abandonment of the phreatic drainage route.

The active stream passage is presently partly phreatic, partly vadose, and for a large cave possesses the unique features of being partly intertidal. The stream flows from a height of 21m O.D. at Sump Two down to the intertidal parts of the cave at Sump One. For much of its length the streamway consists of one straight rift which follows a fault. Here, passage enlargement up joints and faults indicates that part of the development could have been phreatic. Upstream from the rift is a short section of anastomosing bedding cave, where both roof and floor have strongly pitted surfaces of 'egg-box' or 'spongework' shape. Another similar section of 'flat-out' bedding passages has developed near the entrance, and both these bedding cave networks are thought to have formed under phreatic conditions. The entrance forms a partially abandoned resurgence which still floods to the roof during wet weather.

The intertidal sections of the cave are of particular interest, mean tides reaching some 350m into the cave. The passages are filled by large quantities of alluvial mud which coats all parts of the passage and formations. The mud prevents access to the streamway between Sump One and the resurgence. Dried mud coats passage walls above the level reached by mean spring tides, and was probably deposited during combined fresh water flooding and high spring tides, in the not too distant past.

CONCLUSIONS

This study of Otter Hole records phases in cave development which correlate closely with evolution of the River Wye. The first phase is that of a phreatic drainage route along the upper passage, at a height which correlates with the second terrace of the Wye. Welch and Trotter (1961) consider the second terrace to have formed before the end of the Last Glacial phase (Devensian), and it is proposed here that the cave passage is of comparable age.

The second phase of cave development was initiated by capture of the stream flow to its present lower route. Capture may firstly have occurred near Crystal Ball Passage, down the route which today connects the upper passage and streamway, but now occurs further upstream. The present streamway developed under vadose and phreatic conditions, during progressive downcutting of the Wye to approximately - 15m O.D. up to the end of the Last Glacial phase.

A third and final phase in cave development is represented by inundation of the lowest parts by tidal water and alluvial mud. This took place during post-glacial rise of sea-level in the Wye Valley region by about 15m.

A number of geological controls have been important in locating the cave. Firstly, the cave as a whole has formed at a particular stratigraphic position in the Lower Dolomite, and secondly, individual passages have formed along structural features such as faults and joints. Faults are of the greatest importance, forming lines of high permeability and mechanical weakness, while joints related to folds are considered to be less important.

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THE BIOLOGY OF OTTER HOLE, NEAR CHEPSTOW

by Philip Chapman

SUMMARY

52 invertebrate and 1 vertebrate species are recorded from Otter Hole cave. Of these, 32 are troglophiles and 5 are troglobites or phreatobites. 4 species have not previously been recorded from British caves and a further 9 are new Welsh cave records. The role of individual cavernicoles in the cave community is discussed serially by taxon groups, and the account ends with a discussion of the ecology of the cave, aimed at generating ideas for future research.

British caves are not generally noted for the richness of their faunas. Jefferson (1976) summed up the general picture as follows: "..in British caves, the animals, being few in number and usually small in size, are mostly inconspicuous. Elsewhere cave faunas may be richer and include more striking creatures. This...probably explains why the biological study of caves...was slow to develop in Britain." In British caves which do support large animal populations, these are often accidentally-introduced species of little interest to the speleo-biologist. Otter Hole offers a pleasant contrast to this somewhat depressing scene.

I was introduced to the unusual nature of the fauna when presented with a strange little beetle collected by Andy Eavis in August 1977. This proved to be *Trechus micros* , a fairly rare predatory ground beetle which has been recorded from several caves, particularly in the Mendip area. Curiosity aroused, I made the first of a series of trips into the cave a couple of weeks later. It was a delightful experience. The biological interest of the muddy crawl sections eventually gives way to the beautifully decorated 'Extension' which also contains one of the most diverse communities of animals to be found in any British cave.

The work is still at a very early stage. Basic collecting has led to a list of the majority of the more common and conspicuous species, which is still far from complete. The purpose of this paper is to summarise present knowledge of the cave's fauna and to point to some possibilities for future work.

THE FAUNA

The chief biological interest of caves lies in their dark zone faunas. Little attention has therefore been paid here to the threshold, or liminal, fauna of the cave and the list of such animals is highly incomplete.

Each listed species is provisionally assigned to one of 4 classes, reflecting its degree of ecological dependence on the 'hypogean domain' (defined in Glennie, 1965). These classes (Troglobite=Tbt.; Troglophile=Tph. Habitual Trogloxene=Tx.; Accidental Trogloxene=Acc.) are used according to the generally accepted definition quoted by Barr (1968), but with 2 slight differences. Firstly, the definitions refer not to the species as a taxonomic unit, but to it as it occurs in a given locality. Secondly, I have subdivided 'Troglobites' into two subgroups: Palaeotroglobites (Tbt.) and Neotroglobites (nTbt.), following Matile (1970). Neotroglobites need show no morphological 'cave-associated' modificatios. They are recognized purely by their known local distribution. This classification is obviously tentative, and some species given nTbt. status may need to be 'demoted to Tph. status in the light of further knowledge. Where members of any of the above categories are normally found only at the cave threshold, or limen, this is indicated - for example, *Culex pipiens* is a 'Liminal Habitual Trogloxene' (LimTx.).

New cave records for Wales are prefaced by a single asterisk, and new British cave records by two asterisks.

TURBELLARIA

TRICLADIDA	Planariidae	*Phagocata vitta* (Duges). Tph.

Phagocata vitta is the most frequently encountered flatworm in British caves. According to Hazelton (1977), it prefers to shelter in the fine mud or silt at the bottom of shallow still water, from where it emerges to devour small creatures such as Acari and Collembola trapped on the surface film of the water. The Otter Hole specimens were observed gliding about on the underside of the surface film of such a pool in the entrance series. Such behaviour is characteristic of the more highly adapted troglobitic flatworms (e.g. Nixon, 1974).

NEMATOMORPHA

GORDIOIDEA	Gordiaceae	Gen. et sp. indet. Acc.

Some American and European gordians, or horse-hair worms, spend the early part of their lives as internal parasites of cavernicolous arthropods (e.g. see Bareth, 1975). However, as there are no records of such an association occurring in Britain, and as gordian cysts are small and could well be carried by percolation water entering the cave through narrow fissures in the limestone, it is perhaps safest to assume that the Otter Hole record is of an accidentally-introduced species.

GASTROPODA

MESOGASTROPODA	Hydrobiidae	Gen. et sp. indet. Tph.
STYLOMMATOPHORA	Zonitidae	*Oxychilus cellarius* (Muller). Acc.
	Limacidae	Gen. et sp. indet. Acc.

Shells of *Oxychilus cellarius* turn up commonly near entrances of Mendip and S. Wales caves, but the species is probably introduced accidentally. The little aquatic hydrobiid snail is not uncommon in the muddy, flood-prone pools along the main streamway, and may be common in the stream itself. It may be considered as a potential troglophile. A number of slugs were taken on and around the 'Camp 1 rubbish tip'. They were almost certainly accidentally introduced, and thrived only as long as the plentiful food supply lasted.

CHAETOPODA

OLIGOCHAETA	Enchytraeidae	Gen. et sp. indet. 1. Tph.
		Gen. et sp. indet. 2. Tph.
	Lumbricidae	**Allolobophora chlorotica* (Savigny). Tph.
		**Dendrobaena veneta* (Rosa). Tph.
		**Octolasion cyaneum* (Savigny). Tph.

Enchytraeids are semi-transparent, inconspicuous little worms, around 5 mm. long, which are probably common and widespread in the silt floors of shallow pools in caves. I have also taken them in a fungus-infested dipteran carcass, and in patches of decomposed cow faecal material present on the banks of the main stream passage. But their strangest habitat is inside the domed, sponge-like mass of a crimson-coloured encrusting 'creature', which is so far unidentified. This was found on damp, muddy flowstone in the Hall of Thirty, and in a pool near Long Straw Chamber.

The lumbricids include one species, *Dendrobaena veneta*, which though common in several localities in Britain, does not appear to have been previously recorded from the Chepstow area. All 3 of the species listed here occur on the extensive mud banks close to Long Straw Chamber. *Allolobophora chlorotica* is widespread throughout the cave in damp, slightly sandy mud.

MYRIAPODA

DIPLOPODA	Glomeridae	*Glomeris marginata* (Villers). LimAcc
	Brachychaetumidae	***Brachychaetuma melanops* Brade-Birks. Tph.
	Polydesmidae	*Polydesmus angustus* Latzel. Acc.
	Blaniulidae	*Blaniulus guttulatus* (Bosc). Tph.

Blaniulus guttulatus is a troglophilic species common in many British caves. *Brachychaetuma melanops* has a very local distribution, having been previously recorded only from Cornwall, South Devon and Dorset. As this record represents such a large departure from its 'usual' range in Britain, it may just be possible that *B. melanops* is troglobitic in the Chepstow area (Fig. 1).

INSECTA

COLLEMBOLA	Hypogastruridae	*Schaefferia lindbergi* da Gama. Tph.
	Neanuridae	*Anurida granaria* (Nicolet). Tph.
	Onychiuridae	*Onychiurus schoetti* (Lie Pettersen). nTbt.
	Isotomidae	**Cryptopygus garretti* (Bagnall). Tph.
		Isotoma ?agrelli Delamare-Deboutteville. Tph.
		Folsomia candida Willem. Tph.
	Entomobryidae	*Heteromurus nitidus* (Templeton). Tph.
		**Pseudosinella dobati* Gisin. nTbt.
	Neelidae	*Megalothorax minimus* (Willem). Tph.
		Neelus murinus Folsom. Tph.
	Sminthuridae	*Arrhopalites caecus* (Tullberg). Tph.

In some ways it is surprising that so few species of Collembola are recorded from Otter Hole, for they are greatly in evidence throughout the cave. They thrive where there is organic detritus, where they probably 'graze' on the bacteria and fungi present. The various species appear to have some marked habitat preferences. The round-bodied Symphypleona (Sminthuridae and Neelidae) are found almost exclusively on pool surfaces, as are the eyed Hypogastruridae, and the sluggish Onychiuridae and Neanuridae. These animals have extremely effective waxy, water-repellant body coverings, which, together with the high surface tension of the cold cave water renders them virtually unsinkable, and allows them to hop about and land on pool surfaces freely. However, if removed from the cave and warmed up under a lamp, they readily become trapped on the surface film as they try to jump. This may be due to lowered surface tension of the warmer water and/or melting of the waxy, waterproofing body covering. Other species, notably the Isotomidae *Folsomia candida* and *Cryptopygus garretti* and the troglobitic entomobryid *Pseudosinella dobati* are more often found on damp mud or muddy flowstone and under rocks. *P. dobati* may be considered to be the 'dominant' collembolan in the cave. It is found in every part, though never in great numbers, is large, robust and highly mobile and is one of the first species to appear at a rich source of food, as well as being found in the really remote 'oligotrophic' areas of the cave. *F. candida* is a slightly less mobile 'opportunistic feeder' which is never far behind *P. dobati* in reaching a rich food source. Once there, it rapidly takes over, apparently having a high reproductive rate, and may quickly reach very large population densities. *C. garretti* looks very like a smaller, more slender version of *F. candida*. It has been recorded from caves in Somerset and chalk mines in Surrey as well as the inter-tidal zone of estuaries.

COLEOPTERA	Carabidae	*Trechus (Trechoblemus) micros* (Herbst). Tph. (Fig3)
	Leiodidae	*Choleva spadicea* (Sturm). ?Acc.
	Staphylinidae	*Ochthephilus aureus* (Fauvel). Tph
		**O. aureus* larva
		***Aloconota* sp. *(?subgrandis)*?Tph./nTbt. (Fig. 4)
		Lesteva pubescens Mannerheim. Tph.

It is probably fair to say that Otter Hole contains the largest population of *Trechus micros* of any cave in Britain. I have not yet visited the cave without seeing at least one of these handsome little beetles, usually running about on damp flowstone, somewhere between the Hall of Thirty and Long Straw Chamber. One small crystal pool beyond Camp 1 contains the entire exoskeletons of about 50 of the beetles, and their remains can also be seen lying on-, or

FAUNA OF OTTER HOLE

Phil Chapman

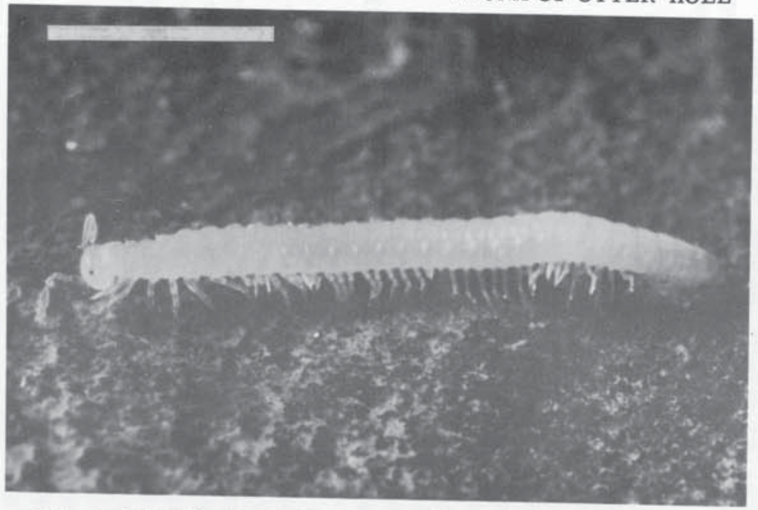

Fig. 1. *Brachychaetuma melanops*, a millipede previously recorded only from Cornwall, south Devon and south Dorset.

Fig. 2. *Porrhoma convexum*; usually black, this linyphiid spider has a white abdomen and brown-orange prosoma and legs in Otter Hole specimens.

Fig. 3. *Trechus micros* in a characteristic "alert" stance with antennae held stiffly forward. This fairly rare ground beetle is common in the decorated sections of the Otter Hole Extension.

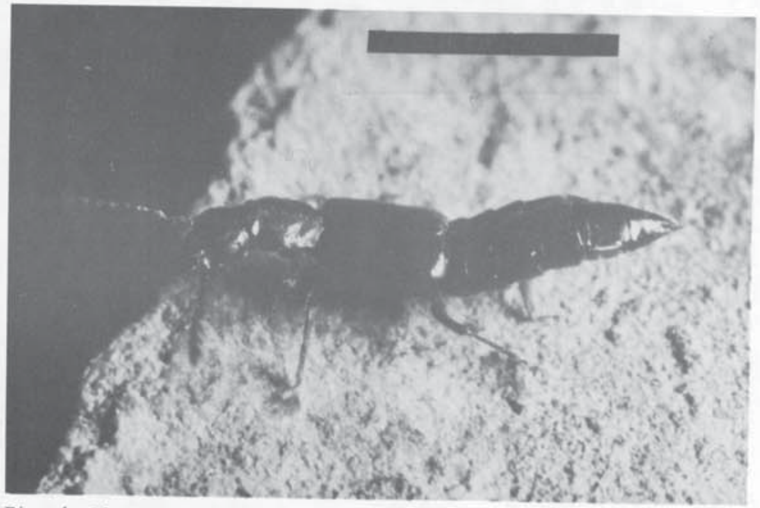

Fig. 4. *Aloconota? subgrandis*: a rare beetle so far only known in Otter Hole in Britain.

Scale bar is 2 millimetres.

cemented into flowstone throughout the Extension. One specimen was observed poking about among worm casts on a mud bank in the entrance series. It may have been seeking enchytraeid worms or Collembola (a number of *Folsomia candida* were taken in this area).

