

Cave Science

The Transactions of the British Cave Research Association

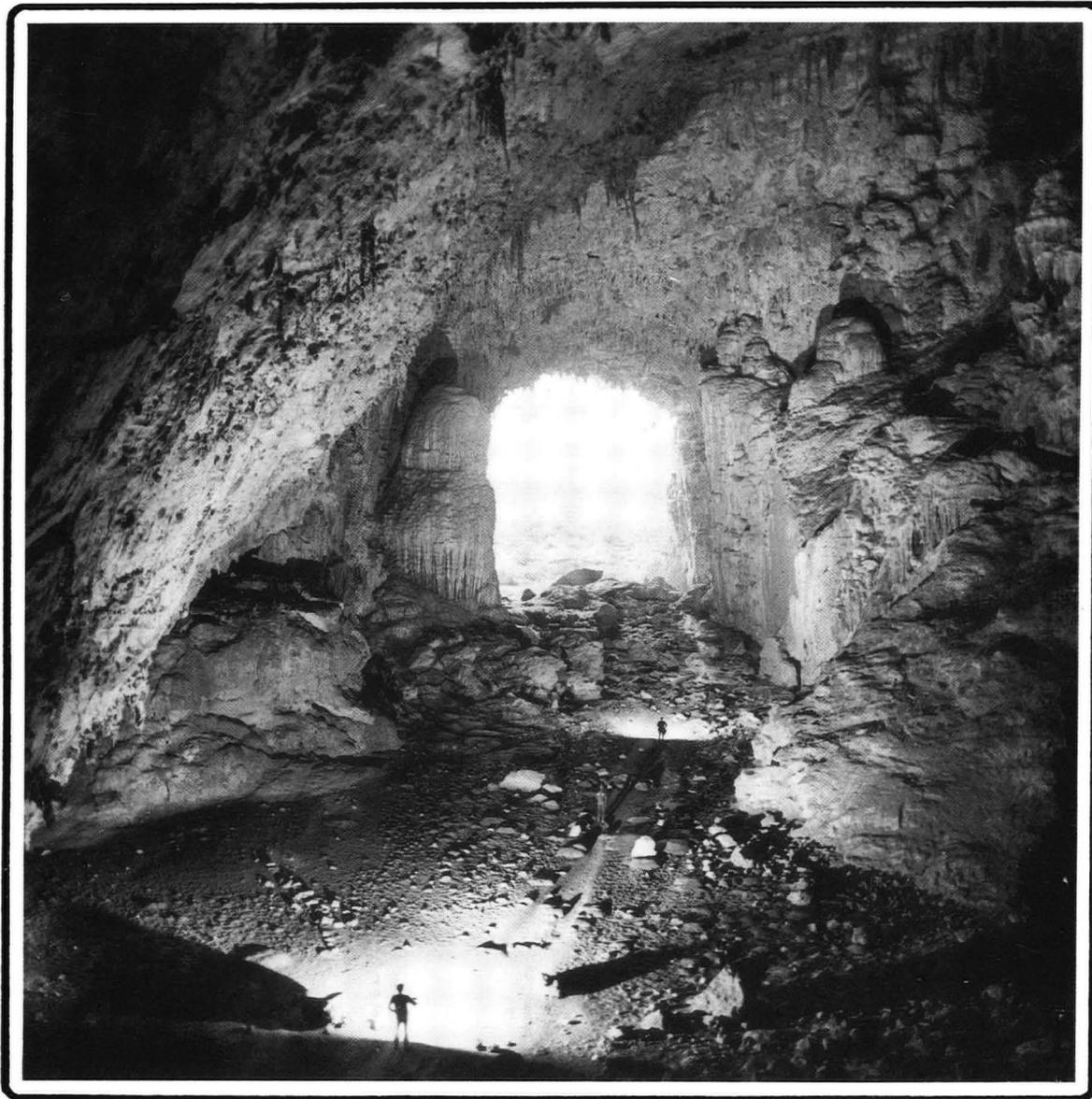


BCRA

Volume 15

Number 1

April 1988



Sediment Paleomagnetism at Llangattwg

Natural Tunnel, Virginia

Tufas and Travertines from Yorkshire

Pigments in Cave Organisms

Survey Reduction by Least Squares

Cave Science

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Cover: The massive fossil trunk passage of Qian Dong in the Bama karst of western Guangxi, China. By Jerry Wooldridge. This is one of the many spectacular photographs of the Guangxi caves and karst in the report of the 1987/88 phase of the China Caves Project, available this summer for £4 including UK postage from BCRA Sales.

Editor: Dr T.D. Ford, Geology Dept., Leicester University, Leicester LE1 7RH

Production Editor: Dr. A.C. Waltham, Civ. Eng. Dept., Trent Polytechnic, Nottingham NG1 4BU

Cave Science is published by the British Cave Research Association, and is issued to all paid up members of the Association

1988 subscription rates are: Individual - £10.00, Institution or Club - £12.50

Membership Secretary: N. Briggs, 68 Poitiers Road, Cheylesmore, Coventry CV3 5JX

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ISSN 0263-760X

Paleomagnetism of Cave Sediments from Mynydd Llangattwg

Mark NOEL

Abstract: The palaeomagnetic study of British cave deposits began with an examination of sediments within Mynydd Llangattwg, Powys. This paper reviews the results obtained from a total of 77 specimens collected in the Agen Allwedd and Pwll y Gwynt cave systems. The evidence suggests that these silts and clays acquired a stable remanent magnetisation through the alignment of magnetic minerals, by the geomagnetic field, during deposition. Similarities in remanence directions within the 'Cap Mud' at five sites in Agen Allwedd suggests that deposition of this unit was simultaneous throughout the cave during a period of normal geomagnetic polarity. A sediment section near the top of the 5th Aven in Pwll y Gwynt includes a clay horizon with reversed magnetisation implying that these sediments record either a recent geomagnetic excursion or fields during the reversed Matuyama chron (>720 Ka). Magnetic fabric data provide evidence for directions of water currents and mass flow in these cave sediments

INTRODUCTION

Sediments formed by slow deposition in water often contain a weak remanent magnetisation. This depositional remanent magnetisation can therefore provide a record of geomagnetic secular variation extending beyond historical observations. This concept has been applied to palaeomagnetic studies of glacial varved sediments from Scandinavia and North America (Noel 1975; Johnson et al. 1948). Lake and marine sediments (Creer 1974, 1981) and surface terrestrial deposits (eg. Heller & Tung-Sheng 1982). These studies have provided important palaeomagnetic constraints on models for the geomagnetic dynamo; they have led to the dating and correlation of Quaternary sediments (eg. Creer 1982) and they have helped to refine and verify a reference curve for archaeomagnetic dating (Aitken 1974).

Due to the glacial erosion which affected many lake basins during the Devensian and the problems of retrieving longer core samples, it has proved difficult to extend existing lake sediment magnetostratigraphies much beyond 13000 yr BP. Although marine sediments have the potential for providing a much longer timescale, bioturbation and slow sedimentation rates severely limit the resolution attainable with this material. Finally, surface terrestrial deposits seldom provide the long sequence of unweathered material which is a prerequisite for accurate palaeomagnetic studies. Cave sediments, on the other hand, are usually preserved under favourable conditions of low weathering, with little bioturbation or desiccation, particularly in the interior zone. They therefore have a capability for detailed palaeomagnetic studies of the Quaternary geomagnetic field. Evidence from U/Th dating of associated speleothems suggests that cave sediments, at some localities, may have ages in excess of 350 Kyr BP (Atkinson et al. 1978).

Cave sediment palaeomagnetic research has been slow to develop largely due to the logistical problems of sampling. The potential of this material was first confirmed in studies of sediments from caves in Spain, Majorca and the Lebanon (Creer & Kopper 1974, 1976; Kopper & Creer 1973, 1976). The earliest investigation in Britain concerned rhythmites from the entrance to Victoria Cave, Yorkshire (Stober 1978; Homonko 1978) but Agen Allwedd provided the first palaeomagnetic data for sediments from a deep cave environment (Noel et al. 1984; Noel 1986; Noel & St. Pierre 1984; Noel & Bull 1982; Schmidt 1982). There is now evidence to suggest the speleothems may also contain reliable records of the geomagnetic field (Latham et al. 1979).

This paper summarises the palaeomagnetic results obtained from samples of silt and clay from five sites in Agen Allwedd and one site in Pwll y Gwynt. Further details are given in Noel

(1983, 1986). The results provide evidence for the relative ages of the deposits and for a palaeocurrent direction in Agen Allwedd.

METHODS

Lightweight, robust sampling equipment was developed to overcome the special difficulties of sampling underground. The entire apparatus, including a camera, can be carried in a standard 7.6cm wide ammunition case and weighs approximately 2 kg.

A clean, horizontal or vertical sediment surface is first prepared with a brass scraper blade. 2.54 x 2.54 cm plastic tubes are then pressed into the sediment using an angle plate fitted with a bullseye spirit level. The orientation of each tube is then recorded in situ and the direction of down (or magnetic north) scribed on the sample tube. The specimens are then extracted, trimmed and placed end to end in sealed storage tubes for transport to the laboratory.

The natural remanent magnetisation of the specimens is measured in a fluxgate spinner magnetometer (Molyneux 1971). The results are expressed in terms of the magnitude and direction (declination, inclination) of the remanence vector. The stability of the magnetisation in representative samples is then examined using alternating field demagnetisation. For further details of this and other laboratory techniques the reader is referred to Collinson (1983). On the basis on the demagnetisation tests, each sample is next exposed to an alternating magnetic field chosen to isolate the primary component of magnetisation in the sediment. This is finally measured in the magnetometer.

The magnetic susceptibility anisotropy (magnetic fabric) of the sediments has also been examined. In a sediment which contains the mineral magnetite, the magnetic fabric can provide an indication of the degree of preferred orientation of non-spherical magnetic grains. This orientation arises from the interaction of magnetic gravitational and hydrodynamic forces on the settling particles (Hamilton & Rees 1970). Hence the style of the magnetic fabric can be used to infer the direction and the velocity of flow through a flooded passage or to indicate the nature of grain interactions which occurred during a mudflow.

The susceptibility anisotropy is measured in modified spinner magnetometer (Collinson 1983). This instrument measures the directional variation of susceptibility within the specimen and expresses the results in terms of an ellipsoid of susceptibility specified by the magnitude and direction of three principal axes. These are generally displayed on a stereographic projection.

RESULTS

Ogof Agen Allwedd

As part of a preliminary study in 1979; ten specimens of horizontally bedded surface silt ('Cap Mud') were obtained near the northern end of Main Passage (Fig. 1). This finely laminated silt was probably derived from surface periglacial weathering of Millstone Grit on Mynydd Llangattwg which then entered the flooded cave via vertical joints and fissures.

These samples were found to contain a stable magnetisation recording a period of Normal geomagnetic field polarity (Noel et al. 1979). The mean remanence inclination, (40.7° ; Fig. 2), is somewhat shallower than would be expected for geomagnetic secular variation at this latitude. However, this can be explained in terms of an 'inclination error', d , which arises from the rolling of particles as they come to rest on the sediment surface (King 1955).

A 'Primary Style' of magnetic fabric (Hamilton & Rees 1970) was found in these sediments. This is characterised by a near-horizontal magnetic foliation plane (minimum axes vertical). The maximum axes define a lineation which is deviated away from the remanence direction, implying that water flow down the passage has been an important control on the magnetic fabric. The results of thermomagnetic measurements on a magnetic extract from the 'Cap Mud', (Fig. 3), suggested that the main magnetic mineral in the sediment was magnetite.

Encouraged by these early results, a further 30 samples were obtained from three sites in Main Passage and a site in Keyhole Chamber, (Fig. 1; Noel et al. 1981). Sites 4 and 5 were again located on horizontally bedded 'Cap Mud' but sites 2 and 3 were at two levels on the flanks of a

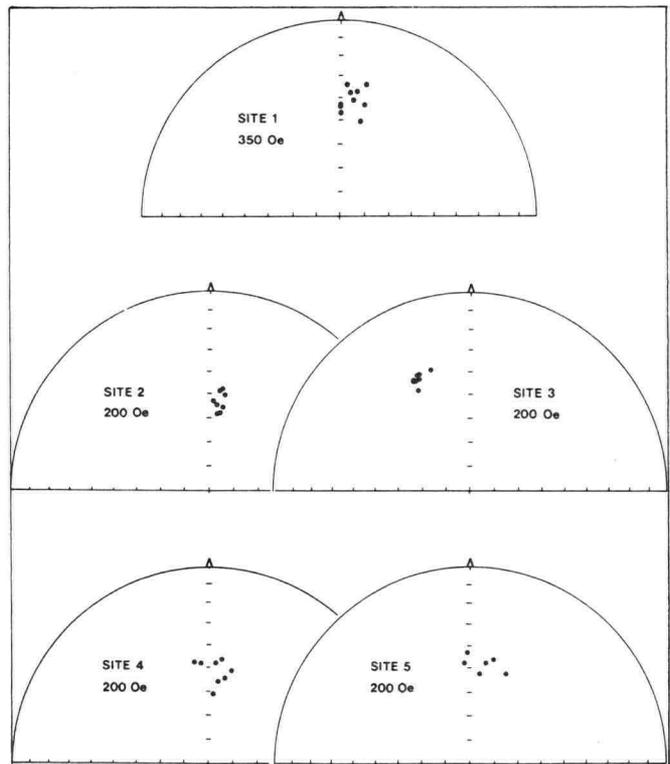


Figure 2. Remanence directions for the five Agen Allwedd sites after partial demagnetisation in the alternating magnetic fields shown.

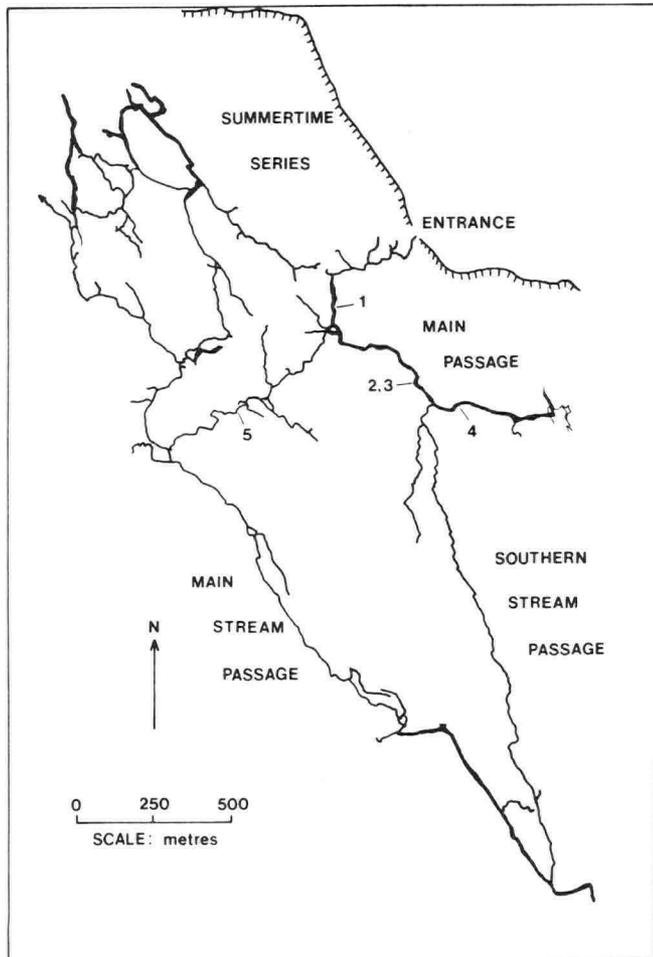


Figure 1. The Agen Allwedd cave system showing the location of the sampling sites. Site 5 was in the upper level of Keyhole Chamber.

steep sediment connected to twin vertical cracks in the western wall of Main Passage, (Fig. 4).