The staphylinid beetles *Ochthephilus aureus* and *Lesteva pubescens* are widespread in British caves and are probably troglophiles (a larva of *O. aureus* was taken on a high level mud bank quite close to the tidal sump, among eggs and young *Folsomia candida).* The *Aloconota* is a species apparently not previously recorded from Britain (absent from the B.M. (N.H.) Collection). According to P. M. Hammond, it is a torrenticolous species. Several specimens were seen in the narrow passage between the Hall of Thirty and Camp 1, together with numerous staphylinid remains. It is an exciting possibility that there may be a well-established troglophilic population of this species in the cave.

TRICHOPTERA	Polycentropodidae	*Plectrocnemia geniculata* McLachlan. Acc.
PLECOPTERA	Nemouridae	*Nemoura* sp. Acc.
LEPIDOPTERA	Geometridae	*Triphosa dubitata* (L.) LimTx.

Triphosa dubitata, the tissue moth, hibernates in the deep threshold of many British caves. The caddis and stonefly imagines have metamorphosed inside the cave from aquatic larvae accidentally introduced by the stream. It is perhaps surprising that adult caddis flies can make their way as far away from the stream as Tunnels Junction, and are quite commonly seen even in Long Straw Chamber.

DIPTERA	Mycetophilidae	*Speolepta leptogaster* (Winnertz). Tph.
		S. leptogaster larva.
	Sciaridae	*Sciara (Bradysia)* sp. Tph.
	Culicidae	*Culex pipiens* L. LimTx.
		Culiseta annulata (Schrank). Lim Tx.
	Chironomidae	*Limnophyes* sp. larva. Acc.
	Sphaeroceridae	*Copromyza nigra* (Meigen). Tx.
		Leptocera silvatica (Meigen). LimTx.

The fungus gnats *Speolepta leptogaster* and *Sciara* sp. are common troglophiles in British caves, though there are surprisingly few records of sciarine larvae. It was my impression that numbers of *Speolepta* larvae declined in the first and second boulder chokes in Otter Hole from Aug. 1977 to Oct. 1978. It would be interesting to monitor changes in larval populations of this species in a freshly opened cave system in Britain. Perhaps surprisingly, adult sciarids appear to be more common in Otter Hole than are *Speolepta,* despite the latter's more obvious larval presence.

The little black sphaerocerid fly *Copromyza nigra* is fairly common well into the dark zone of Otter Hole, though it is far from clear why it enters caves at all.

CRUSTACEA

COPEPODA	Cyclopidae	*Paracyclops fimbriatus* (Fischer). Tph.
ISOPODA	Asellidae	*Proasellus cavaticus* (Leydig). Tbt.
AMPHIPODA	Gammaridae	*Gammarus pulex* (L.). ?Tph.
		Niphargus fontanus Bate. Tbt.
MYSIDACEA	Mysidae	***Praunus flexuosus* (Müller). ?Acc.

The copepod *Paracyclops fimbriatus* is found in muddy pools in the Extension and can safely be regarded as a troglophile. Perhaps our most widely distributed British troglobite, *Niphargus fontanus,* has turned up only once in Otter Hole (in a small trickle near Camp 1). On the other hand, there is a large population of *Proasellus cavaticus* in clear pools and 'microgours' close to Long Straw Chamber. Their main habitat is right in the middle of the main route and extra care should therefore be taken to avoid muddying this section. In view of the great size difference between mature Mendip and South Wales individuals of this species, it was of interest to see whether Otter Hole might perhaps contain a morphologically, as well as geographically intermediate population. However the specimens examined so far appear to be identical with the 'South Wales type'. This underlines the importance of the Severn estuary as a recent barrier to genetic flow between cave populations of the north and south banks.

Gammarus pulex is common in Sump 2 near the start of the Extension, and in the sump at the end of Tunnel Left. The literature has tended to state dogmatically that *G. pulex* only occurs accidentally in caves (e.g. Hazelton and Glennie, 1962). However recent evidence suggests that troglophilic populations may occur in some Yorkshire and Derbyshire caves (G. Proudlove, pers. comm.). Further study is needed in order to establish the status of the Otter Hole population.

The mysidacean *Praunus flexuosus* is of interest as it has not previously been recorded from a British cave. Two specimens were taken in a mud-floored pool in the entrance crawlways, some 2 months after the previous tidal inundation, by which time the pool water tasted only slightly brackish. This species is known to be markedly euryhaline, but even so, a static pool in a cave is very different from the animal's normal open water estuarine habitat. An extraordinary observation of this species, made by John Elliott and Jim Hay of the Royal Forest of Dean Caving Club is worth reporting at length. Returning towards the tidal sump at high tide, they found the water just downstream of the Traverse had ponded to a depth of several feet, and contained so many 'shrimps' - no doubt *Praunus* - that the surface was 'boiling' with them. They estimated there to be at least one 'shrimp' per cubic inch of the clear green water for as deep as they could see - which was probably nearly five feet. Considering the highly turbid nature of the tidal water in Sump 1, it seems likely that this was partly fresh water from the main streamway, and therefore that the mysids were actively swimming upstream. The reason for such behaviour is far from clear and merits investigation.

The occurrence of *Praunus* in the streamway raises the possibility that other estuarine animals will be found in the cave in future. The locally common estuarine amphipod *Gammarus zaddachi* which has not yet been recorded from British caves, is a very probable future discovery in Otter Hole.

ARACHNIDA

ARANEAE	Nesticidae	*Nesticus cellulanus* (Clerck). LimTx.
	Tetragnathidae	*Meta menardi* (Latreille). LimTph.
		Meta merianae (Scopoli). LimTph.
	Linyphiidae	*Porrhoma convexum* (Westring). Tph. (Fig.2)
ACARI	Veigaiaidae	**Veigaia transisalae* (Ouds). Tph.
		**Veigaia agilis* (Berlese). Tph.
	Parasitidae	**Eugamasus berlesei* Willmann. Tph.
	Rhagidiidae	*Rhagidia* sp. Tph.

The 2 *Meta* species are well known liminal troglophiles. *Nesticus cellulanus,* though a regular inhabitant of the threshold zone in continental caves, occurs rather more infrequently in British caves. *Porrhoma convexum,* on the other hand, is a deep cave troglophile which is well established throughout Otter Hole, as far as Camp 1. All the deep cave specimens have a very pale abdomen and orange-brown prosoma. However, one specimen which was removed from the cave and kept in dim light, developed dark grey, subcutaneous pigmentation of the abdomen without moulting. A similar phenomenon has been observed in some depigmented troglobitic spiders from European caves (Deeleman-Rheinhold, pers. comm.). The main prey seen in webs of these spiders around Camp 1 consists of various collembolan species, notably Entomobryidae.

All the mites recorded from the cave may be considered to be troglophilic; however the *Rhagidia* (probably *R. spelaea)* is the only one which is predominantly associated with caves.

OSTEICHTHES

PERCOMORPHI	Gobiidae	***Pomatoschistus* sp. (prob. *P. Microps* (Krøyer)). Acc.

This is the first record of a goby from a British cave. *P. microps* is a euryhaline species, common in the Severn estuary. The single specimen taken in a pool in the entrance series had doubtless been introduced accidentally by tidal flooding.

TABLE 1. COMPARISON OF NON-ACCIDENTAL FAUNA IN 3 SECTIONS OF OTTER HOLE

Entrance series to first boulder choke.		The Extension
Below 14 m. tide level Flood-liable, dark zone.	Above 14 m. tide level. Non-flooding, dark zone.	deep cave
(a) *Aquatic fauna*	(a) *Aquatic fauna*	(a) *Aquatic fauna*
?Phagocata vitta	Hydrobiid gastropod	Enchytraeidae sp. 1
Hydrobiid gastropod		Enchytraeidae sp. 2
(Gammarus pulex)	(b) *Terrestrial fauna*	*Paracyclops fimbriatus*
	Allolobophora chlorotica	*Proasellus cavaticus*
(b) *Terrestrial fauna*		*(Gammarus pulex)*
Blaniulus guttulatus	*Brachychaetuma melanops*	*Niphargus fontanus*
Anurida granaria	*Polymicrodon polydesmoides*	(b) *Terrestrial fauna*
Folsomia candida	*Anurida granaria*	*Allolobophora chlorotica*
Pseudosinella dobati	*Onychiurus schoetti*	*Dendrobaena veneta*
Lesteva pubescens	*Cryptopygus garretti*	*Octolasion cyaneum*
(Copromyza nigra)	*Isotoma ?agrelli*	*Schaefferia lindbergi*
Rhagidia sp.	*Folsomia candida*	*Anurida granaria*
	Pseudosinella dobata	*Onychiurus schoetti*
	Neelus murinus	*Cryptopygus garretti*
	Arrhopalites caecus	*Isotoma? agrelli*
	Trechus micros	*Folsomia candida*
	Ochthephilus aureus	*Heteromurus nitidus*
	Speolepta leptogaster	*Pseudosinella dobati*
	Sciara (Bradysia) sp.	*Megalothorax minimus*
	(Copromyza nigra)	*Trechus micros*
	Porrhoma convexum	*Ochthephilus aureus*
		Aloconota (?subgrandis)
		Lesteva pubescens
		Sciara (Bradysia) sp.
		Porrhoma convexum
		Rhagidia sp.
		Veigaia transisalae
		Veigaia agilis
		Eugamasus berlesei

ECOLOGY

It is well known that the food nexus in caves is generally much simpler than that of a typical epigean community, and includes fewer trophic levels. The primary reason is the absence underground of green plants (photo-autotrophs). Jefferson (1976) discussed the possible significance of endogenous chemo-autotrophic sources of energy, and the direct absorption of dissolved organics by cavernicoles. Although of great interest to the biologist, there is, as yet, little concrete evidence that either of these contributes significantly to the energetics of cave communities (Barr and Kuehne, 1971). The bulk of evidence points to the importance of hetero-trophic micro-organisms (fungi and bacteria) in the diet of cavernicoles and particularly of troglobites (Barr, 1968). Dickson (1975) found significant correlations between the densities of fungal populations and of terrestrial troglobites on mud banks. Gounot (1960) found large concentrations of bacteria in clays where troglobites occur. Bacteria and fungi flourish where high humidities are coupled with large concentrations of organic matter. It is likely that the tidal mud banks of the entrance series are unusually rich in this respect, though this has not yet been properly investigated. Cavers passing into the deeper parts of the cave are responsible for carrying a significant amount of this rich mud at least as far as the start of the Extension. It would be interesting to compare the bacterial/fungal concentrations on the muddy floor of the 'through route' with sections of undisturbed mud nearby.

In sheer numbers of animals, the entrance series (dark zone) is very rich as compared with the far reaches of the cave; however in numbers of non-accidental species the situation is reversed (Table 1). Smaller numbers of animals are to be expected in the 'deep cave' owing to the (presumably) lower energy input, but why should there be greater species diversity?

Poulson and Culver (1969) studied the factors affecting species diversity in the terrestrial communities of the Flint Ridge - Mammoth Cave system in Kentucky. They found a positive correlation of diversity with stability, food standing crop and substrate diversity, and a negative correlation with intensity of flooding. Christiansen et al (1961), studying Collembola, in addition found a positive correlation of diversity with substrate moisture content. These environmental factors interrelate in a rather confusing way. Flooding increases food standing crop (depositing organics at the high tide mark) and increases substrate moisture content, but decreases stability. In other words, it probably has contradictory effects on diversity. According to Margalef (1963) a few opportunistic species predominate where productivity is sporadically high and many species coexist where productivity is stable over the entire year. Obviously, in order to understand the situation in Otter Hole it will be necessary first of all to measure such factors as frequency of flooding, and organic content of sediments and of the tidal and fresh waters entering the cave.

British cavernicoles appear to be largely unspecialized feeders, a feature which is probably adaptive in trophically poor habitats. Nevertheless, the species listed in Table 1 can be divided into two broad trophic categories. They are: (1) Polyphages (i.e. predominantly detritivorous species which may or may not supplement their diet by occasional predation, scavenging, or by eating bacteria-rich silt, or fungi): e.g. Collembola; Crustacea; millipedes; 'fungus gnats'; worms; and (2) Predators: e.g. beetles; spiders; mites; flatworms. The terrestrial food nexus is built primarily around the polyphagous Collembola. Of the 11 collembolan species known from the cave, 9 are found in the 'deep cave'; 8 in the non-flooding upper part of the entrance passages; and 3 in the lower, flood-prone sections. A similar numerical distribution is seen in the rest of the groups, with a greater variety of troglophile/troglobite species being found in the deep cave than in the entrance series. If the reasonable assumption is made that energy is more plentiful in the entrance series than in the deep cave, then the greater diversity in the latter must be due to some factor other than food availability. Christiansen and Bullion (sic) (1978), working in the Haute-Garonne and Ariège regions in France, have also reported a more complex fauna in 'deep cave' habitats than in other regions of caves. They argue that the deep cave normally is the most stable region of the cave, that stability favours predictability, and that stability plus predictability may lower the extinction rate of small populations, thus bringing about greater biological complexity. Another possibility in Otter Hole is that there is greater habitat diversity in the deep cave (the 'deep cave' region referred to in Table 1 is far more extensive than either of the comparison regions), and this may result in more niches available for exploitation by a greater variety of species. There is some evidence that particular species may prefer particular types of habitat. Some Collembola are usually to be found on pool surfaces, others on damp mud banks. Some species are consistently found on some pool surfaces but not on others; e.g. *Neelus murinus* was consistently present on only one pool surface in the entrance series. Some species pairs commonly occur together, and some apparently exclude each other. A few species appear to have very broad habitat preferences, and these are particularly common in the entrance series. One in particular, *Folsomia candida*, is very numerous around the tidal sump 'high tide mark', sometimes in concentrations of several hundreds to the square metre. It appears that increased food availability may be accompanied by a change in distribution of the collembolan species, resulting in fewer species occupying a greater variety of habitats in greater numbers. Such a situation is seen at Camp 1 in the Extension.

The boulder slope at Camp 1 has been the scene of digging activity by cavers, and a nearby splashing inlet of drinkable water has made this area a popular picnic spot. Unfortunately cavers have abandoned large quantities of half-empty tins which by mid-1978 had accumulated into a sizeable and foul-smelling heap. The ecological effects of this massive energy package were fairly spectacular. The normally scarce spider, *Porrhoma convexum*, had reached 'epidemic' numbers in Sept./Oct. 1978, with densities as high as 3 or 4 per m^2 on the cave walls, and with c.20 egg sacs seen in the Camp 1 area in one visit. Numbers of Collembola had greatly increased also, though fewer species were taken (4 in Sept./Oct. 1978, as against 7 in Sept./Oct. 1977). The only new record was of *Folsomia candida*, whereas *Onychiurus schoetti*, *Cryptopygus garretti* and *Isotoma? agrelli* appeared to have disappeared from the area. The 'usual' predators of this region of the cave: *Trechus micros* and *Aloconota* were not seen, their place apparently having been taken by *Porrhoma* and by 3 species of mites. The area has since been cleaned up to some extent, and it will be interesting to see whether, and, if so, how quickly, the fauna returns to 'normal'.

This leads on to a more general point about the effect of caving on British cave faunas. It has been noted in the literature that some caves entered for the first time seem to contain very little life, and that the visible numbers of animals increases dramatically with increasing human usage of the cave (e.g. see Hazelton, 1977). This is presumably only true of highly 'oligotrophic' caves (i.e. extensive systems below a thick overburden and not entered by large, open stream sinks). While trophic enrichment by cavers probably triggers an increase in the cavernicolous population, it may be that the overall effect is similar to that produced by the 'rubbish dump' in Otter Hole, i.e. there may be a decrease in species diversity. One possible reason for this may be that those cavernicoles which are able to step up their breeding rate most rapidly might be able to 'pre-empt' the available food source and so exclude less fecund competitors. It seems probable that such species would be troglophiles rather than troglobites, as many cave-limited species are known to have extremely slow breeding rates (Vandel, 1965). A laboratory study of competition between naturally sympatric pairs of troglobitic/troglophilic species (e.g. *Onychiurus schoetti/Schaefferia lindbergi*, or *Pseudosinella dobati/Folsomia candida*) under different food regimes (starvation to plenty) might prove rewarding in this connection. Obviously, though, the whole subject should also be studied in a 'real' situation. What is needed is detailed and regular monitoring of the faunal composition/population densities of a suitable, newly-discovered cave or passage. A good chance may have been missed in the case of Otter Hole and Ogof Craig ar Ffynnon. Perhaps the next big Welsh discovery will be put to good use.

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DERBYSHIRE SOUGH HYDROGEOLOGY AND THE ARTIFICIAL DRAINAGE OF THE STANTON SYNCLINE NEAR MATLOCK, DERBYSHIRE.

by Colin D. Oakman

ABSTRACT

This article examines the principles of sough hydrogeology, plotting detailed courses of some of the major soughs, examining the interplay of groundwater flow trends and levels within specific geologic confines with local variability. This interplay is also examined before and after mining activity.

The lead mine drainage soughs were constructed between 1600 and 1900, and acted by suppressing natural water tables, draining phreatic zones and affecting old groundwater flow trends.

Such artificial conditions have affected a large fold structure, the Stanton syncline, by means of the two large sough complexes, Hillcarr and Yatestoop, that drain it to the level of the River Derwent. It can be shown that using the application of sough hydrogeology theory in this real situation can explain such phenomena as loss of surface springs and diversion of surface streams and rivers such as the Lathkill.

I. THE GEOLOGICAL SETTING

The draining of a part of the Derbyshire Lead mining field between 1600 and 1900 has provided an opportunity for a better understanding of the nature of the early stages of a phreatic hydrological system in the Carboniferous Limestone. The lead miners' soughs or drainage levels caused a sudden transition from phreatic to vadose conditions, with the collected waters resurging at artificial sough tails (=outfalls). A study of the flow patterns, areas drained and catchments has been possible through an integrated approach using geological mapping in the field together with published geological maps in conjunction with a critical assessment of lead mining archives in the various manuscript collections.

The area covered by this study is the southern half of the Derbyshire Mining field from Lathkill Dale to Wirksworth, mostly within the Peak District National Park. The drainage is dominated by the River Derwent flowing southwards along the eastern margin, with tributaries joining it from the west, notably the Rivers Bradford, Lathkill, Wye, Millclose Brook, and the Via Gellia stream. These drain the limestone moorlands at altitudes of over 1000 feet O.D. to the river level around 300 ft. O.D. (Fig. 1).

The geology of the area is basically a series of eastward plunging anticlines with Carboniferous Limestone (Dinantian) cores and complementary synclines with Upper Carboniferous (Namurian) shales and sandstones overlying the limestone (Fig. 2). The limestones are interrupted by interlayered basaltic lavas and tuffs, locally known as toadstones, and there are numerous mineral veins. The latter include fissue-filling fractures known as rakes and scrins, ore-deposits along the bedding known as flats and a variety of ancient (late Carboniferous age) cavity fillings called pipes. A general description may be found in Ford (1977).

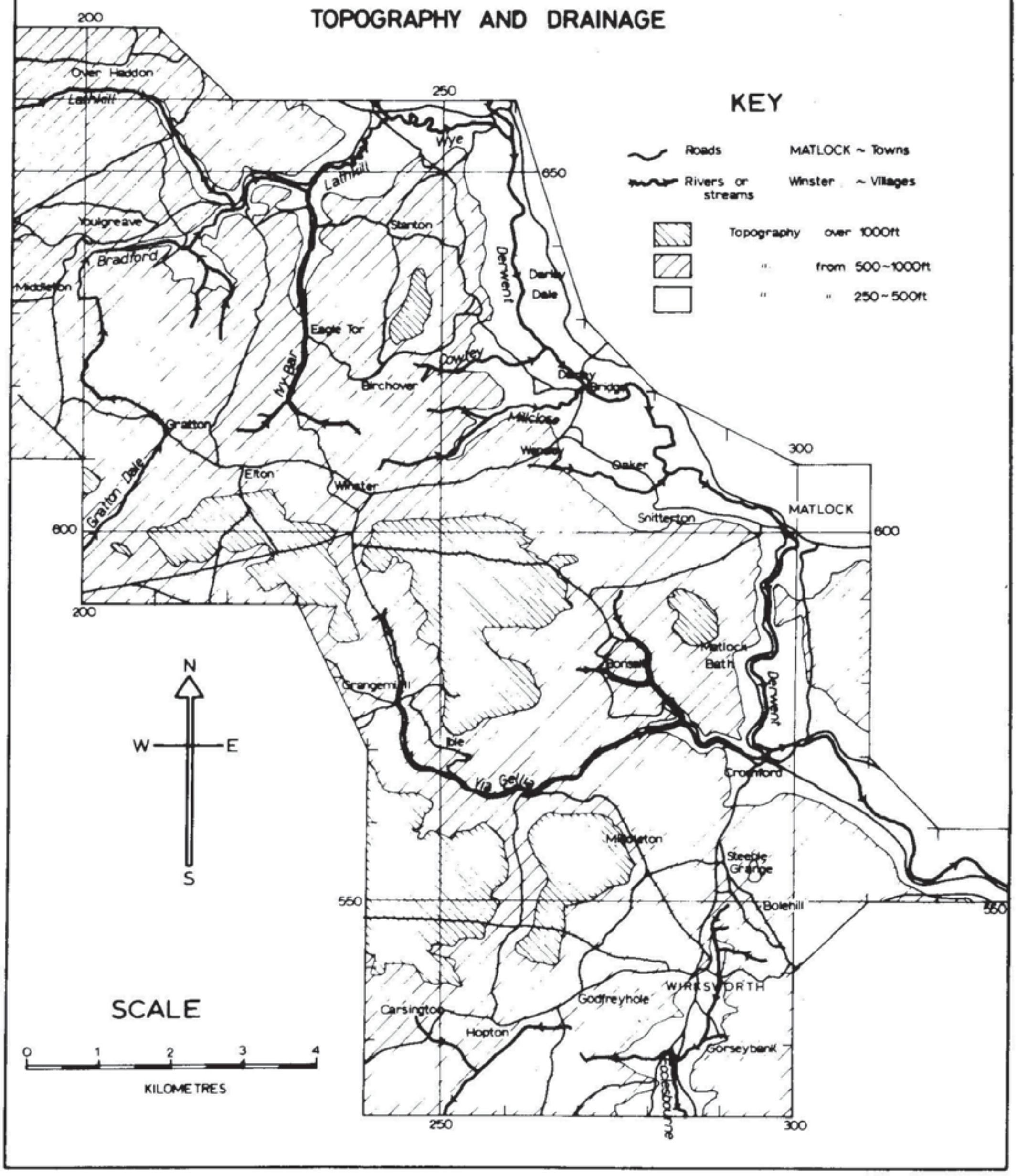
In the Youlgreave-Alport area the mineral field drained by the soughs was in the Upper Monsal Dale limestones above the Conksbury Bridge (=Upper Alport) Lava, with some workings below this lava north of the Lathkill river. The ore bodies in this area are dominantly rake and scrin type deposits. In the centre of the area, around Matlock and Wensley, the area dominated by the soughs was mostly in the Matlock limestones, this sequence containing two lava horizons, the Upper and Lower Matlock lavas. The orebodies in this area are commonly pipe and flat types (Worley, 1978). To the south, the

Cromford-Wirksworth mineral field was in the limestone sequence from the Hoptonwood limestones right up into the Matlock and Cawdor limestones. Both the lava horizons of Matlock have thinned and vanished at Wirksworth, the stratigraphy being complex and dominated by thinning of the Matlock limestones and a drastic change of sedimentary facies.

The structure of the area is dominated by three folds - the Bolehill and Matlock anticlines and the Stanton syncline (Fig. 3). The area can be structurally divided into two by the Bonsall fault (Shirley, 1958), a complex shatter belt with a net downthrow of several hundred feet (Butcher, 1976) to the south. This fault runs from Cromford through Bonsall and continues westwards to Winster moor. North of the fault there is very little faulting worthy of note, excepting the Coast Rake, with a small northerly downthrow, and Long Rake, with a small southerly downthrow, both with some lateral movement.

FIG. 1 THE WIRKSWORTH ~ MATLOCK ~ YOULGREAVE AREA

TOPOGRAPHY AND DRAINAGE



The Winster area has a large fold structure, plunging eastwards, divisible into the Stanton syncline in the north and the Matlock anticline in the south. Minor folds are superimposed onto this structure (Fig. 3).

South of the Bonsall fault, the structure culminates in the Bolehill anticline (Middleton-Alderwasley anticline of Butcher, 1976), plunging to the southeast. The southern limb is dissected by several large faults forming a series of horst and graben structures. These faults include the Gang vein, Gulph, Ranter, Baileycroft and Yokecliffe Rake faults. The latter four converge towards Wirksworth to form a complex shatter zone containing the richest single area of orebodies known in Derbyshire.

The mineralisation is incorporated within the whole of the limestone sequence, both at outcrop and subcrop beneath the shales. The minerals are dominantly galena (PbS), calcite ($CaCO_3$) and barytes ($BaSO_4$), with localised fluorspar (CaF_2) concentrations, and rare lead, copper and zinc carbonates. Certain areas are richer than others in galena, the distributions having been investigated by Butcher (1976) and Worley (1978). The mining areas which resulted in the construction of the soughs are the Alport field (Hillcarr Sough), south-east of Yougreave, the Oxclose mines (Oxclose Sough), west of Matlock, the Yatestoop and Portaway pipe workings (Yatestoop Sough) of the Winster area, and the mines of Wirksworth and Cromford (Cromford and Meerbrook Soughs). The best known and richest mine of the area, Millclose, is not discussed