The samples contained a stable primary component of magnetisation. Fig. 2 shows the directions of remanence after partial demagnetisation in a peak alternating field of 200 Oe (20 mT). The magnetic fabric results are shown in Fig. 5. The sediments again contained a primary depositional style of magnetic fabric but the silts on the flanks of the cone have a fabric related to the strike and dip of the sloping surface. The foliation planes are tilted in the downslope direction, although at lower angles than the bedding, thereby causing an imbrication into the slope. The maximum axes of susceptibility are scattered within the foliation plane at site 2 (8° slope) but are more tightly grouped at site 3 (29° slope). These results conform closely with the

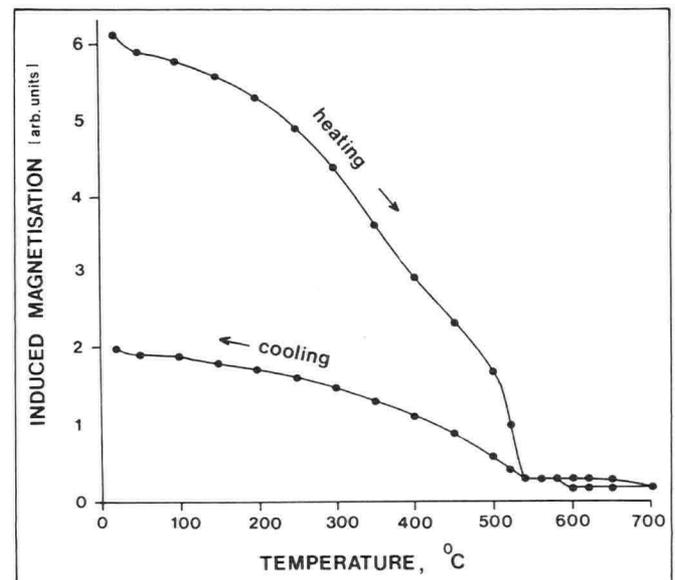


Figure 3. Changes in the intensity of induced magnetisation in a magnetic extract from the 'Cap Mud' during a cycle of heating and cooling.

Figure 4. Plan view of the sediment cone near two fissures in the western wall of Main Passage with the positions of sites 2 and 3. The arrows are the inferred directions of current flow based on the analysis of magnetic remanence and susceptibility anisotropy.

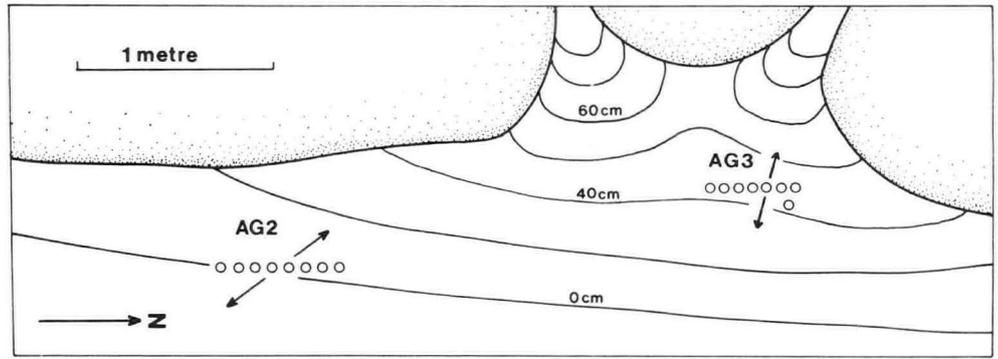
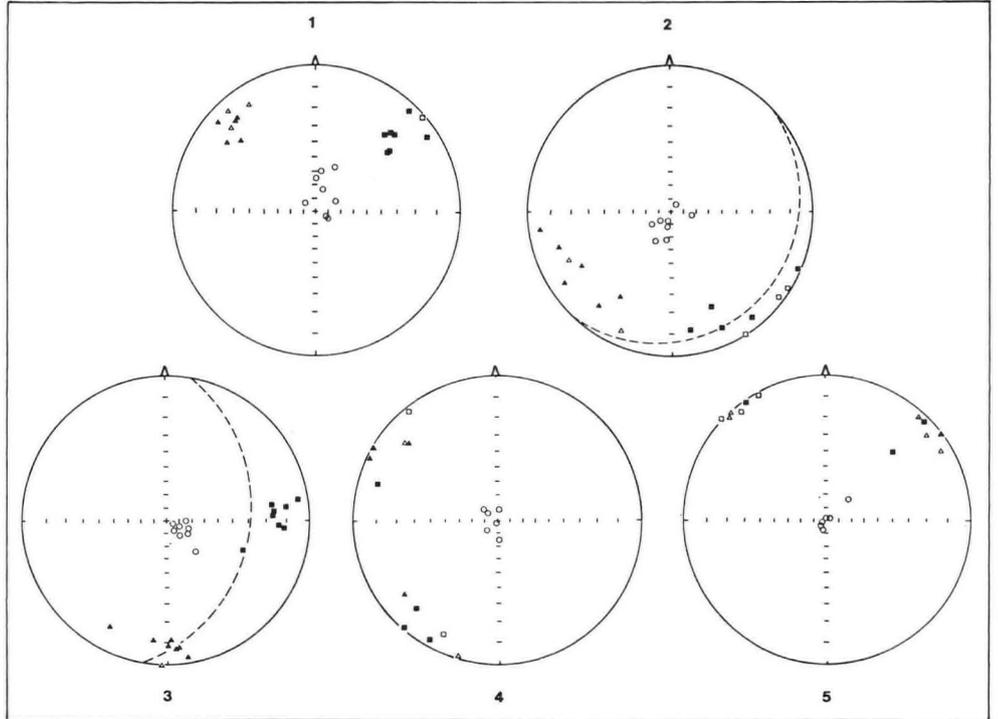


Figure 5. Directions of the three principal axes of magnetic susceptibility in the 'Cap Mud' samples. The dashed lines indicate the downward direction of bed slope. ■ = maximum, ▲ = intermediate and ● = minimum axes. Closed symbols = positive inclination; open symbols = negative inclination.



findings of Rees (1966) who redeposited medium sands onto varying slopes in the laboratory.

The sediments at sites 4 and 5 contain two orthogonal lineations causing a clustering of maximum and intermediate directions (Fig. 5). This unusual result was confirmed using a low field torque magnetometer and is therefore not instrumental in origin. Hence it is probable that these sediments contain two particle lineations, only the dominant one of which can be resolved by the magnetometer. These lineations are parallel and transverse to the current flow directions as defined by the orientations of the passage at the two sites.

A magnetic fabric with lineation transverse to the presumed flow direction has been reported by Rees (1965) in Eocene sandstones which contain two grain alignments and by Granar (1957) in Swedish varved clays. Grain orientation perpendicular to the current has also been noted by Hand (1961). It is possible that these 'Cap Muds' contain magnetite grains whose shapes enable them to take up one of two hydrodynamically stable positions on a horizontal bed.

The sets of remanence vectors for each site are well grouped but there is a significant disagreement in the mean directions for the two sites on the cone (Fig. 2). This can be explained in terms of the tendency for settling magnetic grains to roll systematically downslope before coming to rest thus causing a rotation of the final remanence vector. From the results of laboratory deposition experiments in controlled magnetic fields, an empirical correction has been derived for the 'bedding error' (Hamilton & King 1964). When this correction is applied to sites 2 and 3, (Fig. 6), the mean vectors become

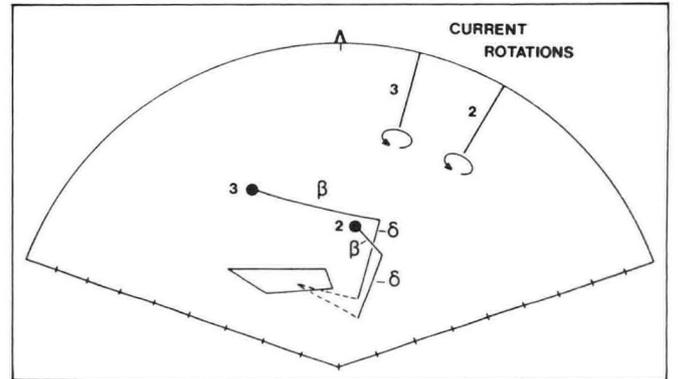


Figure 6. Correction of the sites 2 and 3 remanence vectors for bedding error β and inclination error δ . The resulting vectors are then connected to the estimated field direction by small circles (dotted) which indicate the degree of rotation due to current shear.

indistinguishable (within sample errors) from the palaeomagnetic directions at other sites in the cave (Fig. 7). This strongly suggested that deposition of these surface silts has been simultaneous throughout the cave.

By considering the hydrodynamic information contained in the magnetic fabric it is possible to apply a further correction to the remanence vectors for the effect of water flow. For each sample, the directions of maximum susceptibility and remanence are joined by a small circle which represents the rotation of grains, about horizontal axes, due to fluid shear. When the

small circle for a suite of samples are extrapolated, they should converge on the palaeofield direction. Further details of this method are given by Rees (1961) and Noel (1986).

In Fig. 8 this technique is applied to site 1. The zone of small circle intersections defines a range of directions within which it is assumed the palaeofield vector lies. In Fig. 6 this is compared to the mean remanence directions for sites 2 and 3 (after correction for inclination and bedding errors). The remaining angular discrepancy may be explained by current rotations caused by flow over and around the cone. The small circles correspond to the current rotations shown, indicating that water flowed up the cone and into the wall fissure.

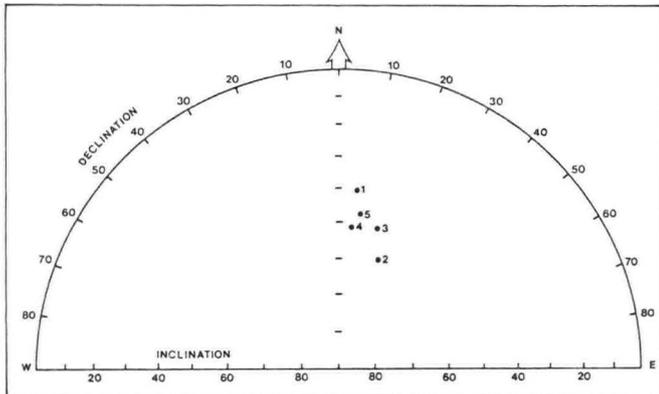


Figure 7. Mean palaeomagnetic directions in sediments from the five sites in Agen Allwedd. Corrections have been applied for bedding error at sites 2 and 3.

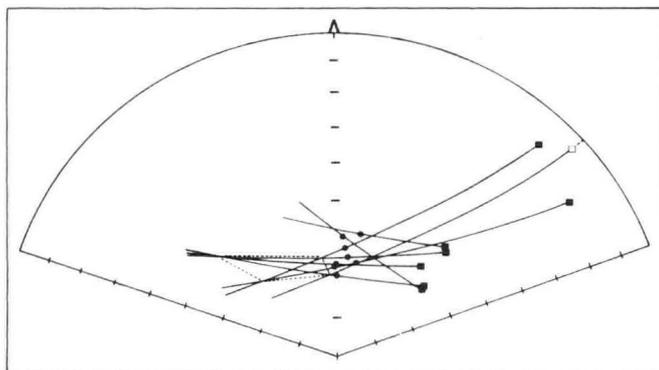


Figure 8. Estimate of the true palaeomagnetic field direction (dotted box) by combining the remanence (circles) and maximum susceptibility directions (squares). The solid lines are small circles.

Ogof Pwll y Gwynt

Pwll y Gwynt is a small cave (213m long) developed beneath Mynydd Llangattwg near the upper limit of the Avonian limestone sequence and about 80m above Agen Allwedd (Fig. 9). The cave consists of a series of narrow fossil phreatic passages linking large vertical avens and probably represents the earliest stage of karst development in the area.

In common with Agen Allwedd (Bull 1976; 1981), Pwll y Gwynt contains an extensive sediment infill and in places this has been exposed in natural stream sections to reveal a complex succession of layered silts and clays. Fig. 10 shows an approximately 1m thick sequence of sediments deposited in a small passage leading to the Fifth Aven. These sediments occur at one of the highest levels in the cave and hence almost certainly predate the deposits in Agen Allwedd.

The lower half of the section comprises a mud flow, as shown by the contorted relict laminations and random intraclasts of layered clay. These sediments are overlain by nine lithologically distinct units of laminated clay, stalagmite and homogenous clay with sand. The presence of desiccation cracks and the thin stalagmite layer at a depth of 12cm is evidence for prolonged breaks in sedimentation. A preliminary interpretation of the section suggests that these sediments record changes in surface climatic conditions which might be equated with a glacial/interglacial sequence. Unfortunately, because of detrital contamination, the speleothem material was unsuitable for radiometric dating. A minimum of seven samples were obtained from each of layers 2, 6 and 9 (Fig. 10). A vertical suite of thirteen samples was also obtained from the slump deposit.

The directions of remanent magnetisation before and after partial demagnetisation in alternating magnetic fields are shown in Fig. 10. Details of the pilot sample behaviour during demagnetisation are given in Noel (1986). The directions of maximum and minimum magnetic susceptibility in layers 6, 9 and 10 are presented in relation to the passage orientation in Fig. 11.

The intensity of the natural remanent magnetisation was in the range $7.7-42.2 \times 10^7$ Am²/Kg. Normal polarity remanence vectors were found in layers 2 and 6 but a reversed polarity magnetisation was found in layer 9. Shallow values of remanence inclination again suggest the presence of an 'inclination error'.

The disturbed clay records an irregular profile of remanence direction (Fig. 12). With the exception of the shallowest sample, the vectors are of normal polarity, however, and within 38° of the present geomagnetic field.

Three contrasting styles of magnetic fabric are present in the Pwll y Gwynt sediment (Fig.