FIG. 2 GENERALISED STRATIGRAPHY

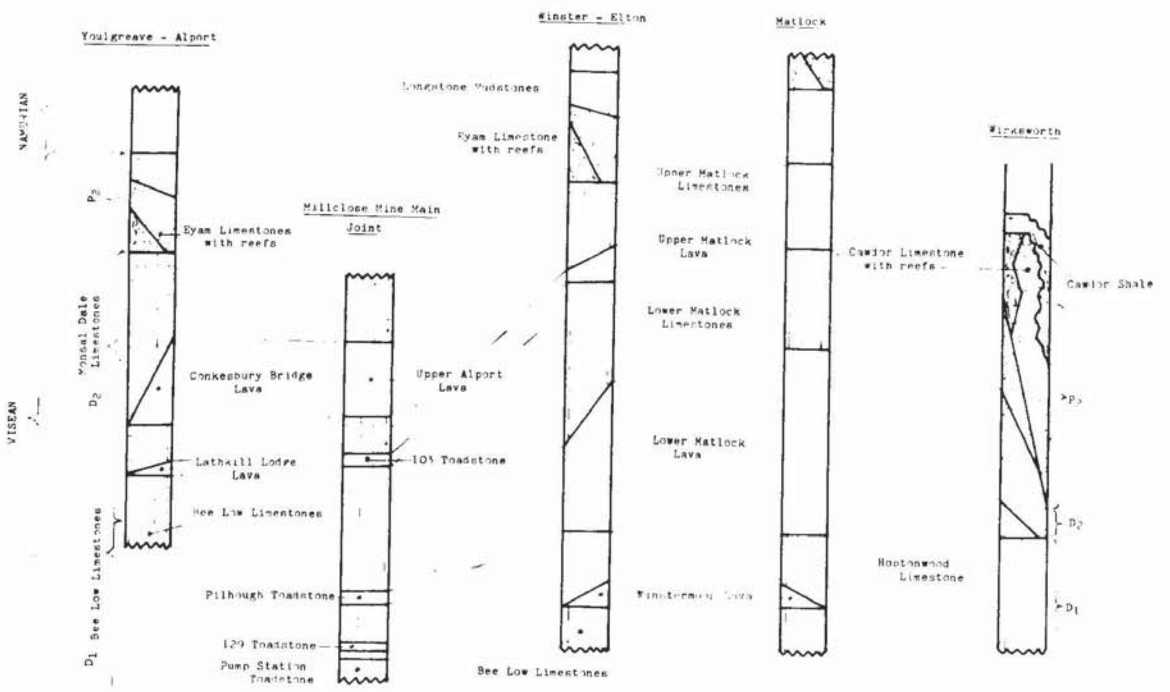


FIG. 3 THE WIRKSWORTH ~ MATLOCK ~ YOULGREAVE AREA:~ STRUCTURE

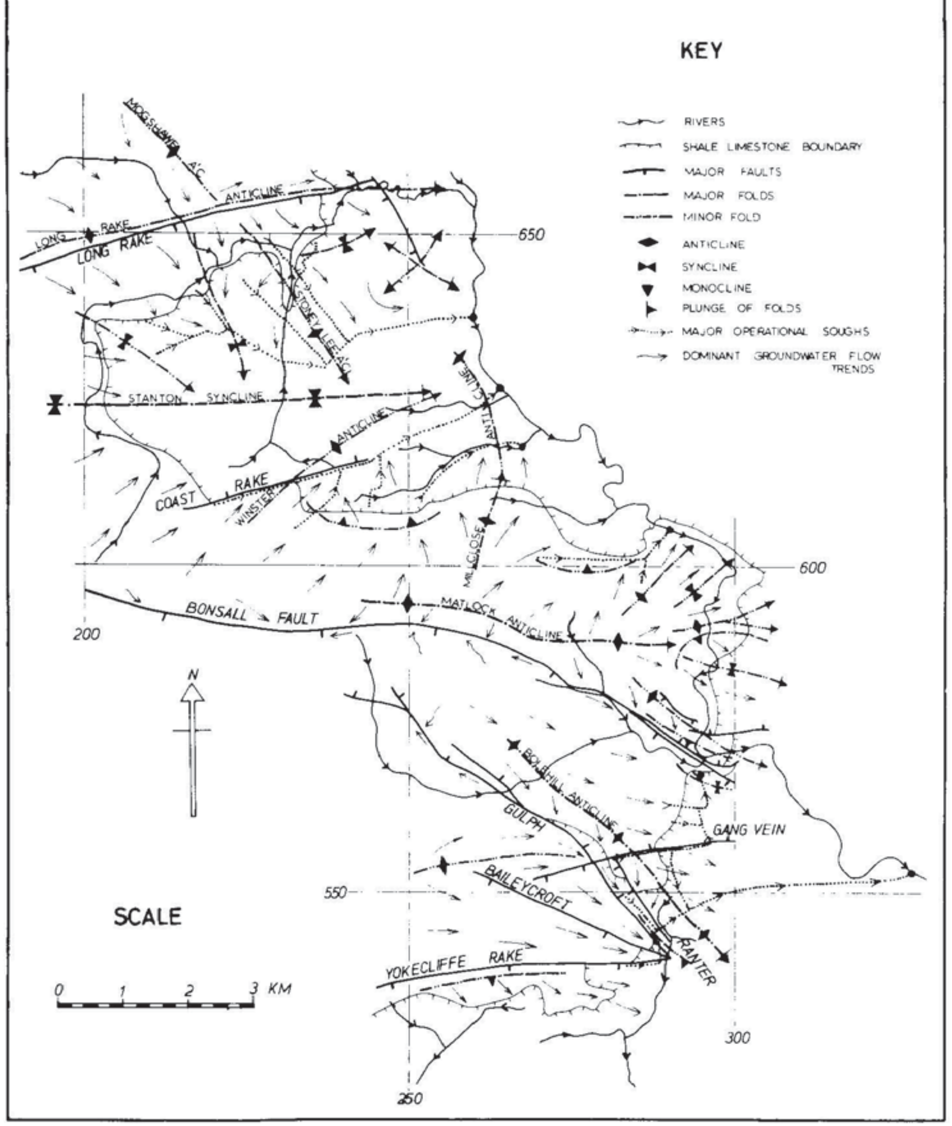
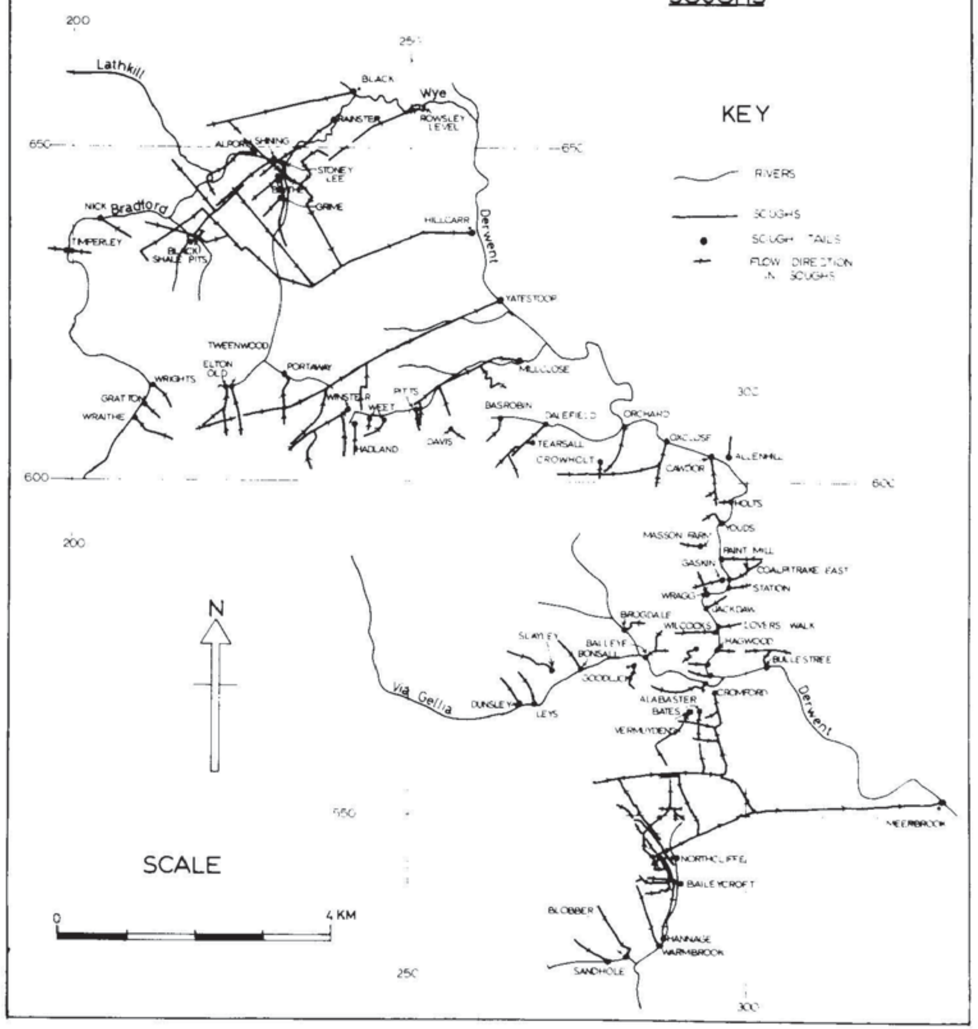


FIG 4 THE WIRKSWORTH ~ MATLOCK ~ YOULGREAVE AREA:~ SOUGHS



here, as most of the workings were below river level and not served directly by the soughs though numerous phreatic feeders were encountered in its workings. The production from this mine reached its peak between the two world wars, long after the last great sough construction phase.

II. OUTLINE HISTORY OF THE SOUGHS.

A sough (pronounced *suf*) can be concisely defined as a tunnel made from a convenient topographic low to a mine, group of mines, part of, or whole of, a mineral field located under a relatively high topographical area, for the purpose of suppression of a natural water table to enable the extraction of the ore from a saturated zone.

The term 'sough' is Derbyshire dialect for a drain or sewer, and in other mineral fields throughout Great Britain, tunnels of this nature have been termed 'drainage adits' or 'levels' (e.g. the Halkyn Level of North Wales). The term 'levil' is occasionally found in the older Derbyshire literature when referring to a sough.

To the uninitiated, the nomenclature surrounding the soughs can be somewhat confusing. A brief glossary of some of these terms is as follows:- the tail was usually the point where driving started and was the outfall of the waters from the area drained by the sough. The process of sough construction is known as 'driving', and the face of advancement of the sough during driving known as the 'forefield'. Measurements made in relation to the soughs were in fathoms, feet and inches, and when driving in a vein, distances were also measured in 'meers' (a length variable from 27 to 32 yards depending on which 'liberty', or legal jurisdiction area, the sough was driven in). Shafts constructed for the soughs are known as 'sough shafts' and the construction of these known as 'sinking'.

The soughs of the southern part of the Derbyshire orefield are shown on figure 4. The more detailed aspects of the hydrogeology concern Oxclose, Yatestoop and Hillcarr soughs of the northern area shown, the general principles evaluated from the soughs concern the whole area covered by figures 1 - 4. A detailed discussion of the sough complexes of the southern part of this area may be found in Oakman (1979).

Sough driving in the Derbyshire orefield can be subdivided into three overlapping phases. The first phase was the initial use of the technology from around 1600 to the early 18th century (Rieuwerts 1980). These soughs were small, generally driven along veins from a valley, less than ¼ mile long, made for and by a small mining company. Their catchments were small, of the order of one square mile, with outfalls probably of the order of less than half a million gallons per day at most. These soughs are generally only known today from documents, having been destroyed at a later date by the large scale soughs and backfilling with waste. The effect of a series of these soughs was to reduce the water table to a local river or valley level, over a very localised area, as exemplified in the case of the old vein soughs of the lower Lathkill valley (omitted from fig. 4 due to their frequency, for more details see Oakman 1979 and Rieuwerts, 1980).

The second phase of sough driving was from around the late 1600s to the 1790s, these soughs being up to 1½ miles long, with catchment areas of the order of 3 to 4 square miles. The soughs of this category include the Hannage, Winster, Rainster and Alport soughs. Many of these soughs were driven from lower down a river valley, following the line of the valley to mines further up and below the valley floor, sometimes crossing underneath the rivers, and in some cases accidentally engulfing part of the river's flow. To preclude this the river beds were 'puddled' (clay lined and weired) to prevent them from seeping into the sough below. Thus the unique situation occurred whereby the river actually flowed on it's own 'perched' water table, with the local water table well below river level. The soughs were driven by separate sough companies, taking payment (composition) from the mines they drained in the form of a share of the ore raised within the zone nearly relieved of water. Towards the end of this phase of sough driving, the sough companies became mining companies in their own rights with the takeover and amalgamation of the smaller mining companies benefitting from the sough.

The final phase of sough driving was from the mid1700s to the end of the 19th century. With the conglomeration of many smaller mining and sough companies, the large sough companies were formed, and all the technology learnt from the smaller soughs was put into practice. The large soughs were up to 8 miles long, multi-branched, and with catchment areas of the order of 20 to 25 square miles. These soughs have present day outfalls of between 10 and 20 million gallons per day and include Hillcarr, Yatestoop and Meerbrook soughs. The financial success of these soughs was enormous by 19th century standards, the individual sough companies having monopolic stranglehold on the few surviving mining companies, to such an extent that sough companies owned whole mining fields. The Meerbrook sough company owned the Wirksworth mines, The Yatestoop company had large shares in the Winster mines, and the Alport Mining Company, an amalgamation of the Hillcarr, Blythe and Shining sough companies, had the Alport-Youlgreave field.

III. PRINCIPLES OF SOUGH HYDROGEOLOGY

Natural Subsurface Drainage Trends.

The factors affecting trends of subsurface flow can be divided into three categories which under natural conditions may operate together. These factors are: (a) stratigraphic control, based on the lithology of the permeable and impermeable horizons; (b) structural control, based on the dip of the strata and natural fractures; and (c) mineral veins and cavities.

All of these are intimately associated, and in the driving of the soughs, the miners attempted to intersect such drainage trends and thereby give maximum relief to certain areas of mines.

Limestone is always considered a highly permeable country rock, which is not strictly true. The void space in a solid Carboniferous Limestone of most lithotypes is very small (of the order of less than 1%); the permeability is very low, and thus flow rate through such a specimen almost negligible. However, limestone is generally a well-bedded rock, and frequently strongly jointed. Also, it is relatively very soluble in rainwater,so that both bedding planes andjoints are widened by action of percolating surface waters. Thus, the permeability of the limestone sequence is due to secondary permeability as opposed to the inter- and intraparticle porosity (Choquette and Pray, 1970) of sandstone aquifers.

Karstic solution has produced the voids in the limestone, although there is little evidence of large scale connective cave systems in the area.

On the other hand, the intermittent basaltic lavas in the sequence of Dinantian limestones tend to show very little permeability. In these thick units (the whole lava flow in some cases representing only one bed) frequency of jointing is poor, and if present, very irregular, so joint or bedding plane permeability in a lava is very weak. However, by far the main reason for the almost total impermeability in the lavas is due to what is locally termed 'Toadstone Clay'. For various reasons, but mainly due to the action of the hydrothermal mineralising fluids (Ineson & Mitchell 1972), the feldspars and augites in the lava decompose to clay minerals such as mica, illite, montmorillonite and the characteristic K - bentonite to form a mottled green clay. With thick lavas, this clay tends to form at the tops and bottoms of the flows, and as the hydrothermal fluids somewhat penetrated the weak jointing, zones of clay form there. On thin lavas, or ash fall deposits and volcanically derived atmospheric dust horizons (the 'clay wayboards' of Derbyshire), the decomposition can affect the whole horizon. Thus the thixotropic clay formed is virtually impermeable, and only joint fractures on the thinner horizons will allow water to penetrate them.

Thus, subsurface water flow is obstructed in its downward movement by the lavas, and will flow as perched water dependent on the dip of the country rock.

One must also consider the effect of dolomitisation, affecting large areas of this part of Derbyshire. Dolomite possesses a much greater interparticle porosity than limestone, so that the water flow in the rock mass is increased, aiding rapid percolation of groundwaters.

The structural control aspect literally means that the water flows down dip along widened bedding planes, frequently dropping in joints and continuing its flow on a lower bedding plane. Water flowing towards a lava or clay wayboard will not pass through it, and the flow trend will be continued down dip on top of the lavas. This assumes that the flow is in the vadose zone, although lavas still act as water barriers in the phreatic zone; the only difference is that the flow trends may be along the strike. In this article, the principles for the soughs are only evaluated for vadose conditions, as a sough is driven into a phreatic zone to make it an artificial vadose zone, and thus all flow trends associated with the soughs are under vadose conditions, although some consideration of the phreatic flow theory must be included, as the soughs would initially tap phreatic springs before they became vadose springs.

If one assumes a hypothetical situation of a plunging anticline with an impermeable lava bed in it, then subsurface flow will radiate from the crestal regions down dip to the nose of the structure. Axial regions of the anticline are strongly jointed, so both bedding and joint flow will predominate, also on a net down-dip trend. In the phreatic zone of such a structure, the flow will be sub-parallel to the structure contours of the anticline. This pattern of flow is seen in all of the fold structures of the area, the best examples being the Bolehill anticline, the Matlock anticline being somewhat more complex as it is cut by the Derwent gorge, producing a break in the flow trends due to a reduction in the natural water table caused by the Derwent in the nose of the anticline. If the nose of an anticline is capped by shale, then under natural conditions, vadose flow would be feeding a naturally confined phreatic reservoir.

When large faults with wide shatter belts occur, open hydrological zones are formed and flow above a lava may be diverted downwards in the fault, where the flow of the water would be free, governed only by the relative water table levels at the termination of such shatter belts. However, many of the faults of this area, until worked out by mineral extraction, were constricted, so such a flow was impeded.

Mineral cavity control under natural conditions is weak, as the pre-worked veins are too constricted for free water flow. Once the miner has worked out a vein or orebody, one approaches the condition of a maze of semi-connective cavities, analogous to a natural cave system. As the mineral deposits fall into basic categories related to both the structure and stratigraphy, they are analogous to the flow trend factors already outlined. Veins which are parallel to the bedding are called flats and pipes, and thus obey stratigraphic control with the overprinted dip control, and the veins perpendicular to the bedding known as rakes and scrins, which are filled faults and joints, have flow in them structurally controlled.

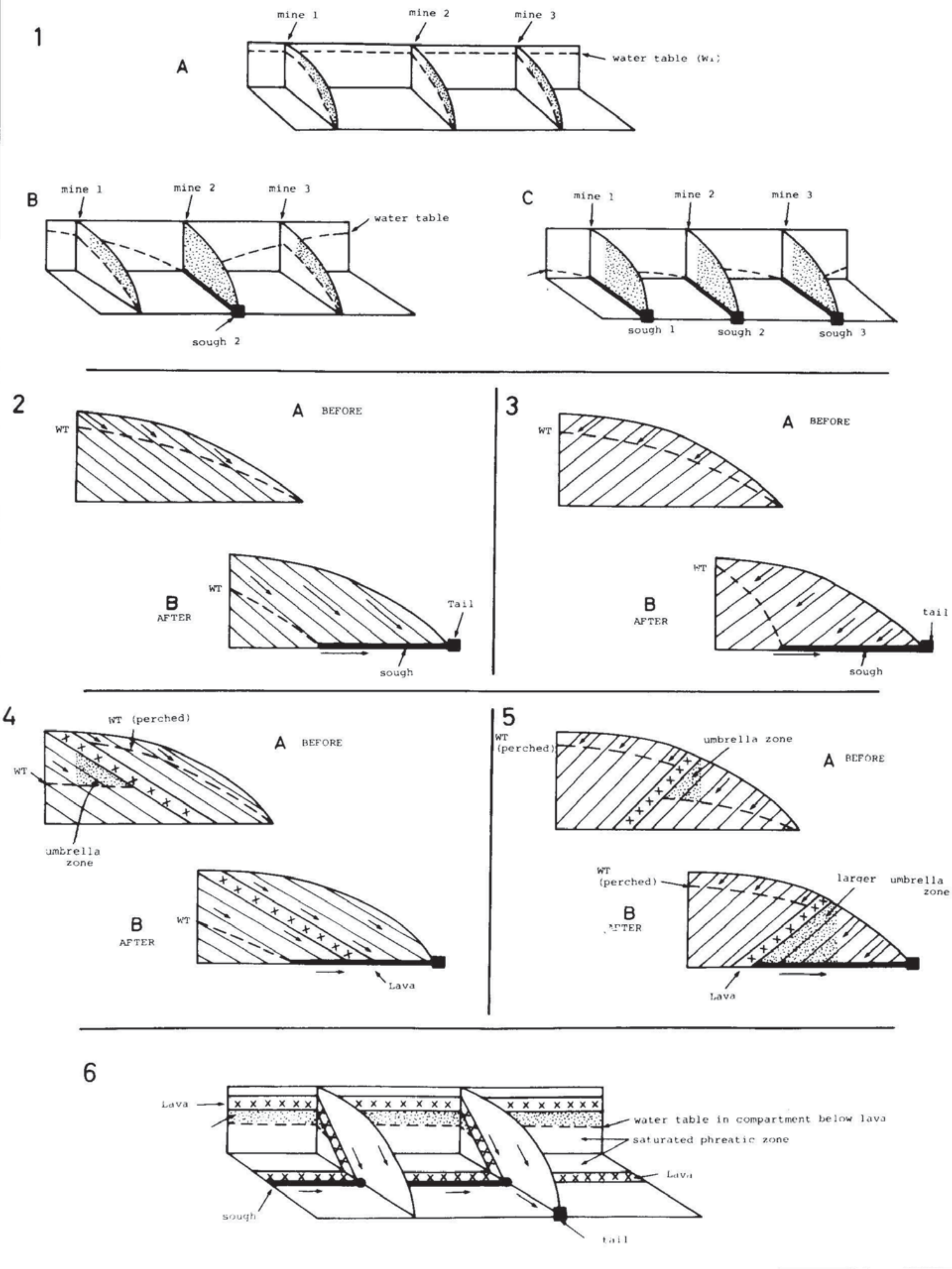
The effect of sough driving

In considering the hydrogeology of the soughs, one must take into account what the lead miner did to assist sub-surface flow. He enlarged the joints and faults by working out the scrin and rake type veins, and he worked the pipe and flat type deposits, which effectively enlarged the bedding planes. All of this was action to enable the more rapid percolation of the groundwater to the level to the water table at the base of his workings.

This was fine when he worked above the then water table, as the water always went downwards in his workings. However, soon, most of the ore had been worked in the vadose zone, and he was following the orebodies down into the phreatic zone with crude pumping methods and with the aid of dry summers to work the seasonally fluctuating zone of the water table. He also worked deeper below a lava "umbrella" where possible using it as a hydrological divide below perched water.

The lead miners gained the idea of sough drainage from the nearby coalfield, and doubtless the concept had been passed on from the Middle East and Roman aqueducts. In their turn it is likely that they observed the courses of groundwater in their mines following natural

FIG. 5 SOUGH HYDROGEOLOGY



cave systems, taking water away from higher workings to a resurgence in a nearby valley. It is only a step further to realise that one can build one's own natural cave system to take such water by working backwards - from the projected resurgence to the wet zone below the operational mines. Alternatively, they could enlarge the natural cave system and drive their own 'cave' from a swallet in the mine to a flooded area of the mine. Thus from primitive beginnings the sough was born, to go on to become the major influence in the extraction of ore below a natural water table.

The effect of the early phase of sough driving can be summarised by figure 5 (diagrams 1a, b, & c.). This diagram assumes uniformity of geology and a high general country rock permeability. A series of such soughs progressively lowered the local water table to a maximum depression governed by the altitude of the sough tails.

Before going on to look at the larger soughs, it is useful to look at how the water levels were affected by sough driving within the geological confines of the country rock. To explain in a more simplified manner, one must take a hypothetical situation of a small sough driving from a valley floor into an area of high land. Initially, one must assume that the sough is not driven in a vein, and so one takes the first case of a sough driving against the dip, i.e. opposite to the direction of dip of the beds. Under natural conditions in homogenous limestone, a natural water table level follows the usual regression curve away from the river valley floor level (fig. 5, diag. 2a), with water flow in the vadose zone being down dip. A sough driven against the dip (fig. 5, diag. 2b) diverts the regression curve base level to retreat to the sough forefield, rendering a vadose zone out of the old phreatic zone.

A situation of a sough driving with the dip (fig. 5, diag. 3a & b) has the same effect as above in the driving against the dip situation. The large difference being the nature of the newly formed regression curve, which within the same distance from the sough forefield has a much higher value. This is due to the down dip flow of water going direct to the sough in the case of the former , whereas in the latter, vadose flow in the area above sough level in advance of the forefield is directed away from the sough. The magnitude of the regression curve in both cases is very much dependent on the nature of any connective cavities ahead of the sough, but the above situations assume none or little of these, assuming only bedding plane control on water flow. The same applies to joints, which would also reduce further the water table regression curve ahead of the sough.

A sough driving in a vein or large fracture would affect an area well in advance of the forefield dependent on the degree of interconnection of caverns within such fractures. The same would apply to a sough crossing a fracture zone at right angles, reducing water levels flanking the sough. One can see at this point, that just by combining the aforementioned geological confines, a complex pattern of water table levels and regression curve magnitudes can be evolved, with variations on the theme controlled by direction of dip and degree of interconnection of fractures related to the sough.

The pattern becomes even more complex when one incorporates into this theory the additional geological confine - that of impermeable horizons. This confine may take two forms, the lava horizons or the shales capping the limestone sequence. At this point one must introduce the concept of water compartments. This is a term which applies to both natural and artificial conditions, and can be defined as water trapped or circulating in both vadose and phreatic zones between confining impermeable horizons. To exemplify this point, take a stratigraphical sequence of limestone - lava - limestone - shale. In this case there are two water compartments delimited between the shale and the lava, and in the limestones below the lava. Both compartments will have their own unrelated water tables, the level of the water table dependent on the vadose zone water input and the phreatic adjustment to such an input, and the lateral uniformity of the compartment; i.e. if the lava flow dies out, the two compartments will become united.

Now one can introduce the structural element to such confines, and examine sough driving into water compartments of dipping strata.

Under natural conditions (Fig. 5, diag. 4a), a dipping lava horizon would divide two water compartments. One of these compartments above the lava has a regression curve for a water table based on both the lava as a perched zone, and the river level. The water compartment below the lava will have a variable regression curve to its water table, and in the case illustrated the level of this water table produces a true perched water table above the lava. This situation may seem somewhat unrealistic, but the Matlock anticline commonly shows such perched water tables with the two perched horizons on top of both the Upper and Lower Lava, and a separate water table related to the Derwent river level. Thus a zone beneath a lava may be completely dry, whereas immediately above it, it may be in the phreatic zone. Such a dry vadose zone area has been termed the 'umbrella zone' (Oakman, 1979), shaded in figure 5, diagrams 4a and 5a.

Driving a sough into the above geological confines has the following effects. Driving against the dip, the sough would reach the lava, and the whole zone above the lava would then be rendered vadose (Fig. 5, diag. 4b). Frequently, at this point, branch soughs would then be driven along the top of the lava at main sough level to give a greater effect in draining the compartment totally to sough level, tapping water on a down-dip movement by following the lava structure contour (fig. 5, diag. 6). Once through the lava, the sough then taps the next compartment, with the new regression curve going away from the forefield as in the case of diagram 2b.

Driving with the dip (Fig. 5, diag. 5a & b), the sough would create a large umbrella zone of the water compartment below the lava, and thus as soon as the lava was penetrated the apex of the second compartment above the lava would be breached, and, although this factor is dependent on the degree of interconnection of the cavernous ground, a large section of such a water compartment would rapidly be laid dry. Thus, passing through an impermeable horizon, regardless of the dip, would tap a large amount of water.

Thus, these are the features of sough hydrogeology. Coupling the lot together produces a complex flow pattern, with new artificial water tables. As most of these geological confines do occur in a single large sough, one can appreciate the difficulty in evaluating the hydrogeology of one such sough. Study of the courses of the soughs shows how the sough engineers used these principles, as the most effective soughs were driven against the dip where possible, along structure contours, and through impermeable zones, with the specific aim to tap and continue to keep dry whole water compartments. Some of the later soughs were also continued to tap feeding vadose and phreatic streams running into the artificially drained compartments nearer their sources.

Having evaluated the basics for the variation in sough hydrogeology, one can now examine the factors governing sough catchment areas. This determination is governed by three basic factors:- (a) the sough altitude in relation to the surface - a factor which determines the maximum depression of the natural water table. The tail altitude is not always reliable in determining sough altitude at any one point, as the sough may have a steep gradient, and thus, say, 3 miles from the tail may be up to 50 feet higher than the outfall. (b) Fractures intersected by the sough - direction of flow in such fractures would be directed towards the sough, and thus would act as a 'natural' sough branch, although nowhere near as effective as a true sough branch. Catchment areas to such a fracture are also catchment areas to the sough, and would be governed by the connectivity of the fracture, any other fractures connected to it, the limits of such fractures, etc. (c) The limit of any impermeable lithologies within a compartment controlled by them affected by the sough - if a sough approaches a totally impermeable lava, but does not pass through it, the catchment area can be delimited by the area of the lava outcrop from the sough approach direction. If such a sough passes through the lava, the catchment area is enlarged by the outcrop expression of the second compartment, and so on. This second compartment can be delimited if there is another lava ahead of the sough, otherwise the catchment area to the sough through the first lava is governed by the trends already discussed -

dominantly structural, that is, down dip flow and connectivity of fracture systems.

Because of the difficulty in determining, or even estimating, sough catchments, it is useful to divide them into:-

(a) Proximal Catchments - those areas in close linkage to the sough, directly connected hydrologically. These are areas which can be delimited by one of more impermeable horizons or known range of fractures likely to connect to the sough. The compartments related to proximal catchment areas rapidly respond to rainfall.

(b) Distal Catchments - those areas likely to be in hydrological linkage to the sough, although indirectly having no reliable impermeable horizons or range of fractures likely to be connected to the sough. The control of water from a distal catchment reaching the sough is purely dependent on the structure of the area; i.e. one can say that if the dip is directed towards the sough, the outcrop areas of such dipping strata may well be within the sough catchment areas. Compartments associated with a distal catchment have slow sough response to rainfall, and are therefore always likely to be flooded well above sough level.

Major Sough Driving.

Over the years of sough driving, one can see a progressive improvement not only in their effectiveness, but also in their construction. Early soughs were often trial and error affairs, but later larger ones were feats of engineering.

During the compilation of data for this article (Oakman, 1979), the author has often mused on just how much the sough engineers knew of the hydrogeology of a mining field before a sough was made. Did they have a clear concept of the geology and the subsurface water flow that we can only theorise and glimpse today in the area, or was it just that they knew which areas were more affected by flooding due to the extensive and easily accessible mines, and thus drove the large soughs to intersect as many flooded areas as possible? Documentary sources frequently hint that they had knowledge of springs ahead of the sough, as seen so frequently in the Meerbrook Sough Company manuscripts (1841-1888, Ilkeston Public Library), although in other places, soughers admit surprise at intersecting some strong feeders.

Analysis of the courses of the large soughs (Hillcarr, Yatestoop and Meerbrook) show just how much the sough construction was dominated by the geological structure of the area (Fig. 3.). Both Hillcarr and Yatestoop Soughs are driven at the lowest possible point into the floor of the Stanton syncline. Yatestoop Sough was driven in a large fracture in the mineral field in limestone, with branches driven against the dip into the limestones of the south flank of the syncline. Hillcarr Sough was driven to the Alport mines by an indirect route along the shale/limestone boundary at the sough contour, around the noses of minor fold structures, with branches out of it heading northwards in major fractures in the limestones of the north flank of the syncline. Some of these branches continued northwards to intersect the main water feeders to the mining field (Figs. 6 & 7).

Meerbrook Sough was driven direct to the lowest level of the nose of the Bolehill anticline limestone, a naturally confined phreatic reservoir, with branches heading into the core of the anticline to the northwest, while the main sough went on to intersect the main feeders under Wirksworth in a large shatter belt.

Thus all soughs create vadose out of phreatic zones, and one would expect to be able to see exhumed phreatic features like tubes. However, the area was still in a very juvenile cave development stage when the phreatic zone was drained, and there is very little mention of any connective cave systems in the area. Virtually all of the caverns intersected by the soughs are pre-Pleistocene mineral solution cavities. The only 'caverns' and phreatic systems worthy of note are under Wirksworth and deep under the Stanton syncline, both of these at present inaccessible due to partial sough collapse and subsequent flooding.

FIG. 6

STRUCTURAL MAP OF THE NORTH FLANK OF THE STANTON SYNCLINE

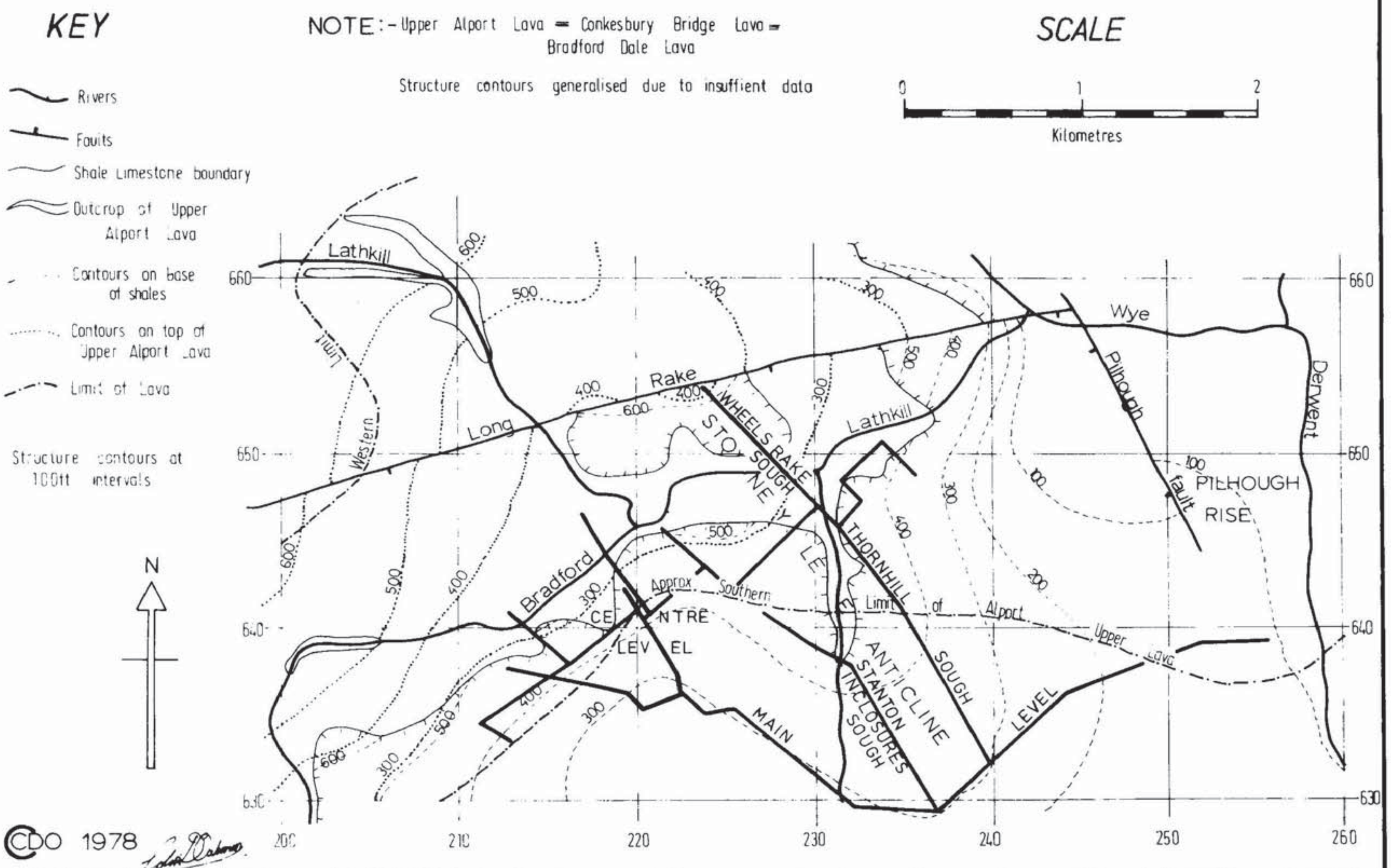
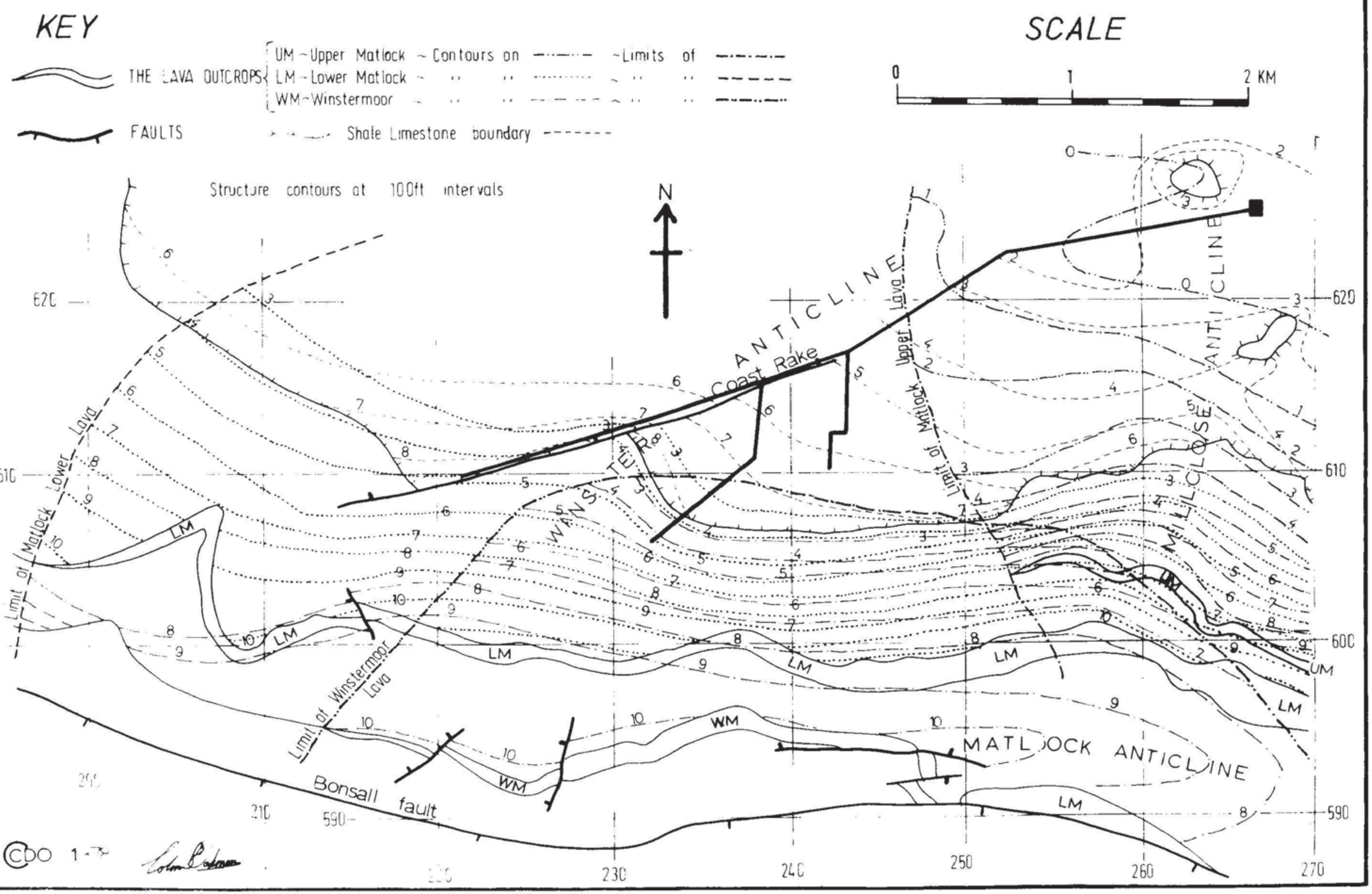