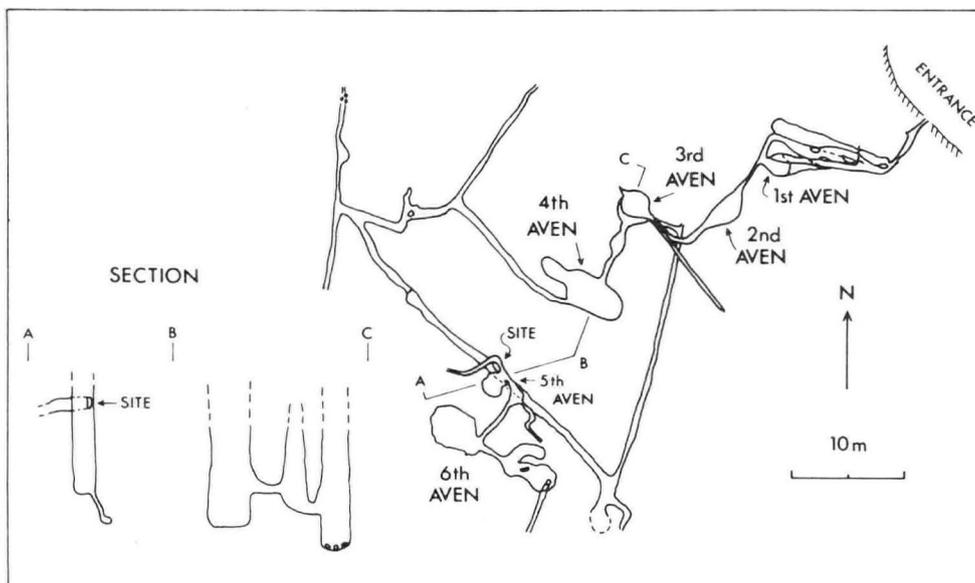
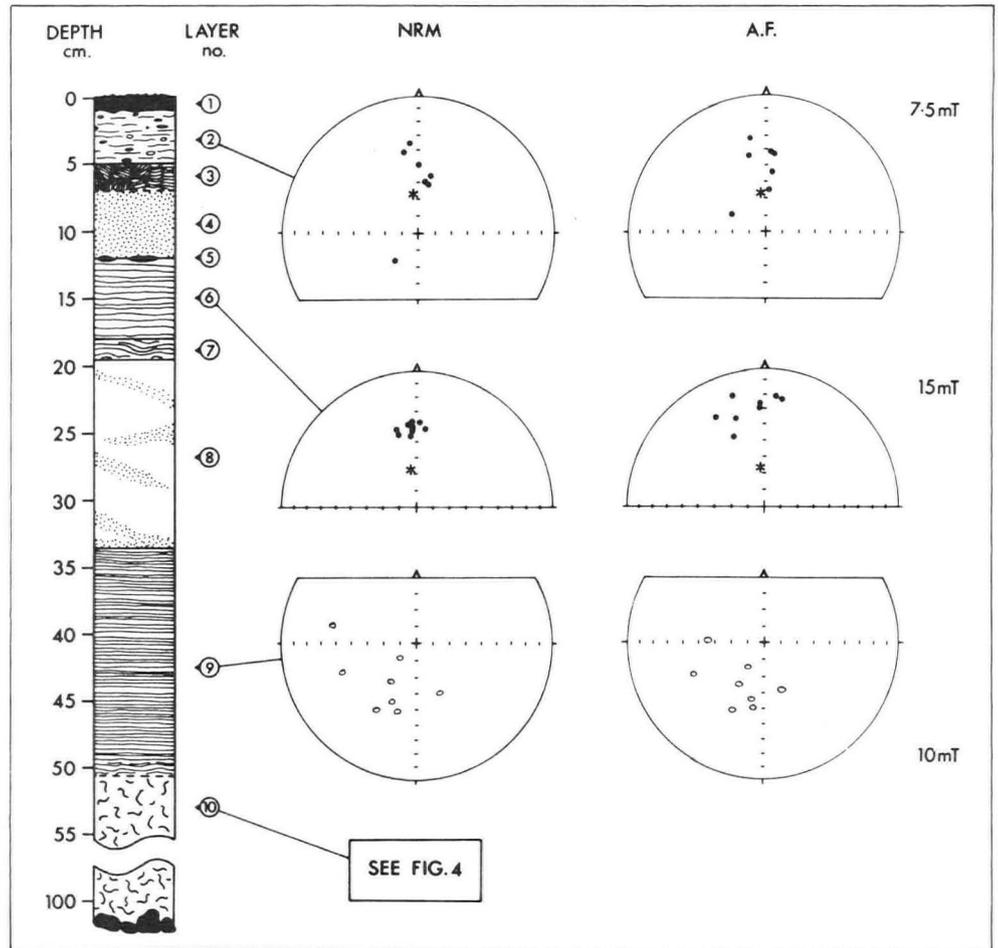


Figure 9. The Pwll y Gwynt cave system showing the sampling location in the Fifth Aven.

Figure 10. Stratigraphy of the sediment section in the Fifth Aven with remanence directions in layers 2, 6 and 9 before and after demagnetisation in the fields shown. Lithologies are as follows: (1) stalagmite; (2) mottled blue-brown clay; (3) dry, black and white laminated slay; (4) clay and sand; (5) stalagmite; (6) brown laminated clay; (7) dry, orange laminated clay; (8) clay with sand partings; (9) laminated clay; (10) slump with clasts of laminated clay. Present field direction is indicated by the star.



11). The susceptibility anisotropy of layer 6 contains a lamination parallel to the dip direction of the clay with an imbrication which is upslope with respect to the bedding (dip $\sim 20^\circ$). A similar style of fabric is seen at Agen Allwedd site 3 (Fig. 5) and in laboratory deposition experiments (Rees 1966). A down-dip lamination is also seen in layer 9 (Fig. 11).

The slumped sediments contain a well-defined horizontal magnetic lamination in a direction approximately parallel to the passage axis (Fig. 11). The minimum susceptibility axes show a girdled distribution. Since magnetic reorienting forces appear to have been unimportant in governing the remanent magnetisation of the deposit, it seems likely that the magnetic fabric

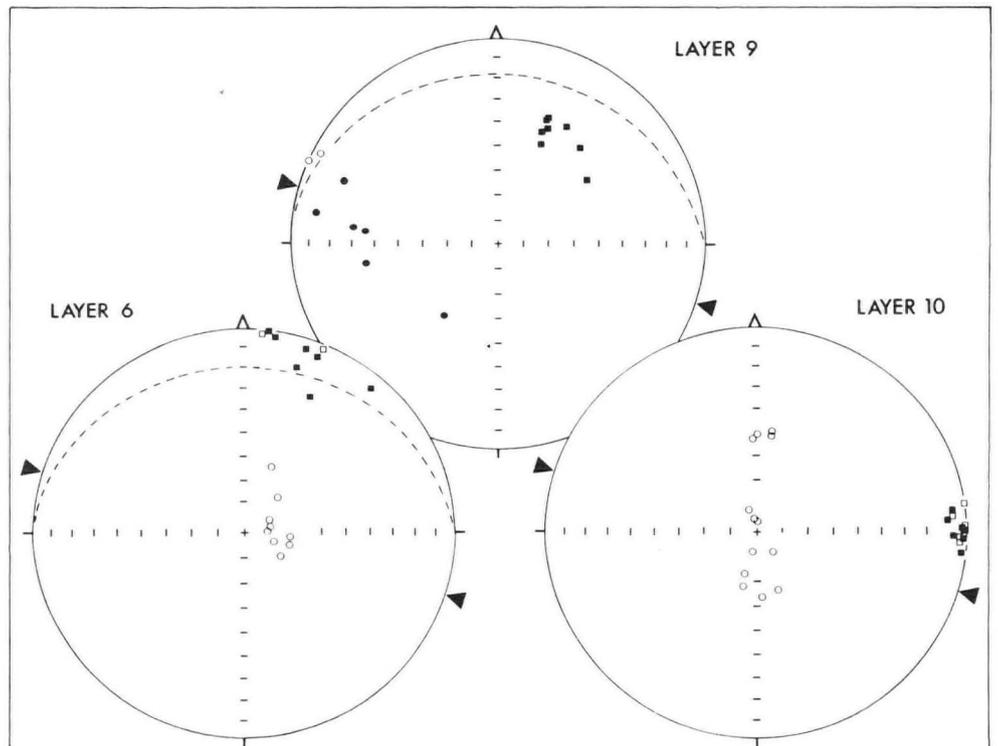


Figure 11. Directions of maximum (■) and minimum (●) axes of magnetic susceptibility in three of the Pwll y Gwynt clay layers. Orientation of the cave passage is shown by the arrows. Solid symbols lower hemisphere, open symbols upper hemisphere.

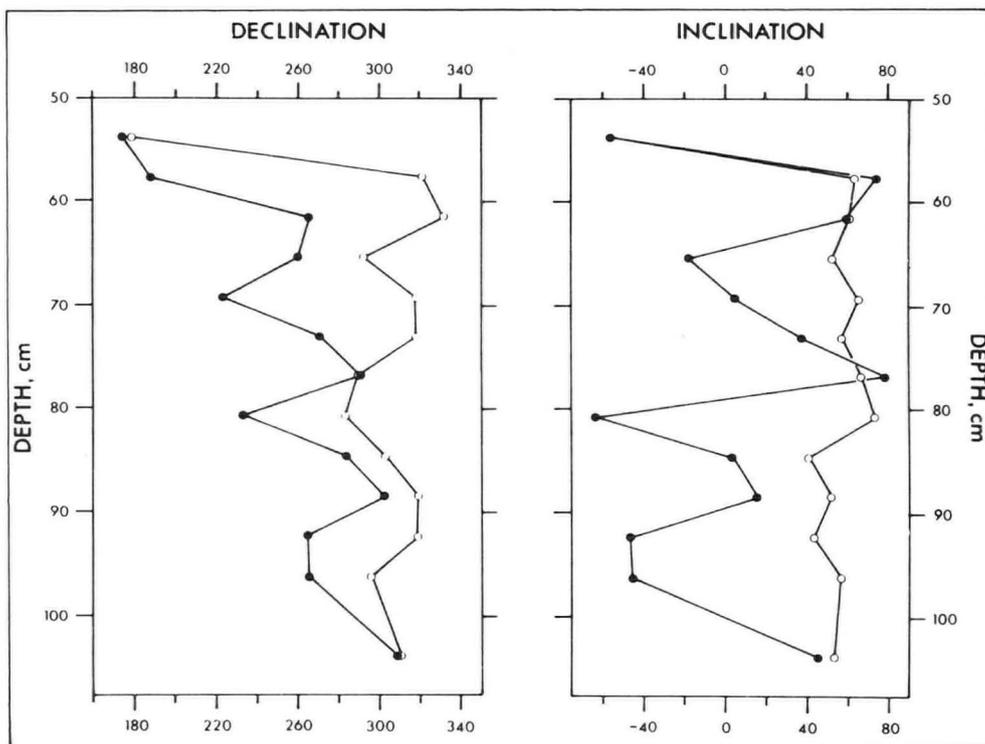


Figure 12. Profiles of remanence directions in the slumped clay before (O) and after (●) demagnetisation in a peak alternating field of 5mT.

has been dominated by the effects of viscous fluid forces or grain collision during the slump event. This caused the grains to rotate about axes perpendicular to the flow direction.

The girdled distribution of minimum axes can then be explained by considering the velocity distribution in the sediment as it flowed through the narrow passage (Fig. 13). The direction of the velocity gradient and hence the shortest axes of the moving grains must have been horizontal near the walls and approximately vertical near the centre of the rift. Since the samples span a width (~10 cm) which is a significant fraction of the wall spacing (15-4 cm) they will, therefore, contain minimum susceptibility directions which depart appreciably from the vertical but which are confined to a plane perpendicular to the flow direction.

CONCLUSIONS

These results from Agen Allwedd and Pwll y Gwynt confirm the value of deep cave sediments for palaeomagnetic studies of the earth's magnetic field. Moreover, since the cave sediments were formed in conditions analogous to those created in laboratory flumes, it has been possible to compare equivalent depositional magnetisations in natural and artificial sediments.

The palaeomagnetic data support the conjecture, based on lamination matching, that deposition of the 'Cap Mud' was simultaneous throughout Agen Allwedd (Bull 1978). It would be interesting to extend this test to similar deposits in Darren Cilau, Eglwys Faen and other caves beneath Mynydd Llangattwg. In the absence of radiometrically dateable material, palaeomagnetism is probably the only technique which can prove contemporaneity of cave sedimentation on a regional scale.

The discovery that some sediments in Pwll y Gwynt date from a period of reversed geomagnetic polarity indicates that these clays must have an age well in excess of the 11000 yr BP conjectured for the 'Cap Mud' in Agen Allwedd (Bull 1980). The sediments may be contemporary with the Laschamp Geomagnetic Event at ~47 Kyr BP (Hall & York 1978). Alternatively, the clays may have recorded an older Brunhes geomagnetic event or may date from the Matuyama Magnetic Epoch (>720 Kyr). Cave silts with a reversed remanence polarity have also been found in Masson Mine, Derbyshire (Noel, Shaw and Ford 1984).

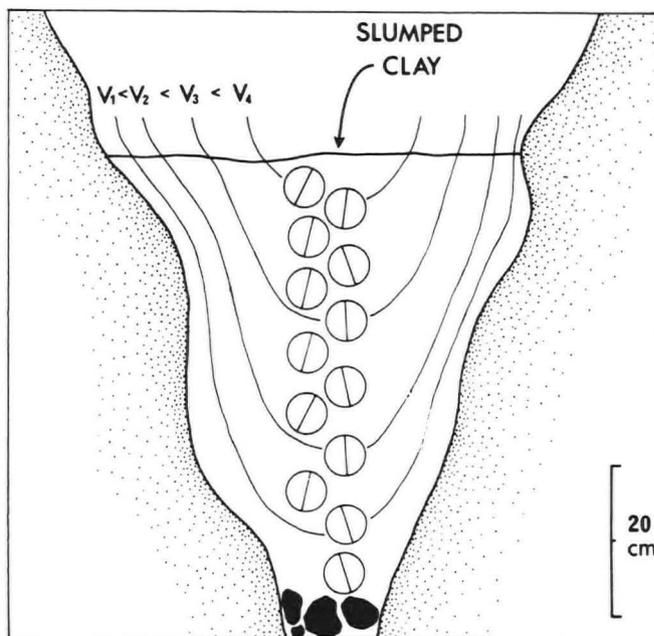


Figure 13. Sketch illustrating the positions of samples in the slumped clay and the form of the along-passage velocity distributions, V , in the deposit during the flow. The shortest axes of moving grains were aligned parallel to the velocity gradient giving rise to the directions of minimum susceptibility in the samples shown by the diametric lines.

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Received December 1987

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Natural Tunnel, Virginia

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Abstract: Natural Tunnel, in Virginia, U.S.A., is a 260m long cave traversed by a standard gauge railway from sink to resurgence. It is a spectacular cave curiosity, yet it remains in relative obscurity. The cave is the rejuvenated remains of a phreatic loop instigated by underground capture of a surface stream.

Natural Tunnel lies in the Allegheny Mountains about 5 km southeast of the small town of Duffield, in the western tip of Virginia, U.S.A., where it pinches out between Tennessee and Kentucky. It is therefore in the heart of the Valley and Ridge karst region of the great Appalachian fold mountains and should not be confused with the well-known but much shorter Natural Bridge, which lies 300 km to the east. The Tunnel has dimensions which are hardly remarkable, though it is a passage of considerable cross-section, and it would probably receive few visitors if it did not happen to have a main-line railway laid throughout its length.

History of the cave

It appears that Indians used the cave long ago as a route between hunting grounds, for a complete traverse is just possible without leaving at least a vestige of daylight. But it is speculated that the first white man through Natural Tunnel was Daniel Boone, soon after 1769 when he lived in the area briefly and was exploring west into Kentucky. Written descriptions of the cave date from as early as 1832, but it then seems to have sunk back into obscurity until 1880, when an engineer, J.H. McCue came across it while surveying a route for the South Atlantic and Ohio Railroad (later to become part of the Southern Railway).

Purchase Ridge is a substantial topographic feature, essentially composed of synclinal limestone escarpments oriented NE-SW in line with the Appalachian structural trend. It separates the valleys of the North Fork of the Clinch River and the main Clinch River (figure 1), both of which drain southwest eventually into the Tennessee River. The Ridge rises to crest elevations of about 600m, 200m above the Clinch Rivers, and the modern highway has to climb to 500m to cross the ridge. However, the narrow valley of Stock Creek cuts right through the ridge at around the 400m level, and this was the route chosen by Mr. McCue. But part way through the Ridge, Stock Creek goes underground, leaving a dry saddle cresting at 448m. This is where Mr. McCue found that Natural Tunnel, the cave which Stock Creek traverses almost beneath this dry saddle, was also spacious enough to take his railway.

A large amount of brushwood and debris had to be cleared out of the cave, and a kink, part way through, demanded 30m of blasted tunnel. Otherwise, a low embankment was built on the firm sands and gravel of the cave sediment to keep the railway above flood levels, and, with a gentle reverse curve in its tracks, the railway gained an underground route 250m long for minimal cost.

The railway through Natural Tunnel is still in use today. This in itself is fairly remarkable

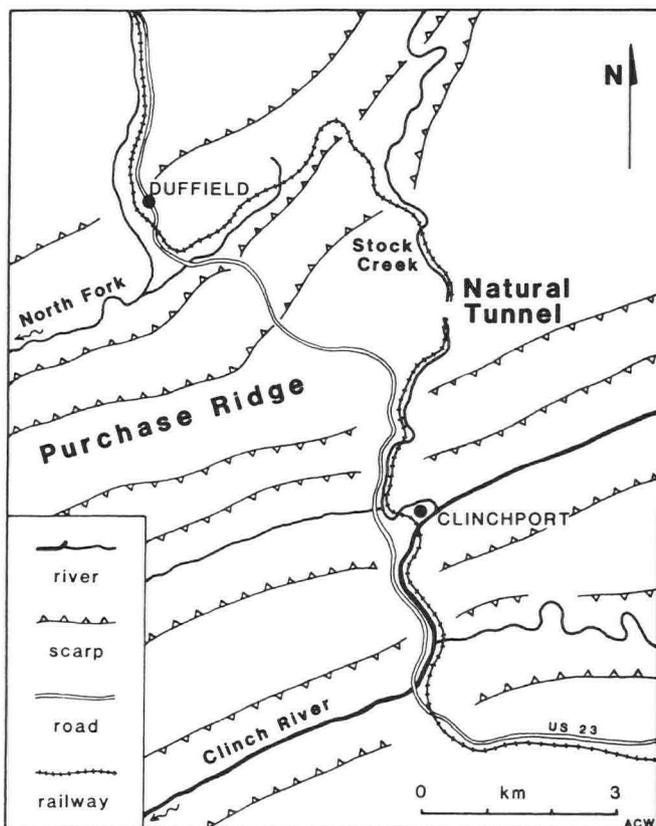
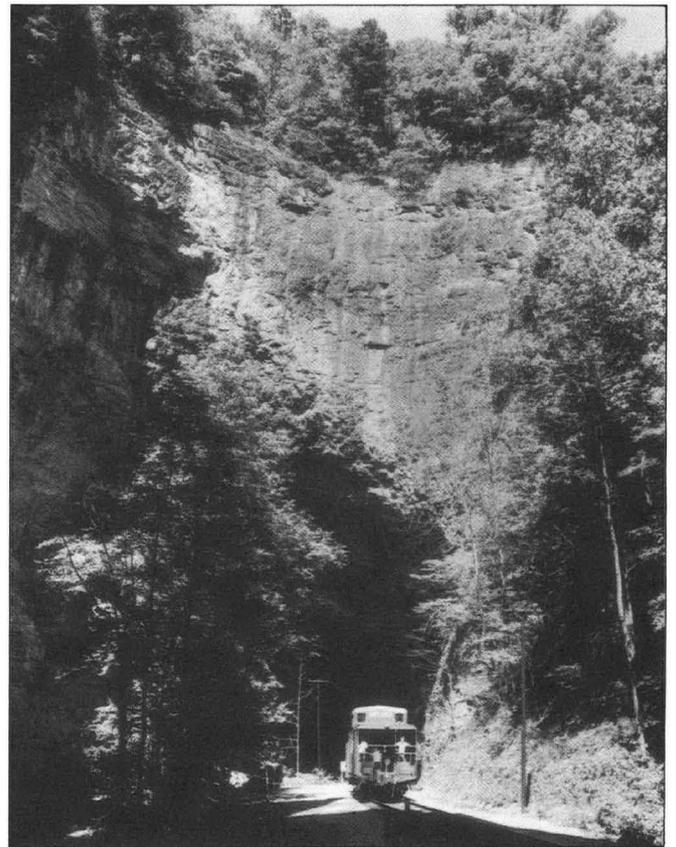


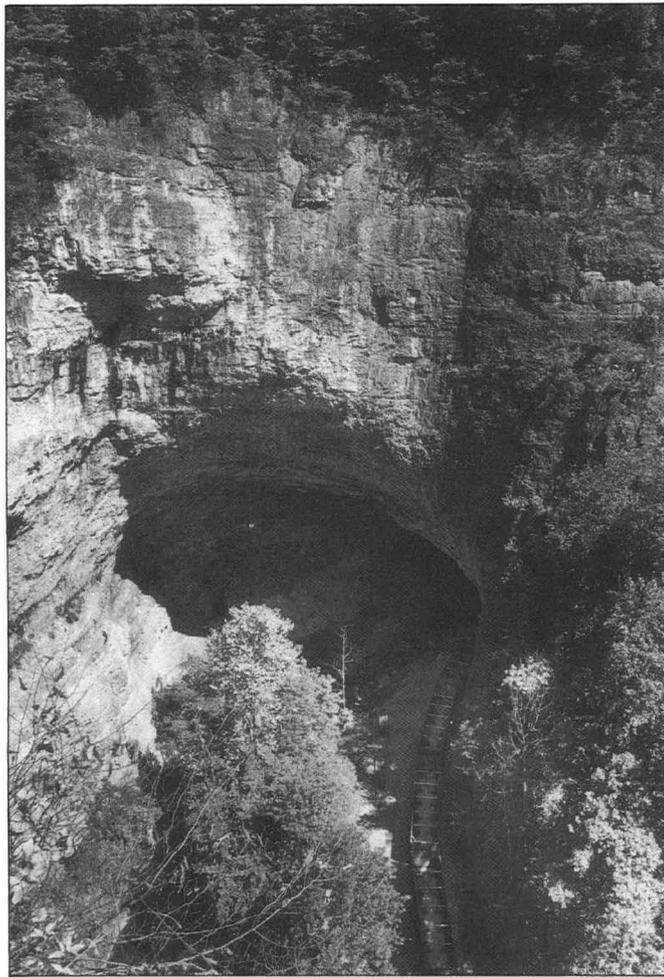
Figure 1 The area of Purchase Ridge and Natural Tunnel



The caboose of a northbound freight train disappears into Natural Tunnel

in America, but the line traverses the great Appalachian coalfields and has been kept alive by coal. There have been no regular passenger trains for many years, but about 10 trains per day still pass through the Tunnel, mostly diesel-hauled very long lines of coal trucks.

Since 1971, Natural Tunnel has been a state park, though its visitor centre and tourist facilities are only currently being developed, and



An empty coal train rolls into the south end of Natural Tunnel, as seen from the top of the limestone cliffs

part of its attraction lies in the campgrounds and foot-trails on the wooded ridge. This does make the site very accessible, with laid paths to critical points including a spectacular viewpoint above the cliffs around the cave exit. A path descends through the woods and reaches the cave after passing through another short railway tunnel. Perhaps surprisingly in a society normally zealous over safety controls, visitors can wander along the railway track through Natural Tunnel, all of which is at least gloomily lit by daylight. Signs warn to "beware of trains", but the sound effect of an approaching train makes an accident a threat only to someone completely devoid of ears or brain.

There is little existing literature on Natural Tunnel. Together with Natural Bridge (also in Virginia) it was described by Woodward (1936), but he lacked cave surveys and was a little over-enthusiastic about collapsed caverns. Since then it has achieved passing mention in various railway journals, textbooks of engineering geology and items of tourist literature (with much of the latter containing grossly distorted statistics). Then in 1977, a very detailed survey was prepared by W.C. Douty and others for the Virginia Cave Survey.

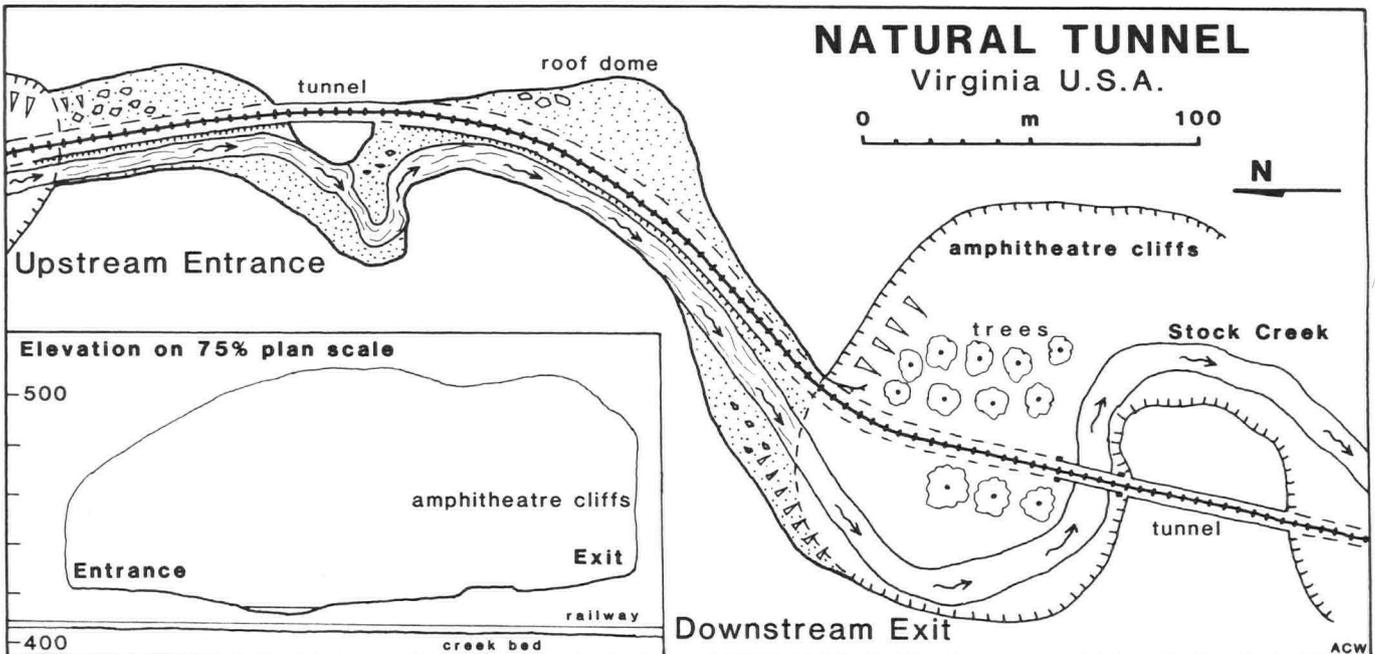
The cave today

Stock Creek is entrenched about 100m in a narrow winding ravine which cuts through the limestone of Purchase Ridge. The stream enters Natural Tunnel where it swings gently left into the cliff forming the eastern ravine wall.

The entrance is over 20m wide and 15m high, and the railway enters on the stream's left bank, which has been modified with a low concrete wall to prevent erosion beneath the tracks. The cave is a simple arched tunnel with minimal breakdown and an undulating roof left from its phreatic origins. No rock floor is visible, and the stream is slightly entrenched in beds of sand, gravel and cobbles; there are no significant calcite deposits. There is a very gentle overall gradient, but the roof falls to a low point on an overdeveloped left bend. There the modern vadose stream swings through a meander notch cut in the rock wall. A short cut section of railway tunnel avoids both the bend and the low roof.

The downstream half of the cave is more spacious, with the railway on a low bank almost down its centre. The roof rises into a shallow dome, blackened by smoke from by-gone stream trains, and then rises towards the exit. The resurgence of the cave is a splendid arch 25m high

Figure 2 Survey of Natural Tunnel



and wide, which appears to have been hardly trimmed to take the railway against the left wall.

Above the cave exit, a vertical limestone cliff rises about 80m, walling a fine natural amphitheatre. Stock Creek swings round the edge of this rock bowl, before rounding a spur into a more open valley beyond. The railway uses a short tunnel through the spur, and then rejoins the creek on a daylight course.

Total length of the Natural Tunnel cave is 260m, and it descends only a few metres. The survey (figure 2) is a low-grade, one-man production, but, because of the simplicity of the cave, it is probably a very fair representation.

Origins of Natural Tunnel

Purchase Ridge is a narrow synclinal core preserved in massive limestone with outward-facing escarpments of which the northern side rises to the higher crest (figure 1). It is part of a belt of sub-parallel structurally controlled ridges, whose pattern is complicated a little by some cross-faulting and over-thrusting. Northeast of Stock Creek, Purchase Ridge widens into a plateau as the syncline opens out. Both plateau and ridge, and also the other limestone ridges in the area, are riddled with dolines, blind valleys and sinkholes, and comprise fine karst landscapes.