FIG.7

STRUCTURAL MAP OF THE SOUTH FLANK OF THE STANTON SYNCLINE



The problem of the partial flooding of the newer sough complexes is somewhat disturbing. Most of the blockages occur in shale sections between the tails and the mineral fields, so perhaps with backing up, the older soughs will resurge again and the artificial water table levels will return to natural conditions again.

IV THE DRAINAGE OF THE STANTON SYNCLINE.

Two sough complexes drain the Stanton syncline to a level approximating to the River Derwent at Darley Dale (c.310 ft. OD). The two complexes, those of Hillcarr and Yatestoop Soughs, drain the north and the south flanks of the syncline respectively. The interplay of these two complexes produces equilibrating water levels across the axis of the syncline in the stratigraphically high limestones, and the artificial drainage of the syncline is at least partly responsible for the intermittent seasonal disappearance of the Lathkill river. Before discussing these factors, it is necessary to look at both sough complexes in brief.

Yatestoop Sough.

This sough was the last one driven to the Winster-Elton mines (fig. 4). The tail is located on the west bank of the river Derwent north of Darley Bridge (SK 26396259), at an altitude of 315 ft. OD. Work on the sough was started in 1752 (Rieuwerts, 1966).

The sough was driven in shale on a WSW heading, above the New Millclosemine workings, and intersected the mineral field in limestone in c.1761 (Southern, 1761) at c.SK24886197, before intersecting the northern end of the northerly dipping Yatestoop pipe vein near Birchover (64356164). At this point, the sough also intersected the Coast Rake, which the main sough followed westwards to Elton, taking down-dip northerly directed subterranean drainage from a series of rich northerly dipping pipe veins, including the Portaway pipe vein west of Winster. This method of driving enabled the sough to drive in a constricted fracture, cross-cutting the nose of the Winster anticline, and crossing all the northerly directed streams in the dipping pipe veins at the lowest possible point (figs. 4 & 8).

Two branches were driven southwards against the dip - one in the Yatestoop pipe vein and the other to the Placket mines and the southern end of the Portaway pipe. Only the latter branch penetrated the Lower Matlock Lava, the Upper Lava being absent over much of the area drained by the sough. The only other point of possible penetration of this lava was in the Coast Rake at Elton, although the historical facts are not clear as to whether the sough went far enough west in this vein to penetrate the lava, as the vein is a fault at this point across the nose of the Winster anticline. Figure 8 shows the north face of the Coast Rake, the south face being downthrown some 50 feet. It is certain that water would have been coming through the lava in the Coast Rake, thus the sough 'penetrated' the lava into the compartment below it.

The evaluation of the proximal catchment of Yatestoop Sough is a relatively simple affair. The proximal catchment can be defined for this sough on the basis of the outcrop pattern of the Lower lava, as the outcropping limestones stratigraphically above it are within the proximal catchment. The distal catchment can be evaluated as the range of dip directed to the sough at the southern end of the Portaway pipe where it passed through the lava, and the range of the Coast Rake west of Elton and the strata dipping towards this vein. In the east of the area affected by the sough, it is difficult to draw a precise line on the catchment boundaries between Yatestoop Sough and the Oxclose Sough complex draining the eastern end of the north flank of the Matlock anticline, as the geological confines of this sough's catchment area are delimited in the same way as for the Yatestoop sough. Thus there is probably some overlap in the catchment areas between these two complexes, as there is likely to be some overlap between the western distal catchments of Yatestoop and Hillcarr soughs.

Hillcarr Sough.

This sough was started in 1766 (Kirkham, 1960/61, 1964/65), and was operational as a sough until 1932 for the activities of the Mawstone Mine south of Youlgrave. It was the last sough to be driven into the Alport mines, and the longest sough in Derbyshire, when one includes all its branches, which went in almost every vein in the Alport field. The tail is located on the west bank of the Derwent below Stanton Moor at 25846372, at an altitude of 315 ft. OD. There are four main divisions to the sough - Main Level, Centre Level, Thornhill Sough and Stanton Inclosures Sough (fig. 6).

The Main Level of the sough is almost totally in shale and extends from the tail to Greenfields shaft (22516351) via a series of deep sough shafts. The sough over the latter half of the section follows the shale limestone boundary contour at sough level (figs. 6, 9 & 11) around the nose of the Stoney Lee anticline, intersecting some upstanding reef masses over the crest.

Two branch soughs were driven out of Main Level in a northwesterly direction against the dip into the limestone parallel to the Stoney Lee anticline axis. The first, Thornhill Sough, drained the Harthill mines, and a continuation of this branch sough, the Wheels Rake Sough, crossed under the Lathkill in the Wheels Rake vein, penetrating the Upper Alport Lava (fig. 12). The second branch, Stanton Inclosures sough, was driven parallel to Thornhill sough into the eastern section of the Alport field. Both of these branches were driven in major vein fractures, against the dip, although shallow in this area, so that both branches became stratigraphically lower as they advanced.

The Centre Level of the sough is the name given to the sough in the Alport mining field, totally in limestone, with all the many branches driven in veins (fig. 9). The network of tunnels connects the Main level to the northern end of the Stanton Inclosures sough, with all the branches except one terminating at the Upper Alport Lava. At three points the Centre Level passed under the Lathkill river - in the Piennet Nest, Bacon Close and Windy Arbour veins. It is in the latter of these that the sough penetrated the Upper Alport Lava in the 1860s (Kirkham, 1960/61). This branch out of the Centre Level was known as Danger Level, and it was intended to continue this branch to the Lathkilldale mines at Over Haddon (Brooke Taylor documents, DRO504B/L366). Tapping the water compartment below this lava forced operations to cease due to flooding in the sough, and the project was abandoned.

EXPLANATIONS TO FIGURES 8 AND 11.

These figures are constructed so as to put as much information onto one diagram as possible. They are compiled by selecting a projection of a base plane grid based on Ordnance Survey maps, and choosing such a projection to show maximum detail when the diagram is complete. Onto this base grid the lines of rivers, veins and soughs are transferred from previously drawn plans. Then using topographical information the lines of the rivers, etc. are projected vertically to form the base diagram. The soughs are then drawn in at their respective altitudes onto the planes, and then geological information is added from appropriate maps, boreholes, shaft sections, sough bedrock data, etc. If, due to the choice of projection perspective, important details on one plane are obscured by a plane nearer to the viewpoint, a 'window' can be cut in the latter to expose it.

The base grid can be chosen at any altitude. In the case of these figures it is selected at 300 ft. OD as this approximates to the lowest level of the sough complexes. Any projection of the vertical planes below the base grid is shown in broken lines, the grid plane intersection with the vertical plane as a solid line on the base plane and the plane above the grid plane as a solid line. The vertical scale may be exaggerated with respect to the horizontal one, as in this case, to enable the detail to be represented more clearly.

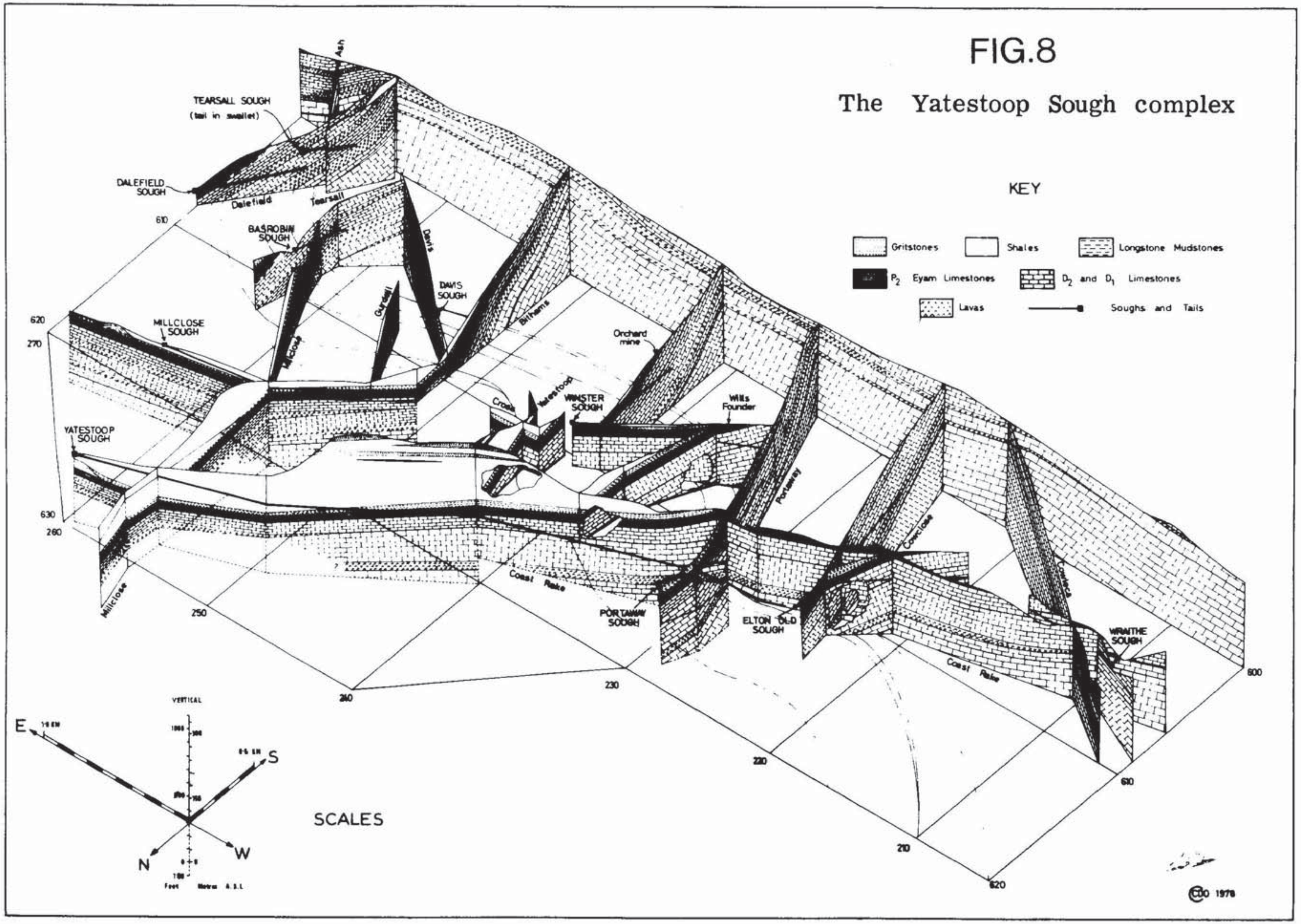
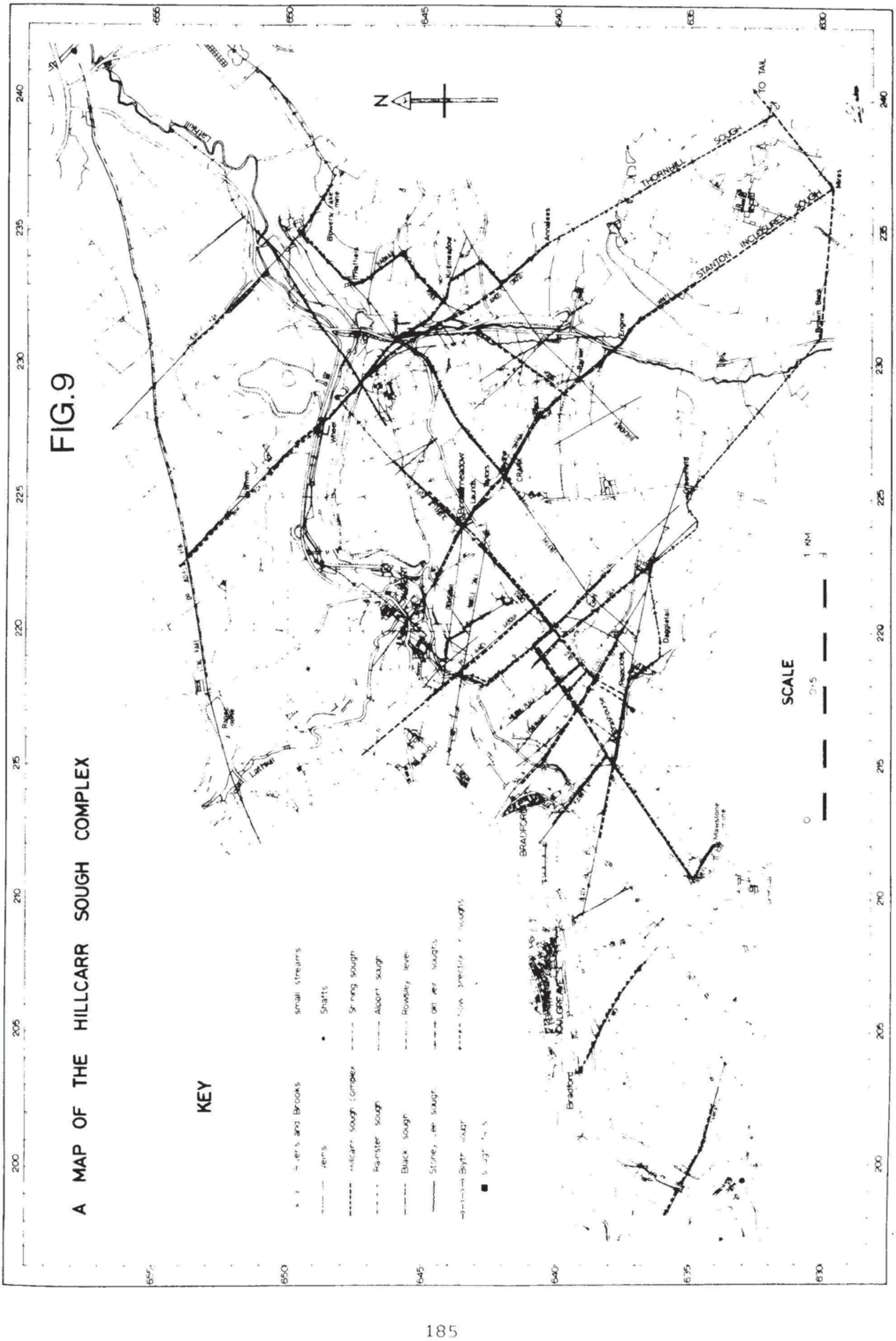