Both the Clinch River and its North Fork are trunk streams flowing parallel to the structural controls. The headwaters of Stock Creek originally drained into the North Fork, and an obvious wind gap survives a few kilometres northeast of Duffield (figure 1). A tributary of the Clinch River then eroded headward into Purchase Ridge and eventually captured the head of the North Fork - to form Stock Creek along most of its present line. There is no clear remaining evidence that this initial capture involved any underground cut-offs, but the possibility cannot be ruled out. And the present drainage pattern is probably superimposed from a landscape of much less relief.

The original route of Stock Creek took it just west of Natural Tunnel, along a still well-defined valley, now followed by a minor road over a dry saddle (figure 3). A section of valley 1500m long was then abandoned when another capture took the water through Natural Tunnel; the wind gap now lies 40m above the present stream level. This capture clearly was underground, as water leaked through the initial opening of Natural Tunnel and into a short tributary valley enlarging headwards from the east bank of the valley 1500m downstream. Development of this underground loop offered hardly any shortening of the surface route, but was probably aided by following bedding

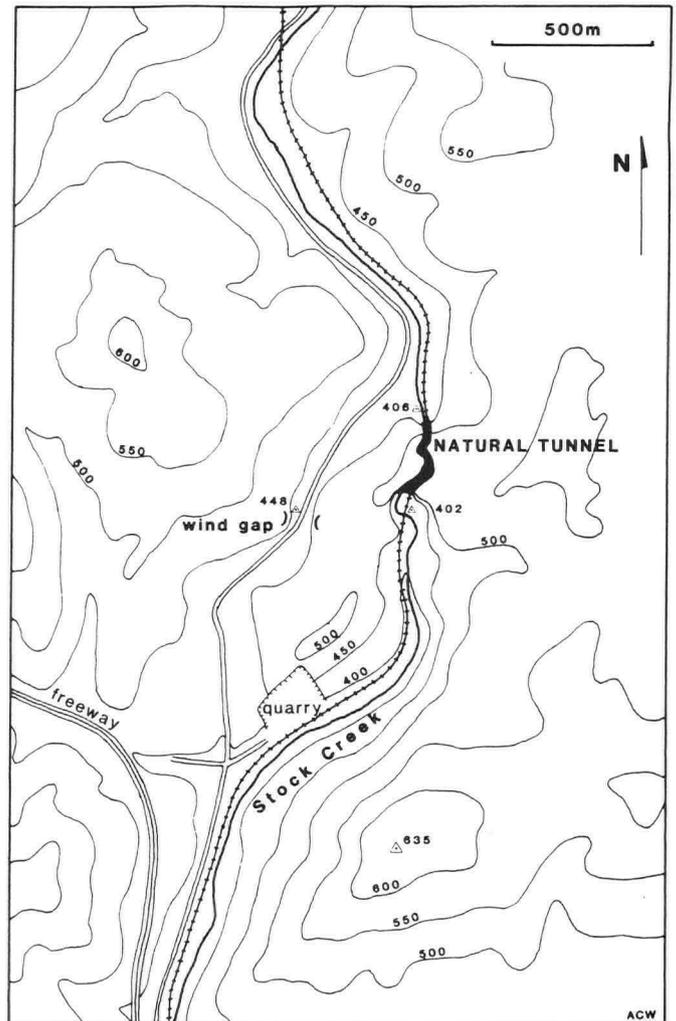
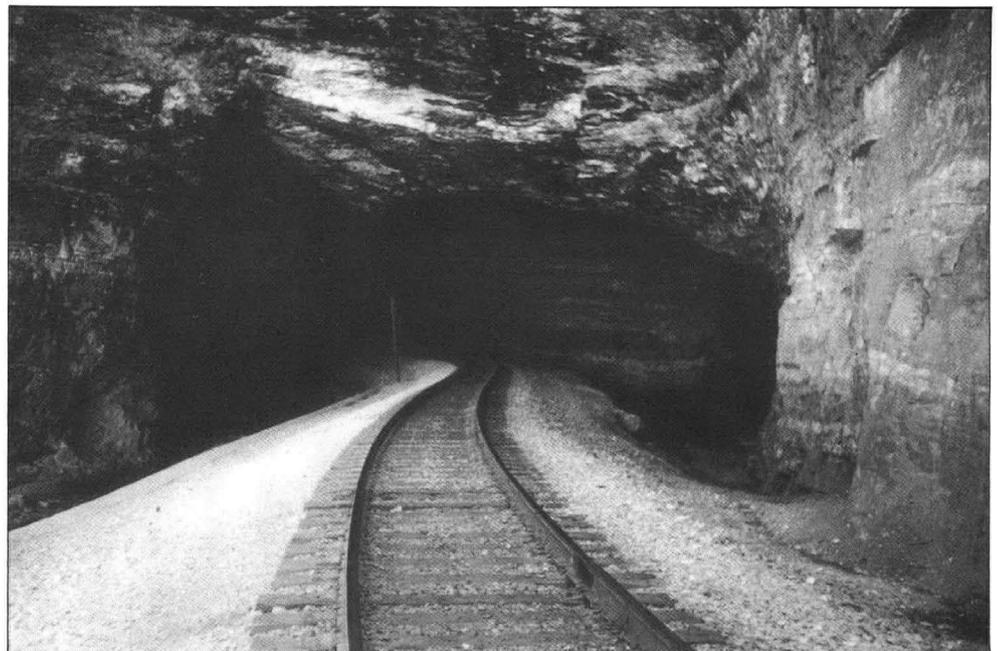


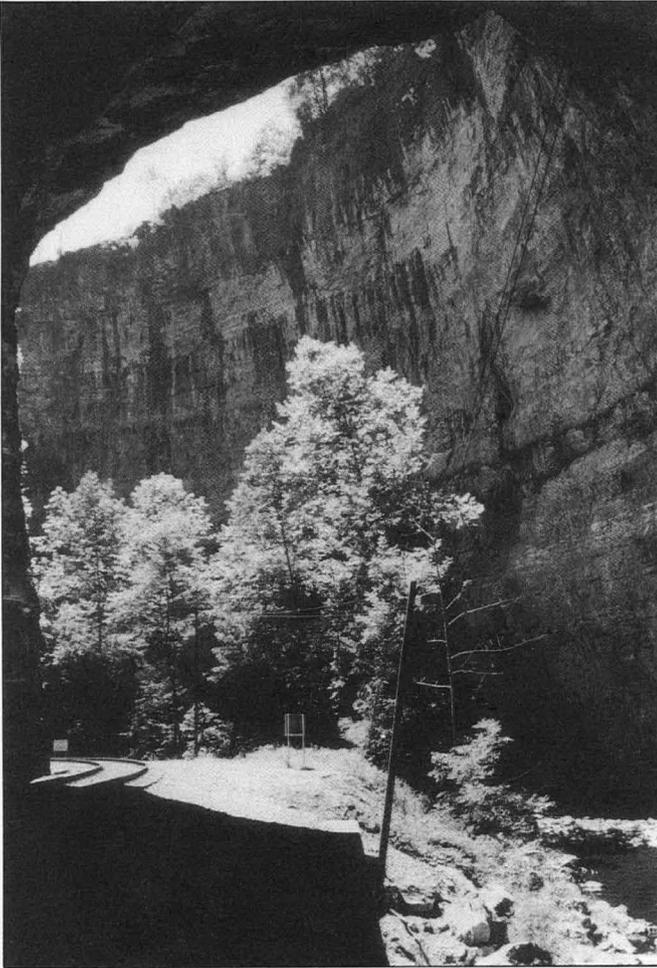
Figure 3 Surface features around Natural Tunnel

planes right across the synclinal core.

The original sink into this phreatic loop was very close to the present northern entrance of Natural Tunnel. The original resurgence was a vauclusian rising with a phreatic lift of close to 40m, as indicated by the level of the wind gap, and appears to have been some short way downstream



The railway track inside the Natural Tunnel cave



of the present cave exit. Subsequent regional lowering of both Clinch River and Stock Creek eliminated this phreatic loop, and left the roof of Natural Tunnel above water level. Vadose modification of the cave since then has been minimal except for an element of collapse back from the original resurgence. There is no evidence, nor any apparent structural control, to suggest that the initial phreatic cave rose sharply to its resurgence at the site of the present cave exit. The rock amphitheatre at the exit has vertical walls, and almost certainly formed by collapse of the cave where it wrapped round an exceedingly sharp left bend, perhaps leaving a cave pillar of inadequate strength. Failure of the roof, itself thinning as the surface slope descended to the south, occurred a long time ago. Stock Creek has since removed the breakdown and graded its course, to leave a spectacular exit to Natural Tunnel.

ACKNOWLEDGEMENTS

The author thanks Tammie Heazlit for chasing various reference items in America, and acknowledges source data from the NSS files.

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Received January 1988

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Looking out of the south end of Natural Tunnel

Postglacial Tufas and Travertines from the Craven District of Yorkshire

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Abstract: Postglacial tufas, travertines and cemented gravels are described from 29 sites. The deposits are classified according to their associated flora, where this is present. Most deposits exposed to light were associated with bryophytes, cyanobacteria and higher plants. Archaeological evidence was obtained at some sites suggesting a phase of rapid or more extensive deposition prior to or during the Atlantic Period (6000-8000 years BP) and this was supported by the large number of postglacial sites where there is little active deposition today. Nineteen sites are described for the first time.

INTRODUCTION

Tufa deposition can occur in any region where limestones are overlain by soil. The soil atmosphere, which contains 10-50 times more carbon than the air is primarily responsible for the dissolution of limestones and subsequent de-gassing and re-precipitation of much of the carbonate as speleothems and tufa. The chemistry of the process is fairly well understood although the mechanism of the recrystallization and the significance of bacteria and algae requires further study. Tufa deposition can result from several unrelated changes occurring in the percolating water. Previous studies in the Craven district have shown that the major change is the diffusional loss of carbon dioxide to the atmosphere (Pentecost, 1981). However, there is some evidence to suggest that the uptake of carbon dioxide by photosynthesizing plants, temperature changes and water loss by evaporation also play some part in tufa deposition (Barnes, 1965), though generally on a smaller scale.

Tufa, when first formed, may be either soft and with a mealy or crumb-like texture, or massive and stone-like. Several attempts have been made to classify the various types, though none appears to be satisfactory when applied to the range of deposits found in Craven. Gruninger (1965) and Frey & Probst (1974) have followed a system described by Klahn (1923) for tufas of the Schwabische Alb. This classification is based upon the shape of the deposit which is influenced by the angle of slope. Although useful, these definitions do not consider the small-scale structure of the deposits. Irion & Muller (1968), attempted a biogenic classification into sinter or travertine, which is predominantly inorganic, and various classes of organic algal and moss tufas.

In this paper we place emphasis on the inactive sites of the district because of their potential value as sources of palaeoenvironmental data (Kerney et al, 1980) and as a medium for the preservation of archaeological material.

CLASSIFICATION

The scheme adopted is based upon the predominant vegetation, where present (Table 1). As plants become encrusted by the deposit, they eventually decay but leave their original structure imprinted on the material. Consequently, the tufa fabric is largely determined by them. Plants are generally absent only where light intensities are low or nonexistent. Such conditions occur in caves and in deep talus. We have reserved two terms for abiotic material; travertine for porous irregularly laminated deposits formed within caves, and clast-supported breccia for cave deposits containing >50% breccia by volume with the interstices filled with travertine.

Some doubt remains concerning the definition of travertine. The term was originally used to describe deposits occurring near Tivoli in Italy and there is some evidence indicating that much of the material is of bacterial origin (Chafetz & Folk, 1984). If this proves to be correct, the term calcareous sinter, which is also used to denote abiotic deposits, may be more acceptable.

Bryophytes are the most conspicuous plants associated with the illuminated and active Craven tufas and there are a number of characteristic species. The plumose variety of *Cratoneuron commutatum* forms yellow-brown mats in seepages or slow-flowing water and is the characteristic moss of hummock tufa. This tufa is found around small springs as irregular unlaminated mounds, sometimes dissected by narrow channels (Fig. 1b). In parts of Belgium such deposits are known as 'crons' (Symoens, 1951).

In shaded seepages, tufa-encrusted mosses with a radiating cushion-like (stromatoid) structure occur (Fig. 1c). Two important genera forming this type of tufa are *Eucladium* and *Gymnostomum*. Finally there are bryophytes which grow in turbulent conditions where the moss stems become aligned with the direction of water flow. As this tufa forms, a series of layers is

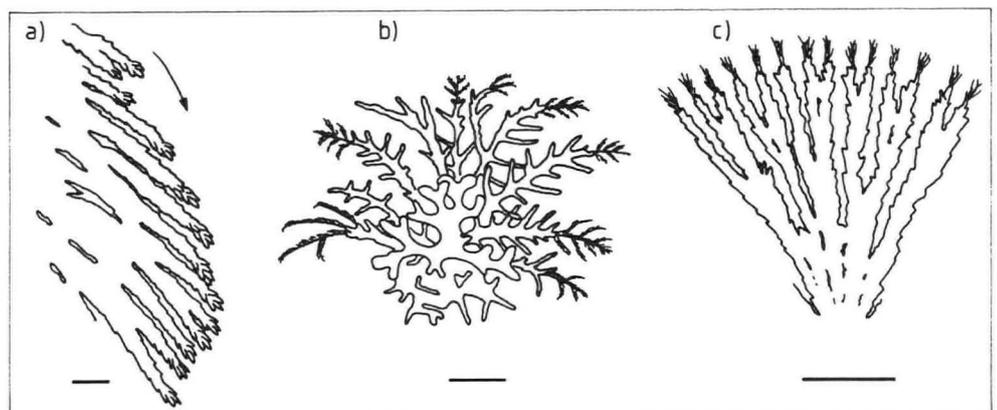


Figure 1. Illustrations of moss-tufa fabrics found in Craven. a) cascade tufa (*Rhynchostegium riparioides*), arrow shows direction of water flow. b) hummock tufa (plumose *Cratoneuron commutatum* and *Pellia*). c) stromatoid tufa (*Gymnostomum*) Bar 1 cm.

Flow regime	associated vegetation			
	absent	cyanobacteria	bryophytes	higher plants
turbulent		laminated tufa	cascade tufa <u>Rhynchostegium</u>	
			non-plumose <u>Cratoneuron</u>	
		<u>Homeothrix</u>		
	travertine	<u>Schizothrix</u>		
laminar	clast-supported breccia	<u>Rivularia</u>	hummock tufa	
			plumose <u>Cratoneuron</u>	unconsolidated tufa
		<u>Scytonema</u>	stromatoid tufa	<u>Carex</u> <u>Juncus</u>
seepages			<u>Gymnostomum</u> <u>Eucladium</u>	

Table 1 Tufa classification

produced. The layers are approximately 2-10 cm thick and consists of slanting moss stems similar in appearance to a section through a thatched roof. This is defined here as cascade tufa. Three moss species are associated with this tufa: Cratoneuron commutatum (non-plumose variety), Rhynchostegium riparioides and Eucladium verticillatum (Fig. 1a). It should be noted that the flow regime largely determines the type of vegetation present (Table 1).