FIG.8

The Yatestoop Sough complex


A MAP OF THE HILLCARR SOUGH COMPLEX
FIG.9
KEY
small streams
Shafts
Shining sough
Alport sough
Black sough
Rowsley level
SCALE
1 KM
THORNHILL SOUGH
STANTON INCLOSURES SOUGH
TO TAIL
N
Mawstone mine
BRADFORD
Bradford

Thus, Hillcarr Sough drained the whole of the mineral field between the shale and the Upper Alport Lava, and affected the water compartments below the lava by the two branches of the sough which penetrated it, and by indirect connection to this compartment via the vein fractures passing through it. Hence, one can delimit the sough's proximal catchment using this lava, and the distal catchment by the Lower Lava. Problems in this evaluation is that both the lavas die out northwards, and only occur at outcrop in the Lathkill valley at Over Haddon. The only way to delimit the catchment areas is by projecting the dip of strata, hence delimiting total sough catchment within a line to the north from Bakewell to Monyash to Middleton-by-Youlgreave. This places the whole of the Lathkill valley into Hillcarr sough's catchment area, a factor to be discussed later in the drying up of the river in summer.

A Possible Phreatic System in the Stanton Syncline.

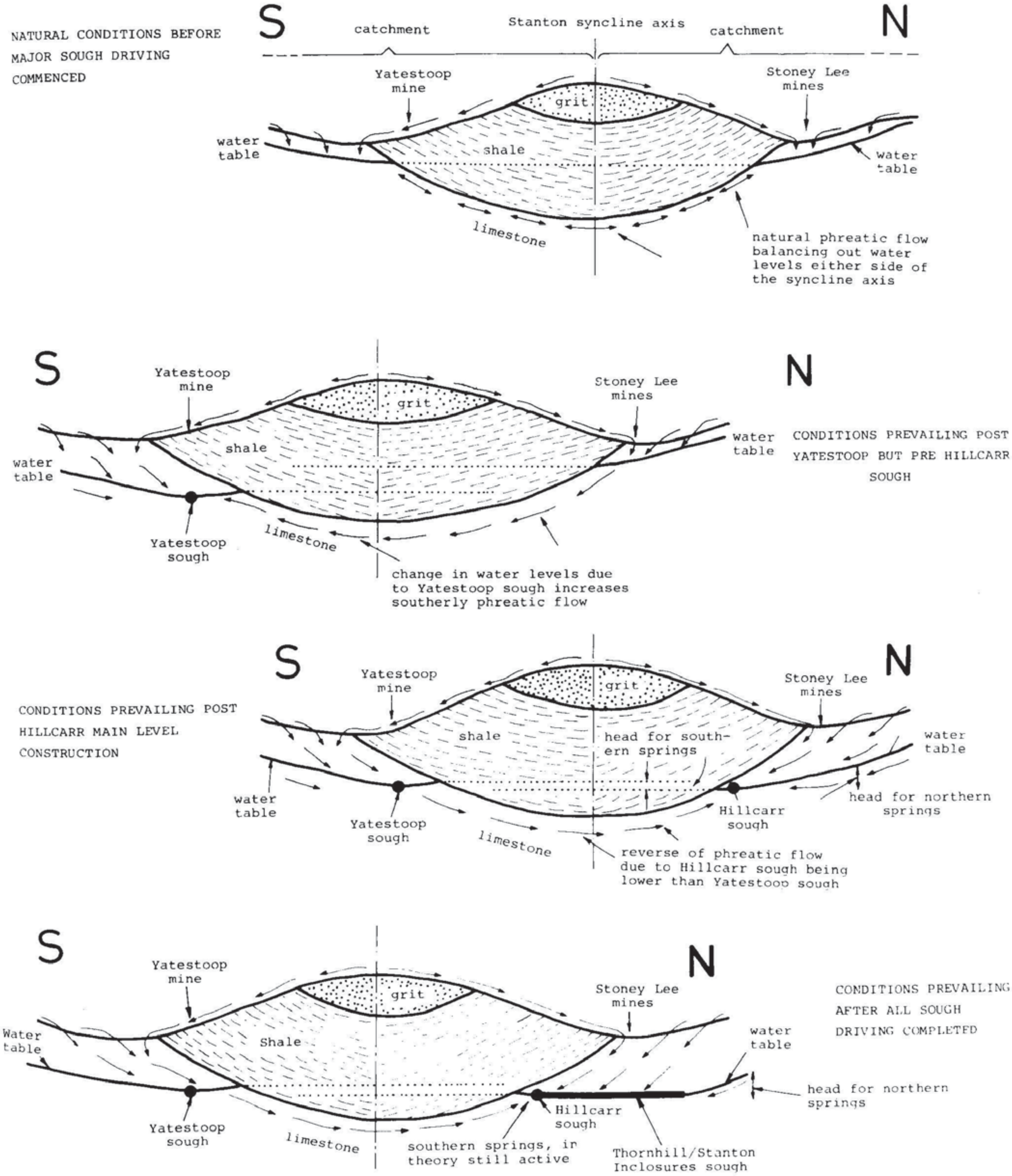
When Hillcarr Sough Main Level intersected reefs lying beneath the shales in the nose of the Stoney Lee anticline at the future site of the Thornhill sough branch (c.23956319, fig. 11) during driving in the early 1770s, a series of springs were cut. Six springs entered the sough from the north side which lowered the water levels in the Harthill mines (some 1½ miles to the northwest) by direct down dip drainage in the Stoney Lee anticline. This first tapping of the water compartment beneath the shales effectively 'pulled the plug' out of the confined phreatic reservoir in the nose of this anticline. These springs were very powerful (Hillcarr Sough Co. Mass. 1772-75, DRO, Matlock), which is not surprising as the head of water above Hillcarr Sough at this time was of the order of 80 feet, and included the volume below the older and higher Blythe and Stoney Lee Soughs. It was from this section of the sough which tapped these six strong springs that the Thornhills and Stanton Inclosures soughs were driven at a later date to widen the old phreatic passages in the Amos Cross and White veins respectively.

At the same time, on the south side of the driving sough, six weaker springs connected to the six stronger northern springs were cut in the limestones which did not affect the Harthill mines, but over a period of a few months actually lowered the water levels in the Yatestoop mine, 1½ miles to the south which was, at this time, working an engine below Yatestoop Sough level. This then raises the question as to whether or not the Hillcarr sough cut into a phreatic system acting across the axis of the Stanton syncline?

What we do not know is whether Yatestoop Sough cut a similar series of springs coming into Yatestoop Sough from the north which had any effect on the Harthill mines on the north flank of the syncline. There are no known documents which chronicle Yatestoop Sough during driving near the Yatestoop vein, and there is no documentary evidence from the Harthill mines at this time to comment if water levels dropped in the mines when Yatestoop Sough cut such a system. If water levels did change in the Harthill mines it is likely that it was unnoticed, as these mines had their own soughs (Grime, Blythe, Stoney Lee and Rainster Soughs) as well as a series of pumping engines operational, and the miners would have put any changes down to seasonal water table fluctuations.

From the effect of Hillcarr Sough on the Yatestoop mine it is obvious that some form of phreatic system did exist. By 1770 the Yatestoop Sough had effectively drained the southern flanks of the Stanton syncline to its level, so to have any northerly flow there would have to be a hydrostatic head between the limestones of the south and north flanks for there to be any flow into Hillcarr Sough from a southerly direction. This implies that Yatestoop Sough at the Yatestoop vein is at a higher level than Hillcarr Sough at the location of the six southerly springs. Both the sough tails are at the same altitude (315 ft. OD), the Yatestoop vein is about 1.5 miles from Yatestoop Sough tail and the Hillcarr springs about 1.3 miles from Hillcarr Sough tail. This is not enough to merit a great difference in water levels either side of the syncline axis, if sough gradients are taken to be uniform. However, it is on this last point that the large differences occur.

FIG.10 THE POSSIBLE PHREATIC SYSTEM IN THE STANTON SYNCLINE



As Yatestoop Sough was comparatively early compared to Hillcarr Sough, it was driven by older methods with steeper sough gradients. It can be calculated from data on sough levels at certain shafts that Yatestoop Sough had a gradient of about 15 ft. per mile, a high figure when one considers that the objective of deep drainage was reduced the further the sough went from the tail. Thus at the Yatestoop vein intersection, the sough altitude was about 338 ft. OD.

Hillcarr Sough, however, had to drain a comparatively shallow mineral field, and a steep gradient sough would have been useless, as there would be little difference between the sough level and the older soughs driven from the Lathkill valley. Hillcarr Sough has a mean gradient of about 2 ft. per mile, just about sufficient to induce tail-directed flow. This also explains why there were so many sough branches in the Centre Level, as the more the tunnels, the more rapid the expulsion of the vein waters with such a shallow gradient. Thus the altitude of the springs in Hillcarr Main Level can be calculated as about 318 ft. OD.

Hence the hydrostatic head for the southern Hillcarr springs is about 20 feet. For such a small head to produce springs over a distance of about a mile, the passage of the water must be through totally connective passages in the phreatic zone, in other words, through a true connective phreatic system.

Figure 10 shows the progressive development of this phreatic system as the two soughs were driven, from natural conditions to total artificial conditions. It is important to note that by examining the soughs in this way, one realises that this phreatic system was operational under natural conditions, and that flow under the syncline was levelling out water tables either side of the syncline axis. The nature of the syncline and the shales in the core at outcrop should have defined the axis as a hydrological divide, which it is not.

Hillcarr Sough and the Lathkill River.

As a corollary of the above argument it is possible to present a new hypothesis on the drying up of the river Lathkill in the summer months above Over Haddon, the virtually complete disappearance of the Bradford river in summer by virtue of the effect of Hillcarr Sough on these surface rivers. This hypothesis could provide an interesting study for anyone interested in monitoring of flow rates of the Lathkill and Bradford rivers over their total courses, precipitation gauging and continual sough outfall determinations, as well as selective dye testing.

As previously said, the Hillcarr Sough complex catchment area can be argued to include the whole of the Lathkill valley from Monyash to the Wye. From Conksbury Bridge to the Wye, the Lathkill flows on the proximal catchment of Hillcarr sough, as does the Bradford river from below Middleton-by-Youlgreave to Alport, where the latter joins the former . This section of the surface drainage is above the Upper Alport Lava (Bradford Dale Lava, Conksbury Bridge Lava). Upstream of Conksbury Bridge, the Lathkill valley is in the distal catchment of Hillcarr Sough.

Logically, the Lathkill below Conksbury bridge should disappear in dry seasons as it is in this proximal catchment, which today it does not. This is due partly to the lava forming an impermeable bed and partly to extensive weiring and clay lining of the river done in the 19th century to keep the river on the surface for fish breeding. It was known then that the river did sink into the Alport mining field and Hillcarr Sough, and was, in part, diverted by the sough due to water tables being lowered to sough level well below the level needed to maintain the river on the surface. The proximity of the sough to the river can be shown at many points, and in some veins, it actually passed directly under the river (figs. 9 & 11). The same story applies to the lower reaches of the Bradford. Parts of the river are floored by the Bradford Dale Lava, and thus the water flow to the sough from its proximal catchment is interrupted by the river, seen in winter as springs resurging on the north and west bank of the river only, supported by a temporary seasonal perched water table (fig. 11, Timperly and Nick veins). Thus, both rivers might disappear if it were not for

The Hillcarr Sough complex

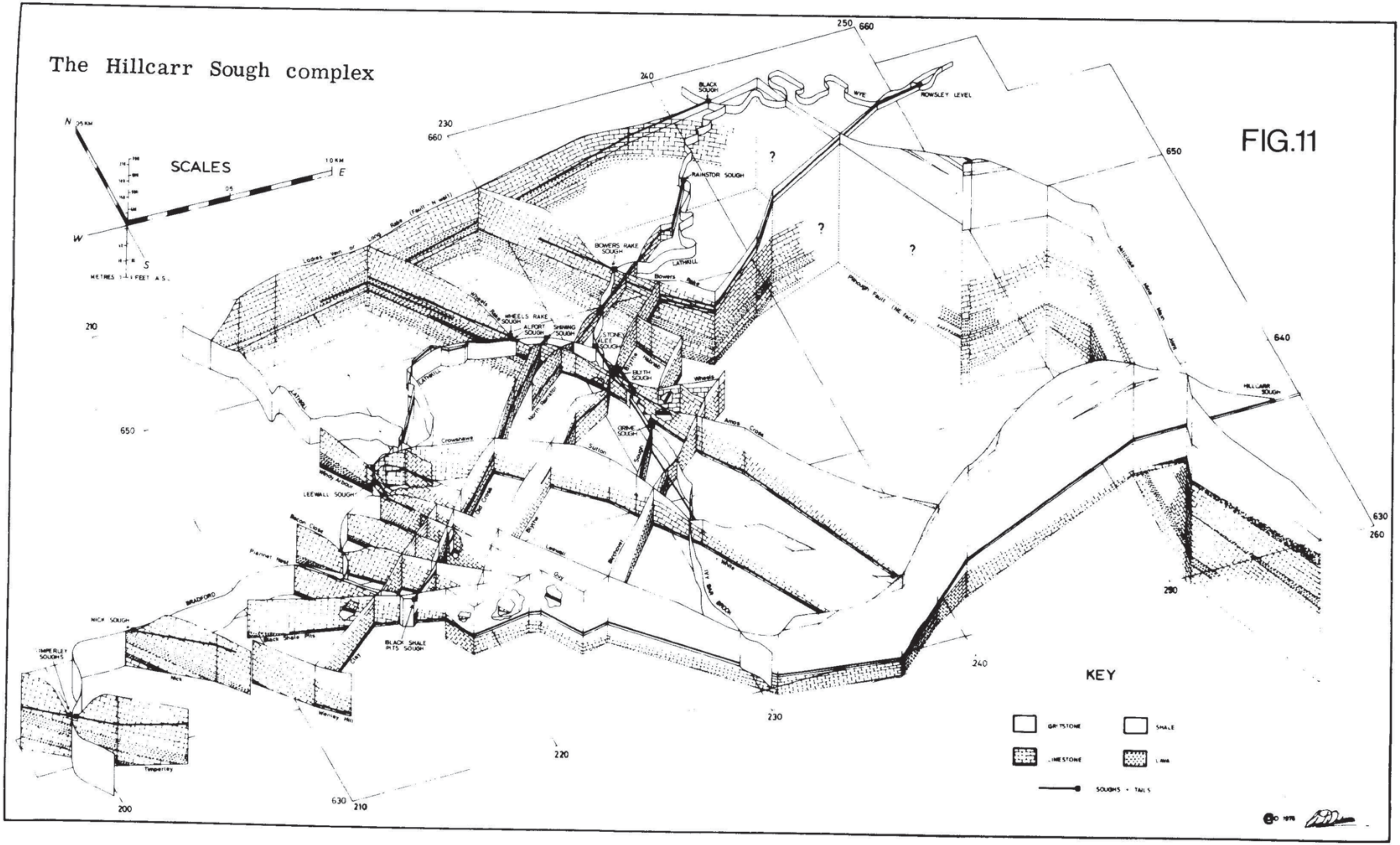
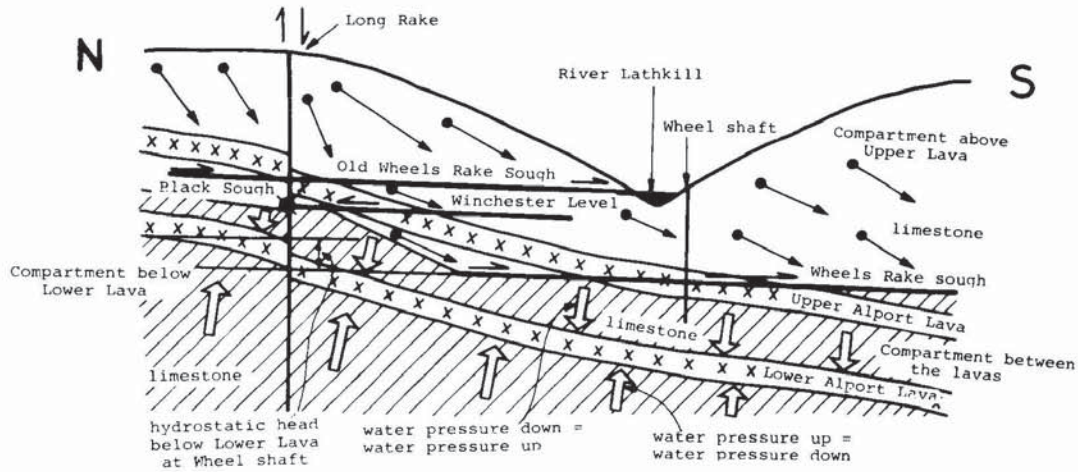