Cyanobacterium tufas also occur. These consist of series of thin encrusting layers. The cyanobacterium colonies (formerly known as blue-green algae) are usually nodular and rarely exceed 10 mm in diameter resulting in a rugose surface. These tufas are less common than bryophyte tufas but occur in fast- and slow-flowing water (Table 1). In some sites, cyanobacteria overgrow bryophytes and here tufa formation must be influenced by both groups of organisms (Pentecost 1978, 1981, 1987).

Unconsolidated tufa or 'spring chalk' forms in mires where higher plants are often dominant.

The deposits often form around the bases of Carex and other wetland species, or produce a marl between the tussocks. Animal remains may be a conspicuous feature and some species of gastropods of narrow ecological amplitude can be preserved in this tufa. These have proved to be useful environmental indicators (Kerney et al., 1980).

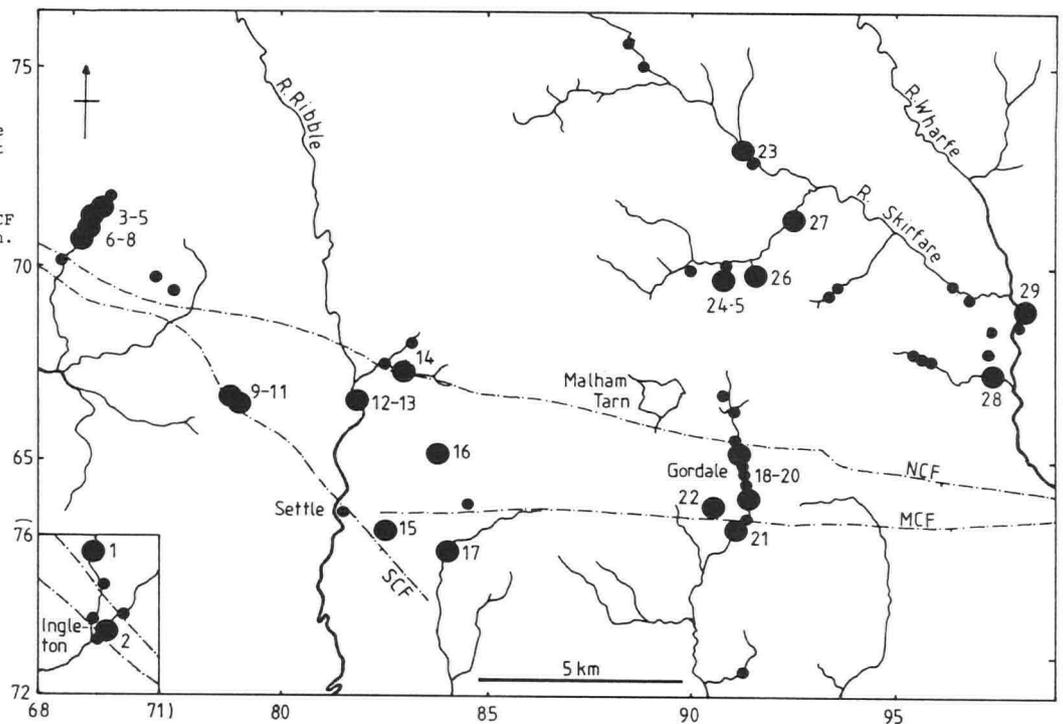
It is important to realise that in any situation, intergradations occur between these types of tufa. With actively forming deposits, it is easy to identify the dominant form of vegetation but with fossilised material this is often not possible.

Most modern tufas in the Craven district consist of micrite. The calcite crystals are often ill-defined, anhedral and 5 um or less in diameter. Bryophyte stems and leaves are sometimes encrusted with calcite 'palisades' consisting of crystals 50-100 um in length with their long axes perpendicular to the moss surface. Microspars are also found, with euhedral, drusy crystals occurring in small cavities, probably as a result of recrystallization or later infilling.



Unconsolidated tufa on the east bank of Clapham Beck (site 7). The beck has exposed a 2 m section through the deposit, top marked by arrows.

Figure 2. Map of sites. Numbered sites with large circles are described in the text. Small circles without numbers depict other active sites. Circle size is not related to deposit size. Faults: NCF North Craven; MCF Mid Craven; SCF South Craven.



Microspars with crystals up to 60 μm in diameter are often found cementing scree. Older tufas generally have a similar petrology to active sites although organic material is usually absent. The tufas of Gordale are exceptional for their pronounced laminations and apparent recrystallization. Here, microspar is found alternating with large calcite palisades up to 3mm in length. Series of these laminae are found sandwiched between micrites built up around *Eucladium*. The petrology of some Craven sites is described in more detail elsewhere (Pentecost, 1978, 1981, 1985).

DESCRIPTION OF SITES

For site positions refer to Figure 2. All grid references are in square SD(34).

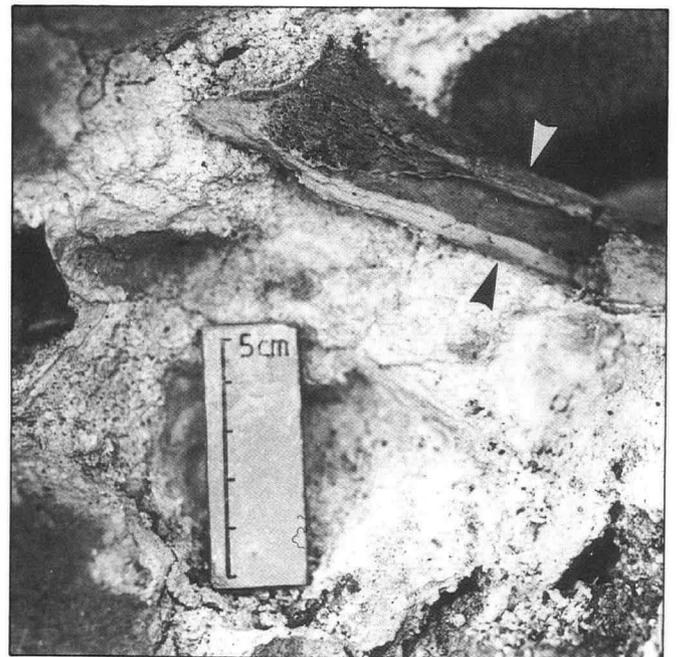
1. 695754 alt. 230 m. Cascade tufa 2 m high, just east of Thornton Force.
2. 698735 alt. 130 m. Bench of cemented river gravel 1 m above the R. Doe, 20 m in length with active rimstone travertine nearby. Meal Bank Quarry, adjacent to this Ingleton site may have started as a tufa quarry.
3. 757714 alt. 290 m. Relict hummock tufa, extending 15 m down slope of east side of dry valley above Ingleborough Cave.
4. 757713 alt. 285 m. Relict hummock tufa extending 10 m down slope of east side of dry valley, with protuberant relief.
5. 756713 alt. 280 m. Relict hummock tufa just below site 4. An active *Cratoneuron* tufa occurs 100m lower down the valley near Ingleborough Cave.
6. 754711 alt. 265 m. Hummock tufa grading into travertine at the entrance of Ingleborough Cave. The travertine barrier just within the cave was removed by blasting in c. 1837 (Dawkins, 1874). Impressions of liverworts and mosses (cf. *Conocephalum*, *Cratoneuron*) occur.
7. 752707 alt. 250 m. Layers of unconsolidated and hummock tufa exposed in west bank of Clapham Beck. Exposures up to 50 cm thick extend laterally for 30 m.
8. 751706 alt. 235 m. Small bank of hummock tufa with indurated blocks, in woodland by the footpath along Clapham Beck.
9. 788663 alt. 245 m. Cave Ha 1. Large limestone rock shelter with floor deposits of travertine and clast-supported breccia (McKenny Hughes, 1874). Indurated cushion-like (stromatoid) tufa bosses up to 20 cm wide underneath western extremity overhang. Some of the travertine is reported to have a high phosphate content resulting from infiltration of water through a layer of guano (Marr, 1876).

10. 788663 alt. 245 m. Cave Ha 3. Limestone rock shelter with floor deposits of travertine and clast-supported breccia overlain by uncemented talus. A few stromatoid tufa bosses on the wall. The site has yielded archaeological material sealed within travertine and finds include numerous human and animal bones, a few chipped stone tools and charcoal. The bulk of the travertine formation had preceded the deposition of the occupation horizons. From the typology of the stone tools and the composition of the fauna, the occupation horizons are most likely Atlantic/Sub-boreal in age.

11. 788663 alt. 245 m. Cave Ha 4. Digging has exposed a travertine beneath talus, with a large mammal bone (?human tibia) partly enclosed in the material.

12. 816666 alt. 160 m. Relict hummock tufas up to 15 m wide forming protuberant relief against shallow river terrace above local floodplain level. Abundant impressions of *Cratoneuron*, *Conocephalum*, *Riccardia* with some cf. *Ainus* leaves.

13. 817665 alt. 170 m. Relict hummock tufa extending laterally for 30 m along cliff above the R. Ribble at the southern end of Robin Hood's Wood.



Mammal bone, possibly human tibia, is seen embedded in a layer of travertine beneath an overhang. Cave Ha 4 (site 11).

14. 827674 alt. 240 m. Indurated relict cascade tufa 3 m wide and 5 m high against limestone scar on the south side of Cowside Beck.

15. 826632 alt. 240 m. Large blocks of indurated tufa resting upon unconsolidated material at Mealy Bank. Impressions of *Alnus* leaves have been recovered, with the tufa yielding a corrected 14-C date of 8600±600 yr BP (Pentecost, 1986).

16. 838650 alt. 430 m. Clast-supported breccia at Victoria Cave. Sections of this breccia exposed outside the small opening 15 m west of the main entrance. The breccia was once laterally more extensive, but was removed by 19th century excavations (Tiddeman, 1876). Archaeological and faunal material was recorded from the breccia outside the main entrance. The breccia was overlain by uncemented talus containing Romano-British material.

17. 841626 alt. 290 m. Relict cascade tufa 6 m high and 10m wide just north of Scaleber Force with displaced blocks in nearby gorge. Deposit indurated and undercut by the beck. We disagree with Brumhead (1979) concerning the previous path taken by the beck and suggest that the waterfall has retreated south due to differential erosion.

18. 912648 alt. 340 m. Tufa bank in upper Gordale extending with interruptions over 950 m above the rock arch at Gordale Scar known as the 'Hole in the Wall'. The bank forms a set of two terraces, one downstream of the other, about 4m high and 1-10 m in width on both sides of the beck and sometimes covered by scree. The tufa consists of unconsolidated fragments of encrusted bryophytes, higher plant roots and stems, a few molluscs and oncolites set in a mealy matrix. Some of the material was probably transported downstream prior to deposition.

19. 915641 alt. 290 m. Relict cascade tufa west of the 'Hole in the Wall', Gordale, 9 m wide and 7 m high. Water has not flowed over this since c.1730 (Pentecost, 1981). Locally indurated and well laminated.

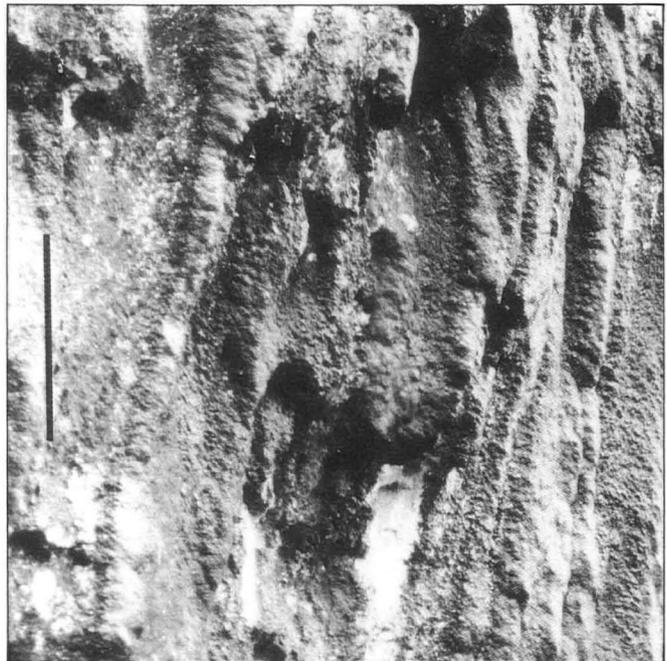
20. 915641 alt. 250 m. Lower cascade tufa, Gordale, 8 m high, 20 m wide. The deposit consists of well-defined and apparently alternating layers of cf. *Eucladium* moss (Pentecost, 1987) and recrystallised laminae formed at least in part by algae or cyanobacteria. There are some *Alnus* leaf impressions and oncolites occur in a few cavities.

21. 912633 alt. 210 m. Janet's Foss. An active cascade tufa colonized by *Rhynchostegium riparioides*, 6 m in height. This well-known site is situated below Gordale Scar at the head of small gorge through reef limestones. The deposit has probably resulted from the recharge of Gordale Beck by the strong, carbon dioxide-rich springs below Gordale Scar.

22. 908639 alt. 290 m. Grey Gill. A dry gorge 500 m west of Gordale Scar. Tufa observed amongst loose blocks of limestone on the floor of the gill (Howarth, 1900). A few fragments up to 0.3 m² remained in 1987.

23. 913726 alt. 230 m. Cemented river gravel 1.5 m high and 15 m long on the south bank of the R. Skirfare.

24. 908696 alt. 380 m. 15 m cascade tufa in Waterfall Beck. This is an active site, where, however, deposition and erosion are currently occurring at approximately the same rate. In the cave just to the east is a deposit of travertine with areas of adjacent allochthonous tufa.



Columns of indurated stromatoid tufa over limestone cliffs at Yew Cogar Scar (site 27). Scale bar for foreground columns 40 cm.

25. 908697 alt. 360 m. Tufa bank above Waterfall Beck, partly covered by scree.

26. 913699 alt. 365 m. 12 m cascade tufa in Lower Beck. On the west bank, 50 m below is a small area of unconsolidated tufa with isolated mounds formed by *Cratoneuron*.

27. 917706 alt. 260 m. Rib-like columns of tough, unlaminated tufa on the cliffs of Yew Cogar Scar, extending 6-10 m below a line of temporary seepage. The deposits were probably formed by evaporation in association with the cyanobacterium *Gloeocapsa* but in some areas traces of a stromatoid structure occur, suggesting that bryophytes may have been present at some stage of their formation.

28. 974673 alt. 230 m. Hummock tufa and unconsolidated material covering c. 0.3 ha. and dissected by a braided stream to the south, with two prominent tufa banks to the north. An *Equus* jawbone has been found near the base of the deposit, 75 cm below ground level. The remains were associated with small tufa nodules and molluscs resting upon a grey-brown marl.