FIG.11

FIG. 12 WHEELS RAKE - HYDROLOGY

BEFORE DEEP DRAINAGE AND PUMPING
AT WHEEL SHAFT



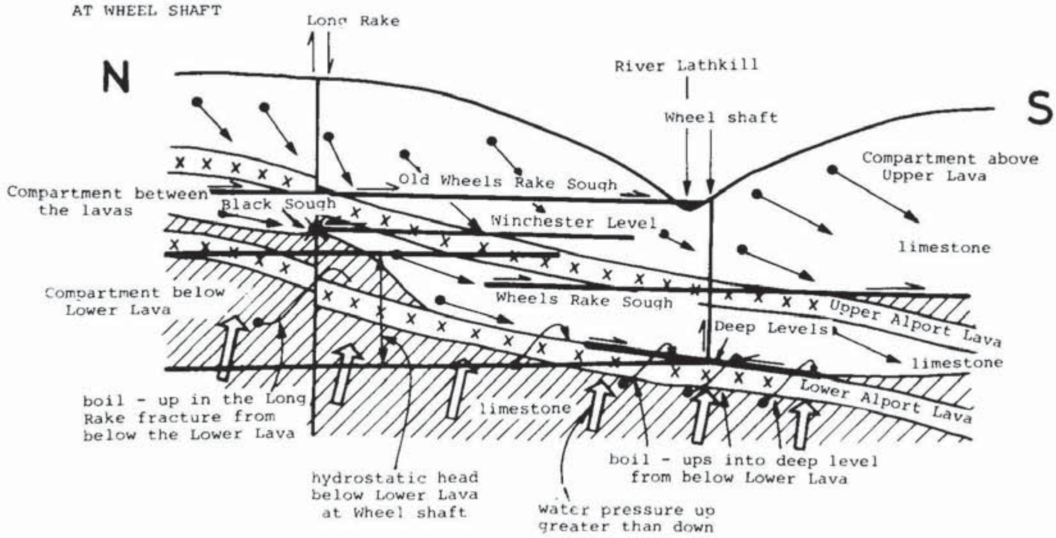
Black Sough previously took water from the upper parts of the compartment below the Upper Lava at Long Rake

Thornhill Sough (Wheels Rake branch) drains lower into the compartment

SATURATED ZONES

SKETCH SECTIONS ONLY - NOT TO SCALE

AFTER DEEP DRAINAGE AND PUMPING
AT WHEEL SHAFT



artificial support for the river beds. Their flow rate has certainly decreased in all seasons due to water from the river catchments flowing into Hillcarr sough. In winter months, the flow rate of the rivers increases drastically, but this is mainly due to feeding streams flowing from the shale highlands of Stanton Moor to the south, not from the limestone in the sough's proximal catchment.

Having discussed why the rivers stay on the surface in the proximal sough catchment area, one must now examine why the upper reaches of the Lathkill, which is on the distal sough catchment, disappears. Firstly, the river is not artificially lined over the whole of this section as it flows for some distance on its own natural bed of tufa. Secondly, it is partly diverted by the Lathkill Dale Sough, though this was blocked to help maintain the river on the surface; thirdly, one must look at the evidence for the extension of the sough through the Alport Lavas to tap the water compartment below both lavas, and thus include the Upper Lathkill valley in its catchment area.

Only two branches of Hillcarr Sough are known to have penetrated the Upper Lava - Danger Level and Wheels Rake Sough branches. Although the former was intended to go on to penetrate the Lower Lava (it is not certain as to whether or not the Lower Lava is actually present at this locality due to lack of geological information), it never did. If it had been driven to the Lathkilldale mines at Over Haddon as intended, there would be no need for this discussion, as the Upper Lathkill would have certainly been influenced by Hillcarr sough. Due to drastic flooding of the sough when the lava was breached, it is obvious that the soughers had tapped a new water compartment, previously untapped by the other sections of the sough in this area.

The other point of breaching of the Upper Lava was in the Wheels Rake vein, which also breached the Lower Lava. The story of this section of the sough is summarised in figure 12, and shows how the study of archival documents on the soughs can give great insight into complex sough hydrogeology.

It is not known for sure if Wheels Rake sough branch did penetrate the Upper Lava, but the story lies in the shaft sunk to the sough level whilst actually in the Lava. This shaft was the well known Wheel shaft, the geology of which has been chronicled by James Barker, the engineer in 1836 on the Wheels Rake drainage project, and Green (1887), of the Geological Survey, as follows:

Shaft top at 395 ft. OD	BARKER	GREEN
limestone	60 ft.	52½ ft.
lava	84 ft.	82½ ft..sough at 320ft.OD
limestone	48 ft.	45 ft.
lava	12 ft.+	336 ft. (56 fathoms)

One should add that the thickness of the Lower Lava was unknown, as the pumps were set in the base of this shaft in the Lower Lava. The Wheels Rake company bored the base of the shaft and found the lava to be at least 56 ft. thick, misread by Green as 56 fathoms. There would be no point in boring to such a great depth as Green suggested as the pumps had difficulty when first set up to cope with the water in the compartment between the two lavas, let alone the one below the lover lava.

The magnitude of the water problems at the Wheel shaft and the miners' attempts to cope with it are realised when at this time this was the first part of Hillcarr Sough to be connected into the compartment between the two lavas. Work was started in pumping out the compartment, and was completed in 1836 (James Barker memos, Brooke Taylor Mss., DRO, Matlock), only to have a sudden flow of water rushing into the shaft from the north along Wheels Rake. The early conclusion was that water was flowing backwards in the Winchester branch sough of the earlier and higher Black sough (which served Long Rake to the level of the Wye at Pickory corner). This was occurring, but it was only part of the problem, as a series of powerful "boil-ups" had broken through the Lower Lava into the newly drained compartment. The reason for this boil-up we can see clearly today, as in taking the water out of the compartment between the two Lavas the hydrostatic pressure keeping the water in the compartment below the Lower Lava became zero, and the water broke through the Wheels Rake joint in the lava. Water also broke through in the Long Rake fracture belt to the north. Figure 12 shows this section of the Wheels Rake with its soughs, and is self-explanatory on how Hillcarr sough Wheels Rake branch penetrated the Lower Lava indirectly.

This penetration of the deepest water compartment eventually forced the miners to abandon operations in the vein between the two lavas, and the zone became flooded again, and is so to this day. Thus Hillcarr Sough is still attempting to drain the compartment below the Lower Lava distally by an indirect artificial phreatic route, thus proving how the sough catchment area has become greatly enlarged by this example of 19th century mining technology going wrong.

Having set out in full the reasons for the enlargement of Hillcarr Sough's catchment area covering the whole of the Lathkill valley one must continue to look at the remaining facts to enforce what is so far only a hypothesis on the disappearance of the upper Lathkill in summer.

Various authors have attempted to show that this phenomenon is due to Magpie Sough further north. This catchment area to Magpie Sough is north of the Lathkill valley, with flow northwards to Magpie Sough (Robey, 1965). The hydrological divide between the Magpie and Hillcarr soughs lies between Monyash and Bakewell along the axis of the Mogshaw anticline, an easterly plunging fold. To the south of this line, down-dip easterly and southerly drainage occurs, directed towards Hillcarr Sough. This drainage trend is seen in the wet months of the year in the Lathkillhead/Cales Dale cave complex (Beck, 1978, pers. comm.).

On examining the outcrop of the lava horizons, they both have a brief outcrop in the Lathkill valley - The Upper Lava at Conksbury Bridge, and the Lower Lava (here called the Lathkill Lodge Lava), just south of Over Haddon. It is from this second locality that the Lathkill always flows, resurging as a series of springs in the river bed, and is kept on the surface by the impermeable lavas acting as local bases to the river bed, although this is in turn drained by Hillcar Sough as its proximal catchment, a point previously discussed.

Above these resurgences at Over Haddon, the whole length of the Lathkill dries up in summer, as do the two lead mine soughs of the valley - Lathkilldale Level and Mandale sough. The first of these two soughs has its tail at Over Haddon in the valley floor and follows the river westwards, becoming 80 ft. below the valley floor at the Lathkilldale mine, its farthest reach from the tail. This sough proves that the Lathkill is not only dry on the surface, but that in summer, the water levels west of Over Haddon are suppressed at least 80 feet below the river bed, as Lathkilldale level would otherwise flow at the tail. This tends to disprove the old idea that the river flows just beneath its own tufa bed.

Hence, the water table associated with the river is depressed by 80 feet some half a mile from the resurgences at Over Haddon in dry months. Such a depression cannot be caused by changing natural conditions, so it must be the effect of the river flowing in the distal catchment area of Hillcarr sough. As it is the distal catchment, one would always expect groundwater levels to be well above sough level, which it still is at the Lathkilldale mines, even if the water table here is below river level.

One can continue to show that even farther reaches of the old Upper Lathkill were affected by the sough as far as Monyash.

There is sufficient historical evidence to show that until relatively recent times the river flowed from as far as Monyash (Bamber, 1951) and only in drought was restricted to flowing from Lathkill Head Cave (Burdett's map, 1786). Today, the river only flows from Lathkill Head Cave in periods of excessive rainfall. In 1810 the Lathkill permanently flowed past Mandale mine, as it utilised the river water for driving a waterwheel. In later years, the waterwheel did not have sufficient water to drive the pumps which resulted in a steam engine being erected to work with the water wheels in the 1840s. So by this time, the Lathkill presumably had its summer flow decreasing.

By 1831 it is implied that the Lathkill rarely ran on the surface upstream of Lathkill Head cave. It is around this time that Hillcarr Sough was having a great effect on the Alport mining field, draining its proximal catchment. It is very likely that around this time the sough was taking some drainage from the distal catchment below the Upper Lava through vein joint fractures in it, but the lavas had not been properly breached by this time. It was in 1836 that the lavas were breached in the Wheel Rake vein, and it is soon after this that the waterwheel at Mandale mine started to lose its effectiveness and had the steam engine coupled to it. In the 1860s Hillcarr Sough penetrated the Upper Lava with a branch sough in Danger Level, and by the turn of the century, little is said of the Lathkill except that Lathkill Head Cave only resurged after long periods of rainfall.

No blame can be attributed to the Magpie Sough, as this was not driven until 1874-1881. The Lathkill was affected by 1810, and Hillcarr Sough had penetrated the mineral field by this time and had drained out most of its proximal catchment's water compartment, with some effect on the distal catchment. By the 1870s, the reach of the Lathkill had decreased, and it is around this time that Hillcarr sough had no more driving being done. Over the years since then, the sough has been equilibrating its distal catchment, which has produced the depression of the water table normally associated to the Lathkill. This demonstrates the time factor required to equilibrate a distal catchment and set up a steady regression curve, which fluctuates with the seasons to produce a surface river in wet weather months. To ratify this, Hillcarr Sough would still need to be relatively free of blockages to allow seasonal variations in the level of the water table associated with the distal catchment. The sough does not flood, as various parties have entered it in the Alport field in recent years in dry months. It is partially blocked in places, causing some elevation in water levels in the sough in the wet seasons. If the sough were to block totally, one would probably see the Lathkill return to the surface permanently at Lathkill Head Cave.

V. CONCLUSIONS

Study of archival documents and surface examination of the area under discussion (little work can be done subsurface due to partial blockage of the soughs) proves that one can build up a pattern of how the lead mine soughs worked, and what they did to the natural hydrogeology when driving, and their effect today.

Each sough can have its individual hydrogeology evaluated by combining the many factors of the sough hydrogeology theory. Groundwater flow trends and water table levels are subject to stratigraphic control based on impermeable zones, structural control based on dip and fracture systems and mineral cavern connectivity control (which are all variables), both pre-, during, and post-sough construction. Water compartments can be assessed in both natural and artificial conditions, and new artificial catchment areas delimited.

Evaluation of such features builds up a pattern of post-sough-hydrogeology which can explain the gross drainage of large fold structures, in this case the Stanton syncline, and the effect of a major sough in suppressing area water tables to such a degree as to produce the seasonal diversion of an old river's catchment area, that of the Lathkill.

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AUTHORS

TITLES

OTTER HOLE
Chepstow.
N G R 5253 9627
BCRA Grade 5D/e
Total Length 3200m
Altitude +13m
Surveyed by J.Elliott and D.Underhill + DB, ND, MF & PT. 76-78
metres
0
50
100
150
St. Arvans
A466
Fault Chamber
Gour Passage
Long Straw Chamber
Coral Passage
Tunnels Right
Tunnels Junction
Tunnels Left
Mud Rose Chamber
End Sump
End Chamber
High Aven
Camp 1
Hall of 30
Sump 2
The Extension
Choke 2
Crystal Ball Passage
Rescue Dump
End of Tidal Section
Traverse
Tidal Sump 1
Choke 1
Giant's Cave
Entrance
Sandy Chamber
Resurgence
RIVER WYE
Tidal Mud
Chepstow Race Course
N true
CROSS SECTIONS SHOWN LOOKING INTO THE CAVE
Scale
metres
Projected Section South - North of Tunnels Left and Tunnels Right
Extended Section of side passages from Fault Chamber to High Aven
Extended Section from Entrance to Sandy Chamber
Scale x2
Projected Section West - East
Dye Tested
13m Tide Level
River Wye

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