29. 981688 alt 200 m. Unconsolidated tufa covering c. 0.5 ha., traversed by a small, unnamed stream, rising below the Throstle's Nest. Another smaller area of tufa with some cemented scree occurs 10-40 m south of the active cascade.



Tufa banks in upper Gordale looking south from site 18. A 4 m high bank, partly covered by scree can be seen on the east side (left arrow). Edge of west bank shown by right arrow.

Tufas are widely distributed in the British Isles, occurring in areas associated mainly with the Chalk and Carboniferous Limestone.

In the Craven area, tufa deposition appears to have been more extensive in the past than at present. Active deposition, i.e. deposition which is currently taking place, can be recognised by observing the surfaces of perennial bryophytes such as *Cratoneuron*. Rates as low as 0.1 mm per year can easily be detected in this way (Pentecost, 1987). Active deposition was not detected at 17 of the 29 sites and was only substantial at four, viz 24, 26, 28 and 29. On a small scale, however, tufa deposition is still widespread (Figure 2).

Evidence for high levels of activity in the past comes from 14-C dated sites at Gordale (sites 19, 20) and Mealy Bank (site 15). At site 19, ages of 1910-2340 years BP have been obtained at the surface and 4420-4850 BP at depth (with bedrock-dilution corrections). At site 20, samples below a depth of 2 cm gave dates of 4200-4600 BP (Thorpe et al., 1980; Thorpe, 1981). These dates indicate high levels of activity in the Sub-boreal and Sub-atlantic periods whilst a Boreal date was obtained for tufa containing *Alnus* impressions at Mealy Bank (Pentecost, 1986).

Carbon-14 dating has also been applied to tufas at other British sites. At Folkestone and Watlingbury (Kent) and Caerwys (Clwyd) deposition occurred during the late Glacial or Boreal periods (Thorpe et al., 1981) and at Blashenwell (Dorset) deposition began c. 9000 BP and ceased sometime after 5000 BP (Preece, 1980).

Sediment sequences at cave entrances and rock overhangs also demonstrate past high levels of tufa deposition. Most of the travertine and clast-supported breccia at Cave Ha 3, a rock overhang, was laid down before the occupation horizons containing chipped stone tools and an Atlantic-Sub boreal age fauna. Also, at the entrance of Victoria Cave, the deposition of clast-supported breccia had evidently ceased by the time of the Romana-British occupation in the sub-Atlantic (Tiddeman, 1876).

Cementation of alluvial material probably occurs in a similar manner to travertine formation although the mechanism has not been studied in depth. Active cementation of coarse river gravels occurs at two sites in Craven on a small scale. Cemented screes of postglacial age are widely distributed in Derbyshire (Burek, 1977) and were probably formed under similar conditions though they have not been reported extensively from Craven.

Although the basic mechanism of tufa-deposition is known, much more needs to be understood concerning the rate of deposition as a function of prevailing climate. Tufas form in a wide range of climates today, but rates have only been obtained for a few sites, mainly in the UK and Germany and for a limited range of types. Increased temperatures are known to raise soil carbon dioxide levels and this could provide more tufa deposition given adequate rainfall and providing the vegetation and soil remain unaltered. The mean air temperature is thought to have increased rapidly during the early Boreal (9000-10,000 BP) then more slowly during the Atlantic, attaining a maximum of about 2.5 C above today's levels around 6000 BP. Thereafter, there has been an irregular decline until the present day (Taylor et al., 1975). This period of elevated temperature does appear to correspond to a period when tufa deposition was known to be occurring. This must be tempered by the fact that Holocene vegetation and soils have been profoundly affected by human activity (Evans, 1975; Dimbleby, 1975). In Craven such activity may well have altered soil characteristics and thus affected carbonate dissolution and deposition. Travertine deposition in caves should be subject to the same climatic variables even though the precipitating environment experiences fewer extremes compared with open air sites.

We extend thanks to all land owners for permission to investigate the sites and Mr. K. Iball, warden of Malham Tarn Field Centre for providing research facilities for this work.

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Received December 1987

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Pigmentary Development of Cavernicolous Organisms

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Abstract: Cave colonisation and subsequent adaptation to the hypogean environment is discussed. The major epigeal pigments, the Melanins and Carotenoids are described and the theoretical mechanisms of their loss are detailed and correlated with specific examples of depigmented Cavernicoles. Hypogean evolution is briefly discussed in terms of depigmentation, and the pigmentary development of new Cavernicoles is shown to be dependant upon the phyletic age and mechanism of pigmentation of the organism. Loss of Carotenoid pigmentation is seen as a result of lack of dietary carotenoids in the hypogean environment. The composition of the hypogean aquatic environment is discussed as a causative agent of Melanin pigmentation loss whereas genetic loss of pigmentary mechanisms is seen as a result of the spread of loss mutations in cave populations due to a lack of natural selection maintaining the genes. Fixed colouration is explained by a reduced number of mutations occurring in a given population or by the phyletically young age of such organisms.

INTRODUCTION

The phenomenon of faunal depigmentation in cave-dwelling organisms has been explained in many, often contradictory, ways. This paper brings together the work of many authors, spanning some fifty years of research, and aims to set out theoretical depigmentary mechanisms with field observations, in an attempt to explain this aspect of cavernicolous development. To this end it is necessary to examine several aspects of cave colonisation and the subsequent adaptation to the hypogean environment, which may be defined as the underground environment inhabited by troglobionts. It is also important to understand the major epigeal (above Ground) pigments - the melanins and carotenoids - and the theoretical mechanisms of their loss, correlating them with specific examples of depigmented troglobionts.

The complications of studying such a subject should be realised: experiments are very difficult to conduct - the hypogean environment can never realistically be reproduced in a laboratory and caves do not lend themselves readily to controlled experiments in the field. Therefore, the vast majority of papers on this subject encompass field observations and theoretical mechanisms to explain such phenomena.

Cave Colonisation and Adaptation

The environment of subterranean passages is one of total darkness; the air contains over 90 per cent of the maximum quantity of water vapour it can hold, and the temperature is very low (in British caves temperatures range from 44 F(6.7 C) to 55 F(12.8 C) and relatively constant (Hazelton and Glennie, 1962). In such an environment are found organisms living and reproducing, adapted to their underground world through mechanisms as yet little understood.

The tactic responses (movements of a motile organism towards or away from a source of stimulation) of cave animals are maintained in the hypogean environment or else are considered regressing characteristics of a former epigeal existence; for example, a cave animal, be it troglobiotic or troglophilic, that has any reaction to light at all will avoid it (Beatty, 1949), and yet it is clear that an animal living in total darkness has no opportunity to evolve a reaction to a stimulus it never encounters. Such a phenomenon must therefore be thought of as an inheritance from a past epigeal existence (Hawes, 1947).

The migration into caves and subsequent adaptation has, necessarily, only been made by organisms fairly well equipped for such an existence. Unadapted animals will only enter a cave system by some accident beyond their control. Such an accident is catastrophic and they do not survive long (Hazelton and Glennie, 1962). It is

found that nearest epigeal relatives of troglobionts are photophobic animals of a retiring disposition (Beatty, 1949) and are therefore considered to be 'pre-adapted' to a hypogean existence. However, further pre-adaptation must occur in relation to the low oxygen tensions and depleted food supplies found in subterranean waters, and to other factors of the natural hypogean environment not encountered in the epigeal habitat. It is only when such autoregulatory evolution is complete that an organism is capable of surviving in the subterranean world (Vandel, 1965).

If such a pre-adapted animal entered a cave it would have characteristics no longer required in the hypogean world. With time, characteristics such as eyes, toleration to temperature extremes or to light, and pigment (Maguire, 1961) will be lost provided a barrier preventing gene flow from epigeal to hypogean populations exists. That is to say, it is a genetic necessity that such organisms are separated from their epigeal relatives either by extinction or geographic remoteness (Sbordoni, 1982).

Much hypogean adaptation can readily be seen to be of value to an organism in its new environment: cave species develop elongated antennae and other hypertrophied sensory organs. Yet the loss of pigment by a cave-inhabiting organism cannot be understood in this way (Hawes, 1947). Depigmentation confers no advantage at all, and in a world of total darkness the colour of an animal is of no consequence, and yet the phenomenon is so typical of cave organisms that it is usually taken as a symbol of troglobiotic adaptation.

Peters et. al. (1973) looked at the pigmentation of the troglobiotic tooth carp *Poecilia sphenops* and compared it to its epigeal form: 'concerning ... depigmentation ... a gradient can be observed; those fish found deepest in the cave show the greatest ... loss of pigment ... whereas those living near the cave entrance are very similar to the epigeal form. There exist transitional stages between these two extremes.' This example shows the diversity of pigmentation in cave animals and highlights the two major problems of this field: namely that pigmentation is difficult to quantify, and that it may be exhibited to different extents.

A further factor that deserves careful consideration is the stability of this phenomenon in a given species. This may be illustrated by Hawes, (1950) who described troglobiotic Copepods that remained depigmented even when kept in the light, while some cavernicolous Amphipods were seen to darken when submitted to epigeal conditions. Similarly, some epigeal organisms depigment if found living underground, while others retain their colour in darkness.

It is now apparent that the extent to which an animal living underground is affected by depigmentary adaptation varies greatly from species to species: the phenomenon may be complete or non-existent, reversible or fixed. It is therefore reasonable to assume that the mechanisms resulting in loss of pigment may be equally varied, but before this can be examined, it is beneficial to study the biochemistry and nature of pigmentation, in order to understand the physiological changes that may occur during depigmentary adaptation.

CAVERNICOLOUS PIGMENTATION

The Pigments of Cave Animals

The fact that cave adapted organisms have depigmented shows that pigment can only be an epigean requirement. Lisowski (1979), Maguire (1960) Buchanan (1936) and Vandel (1965) all showed that, in the epigean environment, pigmentation forms a protective barrier against the harmful action of light. Maguire (1960) further made the point that, following depigmentation, light intensities 1/20 that of a normal sunlight were sufficient to kill some Ostracods. Lisowski (1979) also stated that pigment had a function as protection against predators.

The different pigments present in epigean forms must all have degenerated and been lost in depigmented cave forms. It is therefore useful to look at these pigments and their occurrence. It should be noted that essential pigments such as haemoglobin are of course retained: it is the pigments not essential to the physiology of the animal that are missing (Beatty, 1949). Of such pigments, by far the most important discussed in the literature are the Melanins and the Carotenoids. A knowledge of these two pigment types will contribute to the understanding of the ancestral pigmentation of cavernicoles, and to its subsequent loss, far more than any others and therefore discussion will be limited to a brief outline of the role of these two pigments and their biochemistry.

The Melanins are derived from Tyrosine via a seven stage reaction terminating in the polymerisation of Indole 5-6 Quinone (Dagley and Nicholson, 1970). This process of 'Melanogenesis' requires oxygen (Fox, 1960) but to what extent is unclear: It may therefore be that the low oxygen tensions characteristic of the hypogean environment thus restrict Melanin production. The entire Melanogenetic reaction is probably completed by a single enzyme, Tyrosine Hydroxylase (Dagley and Nicholson, 1970). Thus a single genetic defect in the production of the enzyme would result in no melanin production. On the other hand, Beatty (1949) has shown that Tyrosine Hydroxylase is present in many troglotic, stable depigmented organisms and, therefore, loss of Melanin production must occur elsewhere in the mechanism.

Melanin pigmentation is known to account for the yellow-brown colouration of Asellus aquaticus (Baldwin and Beatty, 1941), as well as that of other Isopods (Beatty, 1948). The pigment is usually in the form of granules with a definite form (Fox 1960), held in branched cells termed Melanophores. Upon a stimulus such as light (Noble and Pope 1928), the cells expand producing colouration and bringing about an increase in Melanin content and Melanophore number. Fingerman and Moberly (1960) have shown that in the troglotic Crayfish Cambarellus shufeldti, the ability to generate Melanin has gone, and yet the activators still respond to light and release trophic substances that would bring about the effects described above if the melanogenetic pathway had not broken down. They concluded that the persistence of such activators indicates that either the loss of the controlling mechanism takes longer than the loss of the production pathway, or blind forms have given these trophic substances a new function.

Carotenoids are non-saturated hydrocarbons,

the most common types being B Carotene and Xanthophyll. They may be synthesised by certain fungi and bacteria but as yet no animal capable of doing so has been found. Such species must therefore obtain all necessary carotenoids from their diet (Vandel, 1965). Beatty (in Baldwin and Beatty, 1941) showed that cave pools with a direct connection to the underground river contain much Carotenoid material, possibly due to the preserving qualities of low temperature and oxygen tension found in such environments, whereas pools fed only by water drips are devoid of Carotenoids due to filtration as water percolates through the limestone, or lack of microbes capable of their synthesis. They further showed that three epigean Amphipods, Gammarus pulex, G. marinus and Orchestia gammarella owe their colouration almost exclusively to Carotenoid material. Cave Amphipods were also found to be depigmented. Citing Vire, (1900, 1904) they showed that such troglotic Amphipods remained colourless even if fed material containing Carotenoids and yet the colourless Niphargus puteanus will develop pigment if cultured in sunlight, and the epigean Gammarus puteanus loses its colour when kept in darkness for twenty days. Beatty (in Baldwin and Beatty, 1941) concluded that Carotenoids are in all probability the ancestral pigments of depigmented cave Amphipoda and that the lack of pigment in cave Amphipods is not due to lack of Carotenoids in the diet but may be due to absence of light.

Pigmentary reactions of cavernicolous fauna

If badgers and bats are excluded, cave animals are all very small creatures. Examples of cave-adapted Fishes, Molluscs, Insects, Crustaceans, Millipedes, Mites and Worms may be found in most cave regions of the world. In this paper, only a description of those animals that will lead to an understanding of the phenomenon of depigmentation is required, and to this end discussion must be restricted to cave fauna exhibiting such an adaptation.

In the Crustacea and Diplopoda, the cuticle is hardened by the deposition of lime, and coloured by an independent mechanism not intrinsic to the strength of the exoskeleton. Thus, if such an organism is depigmented it appears white. However, in the Insecta, Arachnida and Chilopoda, the hardening and darkening of the cuticle are consequences of a single process and therefore in a cave, the exoskeleton cannot be produced depigmented as its vital strength would be lost (Hawes 1950); such a phenomenon can only confuse the biospeleologist looking at cavernicolous depigmentation. Therefore a detailed description of such organisms is not relevant to this paper.

It was stated above that the epigean Gammarus puteanus loses its colour when kept in darkness for twenty days (Vire 1900). The same author (Vire, 1904) showed that this was also true for Gammarus fluviatilis when kept in the dark for six months. According to Baldwin and Beatty (1941), the ancestral pigment of such cave Amphipods is probably Carotenoid in nature. In another paper Beatty (1949) stated that above ground Copepods also have a labile Carotenoid pigmentation which is lost when they are kept in darkness. However, it is not just Carotenoid pigments that disappear so readily; Hawes (1947) cited the recording in 1931 of a trout found in a German cave where its occurrence was almost certainly accidental, which, besides losing its reddish spots of Carotenoid colouration, had also lost a great deal of its Melanic pigmentation. He further described two young fish (Squalilus sephalus) found in the Grotte Di Postumia that were quite white. He stated that this modification had almost certainly taken place within the life time of the fish. Thus there is evidence of labile epigean pigmentation, both Carotenoid and Melanic in nature, and by some mechanism, epigean organisms pigmented by such types may lose their colour if subjected to the hypogean environment.

However, such labile pigmentation is not universal; Baldwin and Beatty (1941) showed that the colour of Asellus aquaticus is due mainly to

Melanin, with B Carotene and Cryptoxanthine being present. They showed that the pigment of this organism was not affected when kept in total darkness for 7.5 months and that offspring produced during this period were normal in colour. Thus, the pigment in this organism is not labile and so the depigmentation of the related Asellus aquaticus cavernicolous cannot be ascribed to the Phenotypic effect of the darkness which characterises the cave environment.

It is now necessary to look at the hypogean fauna and the stability of their depigmented state. Beatty (1948) noted that some species of Niphargus were reported to regain pigment in the light; this was supported earlier by Vire (1900) who stated that the colourless, cavernicolous Niphargus puteanus developed a greenish-brown colour after two months exposure to light. Meek (1929) cited the example of epigean Gammarus duebeni which, when found living underground, was a dull transparent white, but after exposure to light it redeveloped the normal colour of the species including the three characteristic red spots. The above species are Amphipodans and Beatty (in Baldwin and Beatty, 1941) has shown that their pigments are mainly Carotenoid in nature, and these examples suggest that light may be a major factor in the pigments' production. However, it is not only carotenoids that can be produced in this way. Pavan (1946) reported that Pimelodella Kronei, a Brazilian cave cat-fish with no eyes, has faintly coloured chromatophores which develop pigment (perhaps Melanin) when the animal is maintained in the light, the degree of pigmentation regained varying from individual to individual. He suggested that this species may be in the process of genetic regression for pigment production. Beatty (1949) also showed that Proteus produces melanic pigmentation in light and loses it again in prolonged darkness. Thus, among cave-adapted species there are examples of unstable depigmentation; however, it is noticeable that the literature contains far more examples of stable depigmentation and this suggests that an inability to develop pigment is the ultimate cave adaptation, a characteristic only of true troglobionts, and that unstable depigmentation is part of the 'period of instability' (Vandel, 1965) troglomorphic stage of cave adaptation.

Rasquin (1947) carried out a great deal of work on two species of cave fish of the Anoptichthys group, one from La Cueva Chica, the other from Cueva de los Sabinos. She found that in light the 'Chica' form develops Guanin colouration but no such effect occurred in the 'Sabinos' type. She further found that, when compared to the ancestral river form, both samples of cave fish exhibited a vast reduction in Melanophore number. Thus the loss of colour in these hypogean strains is not due to fewer Melanic granules within existing cells, but to the actual loss of pigment cells. Finally, she showed that the activator mechanism of pigmentation was working in both species of fish under study and they had lost no power of dispersion and concentration of granules, and exposure to light resulted in an increase in Melanophore number in the 'Sabinos' form. However, none of these effects resulted in increased visible colouration due to the numerical lack of initial Melanophores. The same phenomenon was also shown by Fingerman and Moberly (1960) to be present in the cave Crayfishes Cambarellus shufeldti and Orconectes clypeatus. Here they found the organisms to possess no Chromatophores and yet the pigmentary activator system was still present and functional. Similarly, Noble and Pope (1928) showed that in the cave Salamander Typhlotriton, adult Melanophores do expand when subjected to direct light and yet when under such conditions for 215 days the specimen actually shows no increase in visible pigmentation. However, when the young are exposed to light for 182 days after shedding, pigmentation is distinctly increased. This suggests that immature individuals of certain species possess a labile depigmentation that becomes fixed in adult maturity. Possibly the

number of melanophores remains the same throughout the organisms life. In the young such a number may cause a visible colour change whereas in the adult the number is so small compared to the animal's surface area that no change in pigmentation is seen to occur. Beatty (1949) noted that cavernicolous Copepods did not regain lost pigment when kept in the light, and Vire (1900) showed that the same is true of Niphargus plateaui. An interesting case is that of the cave Crayfish Procambarus s. simulans: Maguire (1961) showed that this depigmented species cannot regain colour in light and yet it can do so if fed Carotenoid - containing material. Anders (1956) showed the same phenomenon occurring in Gammarus pulex subterraneus. However, such an effect cannot be shown to occur in Niphargus plateaui (Hawes, 1950) or in the Isopod Cirolanides texensis (Maguire, 1965). In the above-mentioned Crustacea it is generally accepted that the pigment is Carotenoid in nature (Maguire, 1965) and these examples show that such pigmentation may be due to diet composition.

It is now apparent that there are specific examples of stable and unstable, epigean and hypogean colouration. There are examples of species that show pigment reactions that vary from individual to individual. Anders (1956) showed that with depigmented Gammarus fed on Carotenoid-containing food, most of the animals developed colour but a few were not able to do so. Also, the pigment developed was generally a different shade from the epigean variety. Rodriguez (1985) described a cavernicolous crab, Nuestregeria sheti which shows partial depigmentation of the body and concluded that the species was only in the first stage of its adaptation to cavernicolous conditions. Zander (1980) described large variation in Melanophore pattern on the cavernicolous blennioid Lipophrys nigriceps, and Hensley (1959) described the patchy distribution of Melanophores on the cave Salamander Eurycea lucifuga. Perhaps all these examples show stages in depigmentary adaptation, the organism in the process of regressing to true troglomorphic status.

Hobbs (1979) illustrated another example of a similar phenomenon in the cave shrimp Typhlatya mitchelli: here specimen colour varied from total depigmentation to total colouration, and again Pearce and Cox (1977) showed such colour variation in Gammarus pulex L. from a population taken from the Beck Head Stream Cave resurgence of Ingleborough. Further, Baldwin and Beatty (1941), cited Kosswig's experiments showing that a considerable range of pigmentation was observed in the offspring from a cross of two almost unpigmented Asellus aquaticus cavernicular. However, in all these examples it is unclear whether a barrier preventing gene flow from epigean to hypogean populations existed and, as explained above without such a barrier total troglomorphic adaptation will not occur.

An interesting observation of the literature is that, with the exception of Niphargus plateaui and Cirolanides texensis, lability of colouration appears to be a characteristic of vertebrate Melanic or invertebrate Carotenoid pigmentation. This correlation is by no means proven but merely an observed trend, possibly worthy of further research.

ANALYSIS OF DEPIGMENTARY MECHANISMS

Vandel (1965) stated that 'at all stages and in all fields hypothesis has preceded experimentation' and this is especially true in biospeleology where early scientists looked to the cavernicolous fauna for examples to explain their theories of evolution. Later, theories were generally formulated to explain specific observations, or loss of certain characteristics. It is the aim of this paper to analyse such theories only in terms of their suitability as explanations for depigmentation in cavernicoles and, therefore, their adaptability to explain overall hypogean evolution will not be discussed.

Mechanisms of Environmental Influence

The most obvious difference between the epigeal world and the cave environment is the total lack of light in the latter. However, Lisowski (1979) ascertained that the variable degree of paleness observed populations of Asellus aquaticus cavernicolus cannot be due to the lack of light because all the animals would be affected to the same degree. Thus, if light was the sole factor in depigmentation then we could expect all animals to behave the same way in and out of the stimulus, and yet examples of hypogean species that cannot pigment in light, and epigeal species that maintain their colour in darkness, have already been shown. However, light cannot be disregarded as a causing agent of some depigmentary effect as was shown above and yet, light has not been shown to be a required element for the pigment production of any organism.

The constitution of the hypogean aquatic environment is obviously worth observing and yet little has been written on the subject over the years. Pradhan and Agarwal (1984) surveyed the literature and drew conclusions with references to their own observations. They state that the ionic concentrations of calcium (Ca⁺⁺), Potassium (K⁺) and Sodium (Na⁺) are remarkably high in cave water compared to that outside. They then discussed how this factor could influence Melanic pigmentation and state that aggregation of Melanophores may be caused by high concentrations of K⁺, Ca⁺⁺, Mg⁺⁺ (Magnesium ions), and yet high concentrations of Na⁺ are seen to initiate Melanophore dispersion. With so little evidence on this subject it is difficult to draw any worthwhile conclusions; however, tolerances to salt concentrations are known to vary between all extremes in the animal kingdom and, therefore, reactions, to high concentrations of given salts are specific to each species. Such reactions cannot, therefore, be disregarded as possible mechanisms to explain hypogean depigmentation, but the theory in no way accounts for all cavernicolous colouration. For example, variable pigmentation observed within a species is anomalous to such reactions.

Dietary elements have received much attention in biospeleological studies, especially with regard to Carotenoid content which cannot be synthesised by an animal and must, therefore, be ingested as part of an organism's diet. Baldwin and Beatty (1941) stated that 'detritus carried in by underground rivers is the chief source of food for cave animals, and ... Carotenoid material is found in it in some quantity.' However, whether such Carotenoids are available to animals has yet to be proven (Maguire 1961). Maguire also pointed out the problems of looking at Carotenoid availability and suggests that examples of colourless Cavernicoles that are reported to pigment in light may be explained by the growth, in such experiments, of algae which contain Carotenoids and thus make them available to the hypogea. Therefore, light may be a causative agent of depigmentation by way of facilitating algal growth and thus producing Carotenoids for such cavernicoles as are coloured by these pigments. There is no doubt that food is scarce in caves and so variation in body colour within a species may be proportional to the amount of Carotenoid material an individual ingests. Such a theory could also explain epigeans maintaining or losing colour in darkness, and hypogea gaining colour in light. However, it cannot explain why some hypogea cannot pigment under epigeal conditions. Perhaps this mechanism describes depigmentation for troglaphiles, whereby subsequent hypogean adaptation fixes this state by some other mechanism, producing true troglaphiles, unable to pigment even when fed Carotenoid material. Obviously, such a theory is only applicable to those cavernicoles pigmented solely by Carotenoids.

A final element of the hypogean ecosystem which deserves only a brief mention is that of parasitism. Lisowski (1979) reported that in a population of Asellus intermedius, individuals

infected with an Acanthocephalan parasite were much lighter than those uninfected. However, studies of the same species at another site showed no other differences in the mean Acanthocephalan load among the white, intermediate and dark morphs, and elsewhere, similarly pigmented individuals contained no parasite. Thus, whilst the phenomenon may correlate with pigmentation in some populations, the mechanism cannot be regarded as useful to an understanding of depigmentary development in Cavernicoles.

Mechanisms of Genetic Change

Prior to the birth of genetics as a biological study, E.R. Lankester proposed a theory to explain the origin of Cavernicoles called the 'Accident Theory'. This postulated that if an animal accidentally enters a cave, it would be attracted to the surface by the light. However, if the same thing happened to an organism with deformed eyes, it might remain and reproduce in the hypogean environment. This in no way explains depigmentation, but it was the first theory of cavernicular colonisation based on mutationism. Later biologists, armed with an increasing knowledge of genetics, adapted Lankester's theory, and argued that the existence of albino or eye-less mutants provided the usual method by which cavernicoles could appear (Vandel, 1965). However, such theories cannot but fail: as was discussed above, an epigeal species cannot leap to a Cavernicolous form in one mutation. A long period of pre-adaptation and troglaphilic existence is necessary if an organism is to survive in the hypogean environment. The above theories do not account for such adaptation and therefore cannot be held by the biospeleologist.

Evolutionists have always argued the necessity of natural selection in producing change in species. Such scientists therefore produced theories based on natural selection to explain Cavernicolous depigmentation. Maguire (1961) described selection against individuals possessing an unneeded structure whereby an animal which does not have to waste energy and material in the building of a useless structure will have a better chance of surviving than one which builds the structure. However, Hawes (1947) disputed such ideas, stating that no one can seriously consider that the energy required to produce pigment makes any significant difference to the general metabolic economy of any animal. Hawes then suggested that Cavernicolous depigmentation is a result of lack of natural selection: he stated that in epigeal environments the results of natural selection are such that mutations conferring an advantage on their bearers tend to spread throughout the population; whereas disadvantageous ones are selected out. Further, the genetical pigmentary mechanism of an epigeal animal may be seen as a complex device that is constantly tending to break down, but maintained by the pressure of natural selection, pigmentation being advantageous above ground. But, in the hypogean environment, colour bears no advantage or disadvantage and so is neutral. Therefore, there will be no selection pressure to maintain pigmentation and the process will degenerate. This theory can only relate to animals fixed in their pigmentation, and may explain population variety. However, it does include two large assumptions, that, in reproduction the genetic transfer mechanism is labile, and that depigmentation is a direct result of darkness. The latter has already been shown to be incorrect for many organisms, and as regards the former assumption, organism reproduction is such that genetic transfer must be reliable for progressive evolution to occur and therefore, such replication cannot be termed labile. However, loss mutations are more frequent than positive ones (Baldwin and Beatty, 1941) and it can be understood that in very small groups, as is characteristic of cave populations, such mutations may spread rapidly. Therefore, for an organism in a small population that does have a labile, genetic pigmentary mechanism, and is seen to lose colour in the dark,

Beck Head Stream Cave, the resurgence of water in the Gaping Gill caves. *Gammarus* spp. in this stream show total variation in their pigmentary development.



progressing through a stage of variable population pigmentation, this theory may have a basis. Wilkens (1969) has shown that the Melanin content of Melanophores in the cave fish *Astyanax mexicanus* is the responsibility of a single, recessive gene. Therefore, without selection against it, Melanin production in this organism degenerates. Thus the above theory does have its applications, but such a mechanism in no way explains why some epigeans maintain their colour in darkness, nor the rapidity with which some species lose their colour in darkness, or gain it in light; sometimes within the lifetime of an individual.

Such theories obviously do not explain all observed effects, and yet they do highlight a point made earlier such that genetic change is dependent upon a barrier to gene flow, without which loss mutations would be selected out.

Maguire (1961) discussed another theory to explain selection against organisms possessing a non-useful structure, namely pleiotropism. Under this mechanism, a gene that may be necessary for pigment production may have an unfavourable pleiotropic effect and will, therefore, be selected against, and as a result, pigmentation is lost. No evidence was shown for this mechanism, but there is no doubt as to its plausibility.

Such mechanisms of genetic change can never explain the rapidity with which some organisms are observed to develop pigment in light and lose it in darkness. The spread of loss mutations through a population will inevitably only occur on an evolutionary time scale, and yet such genetic change undoubtedly occurs and may well be responsible for the large group of troglolobionts, unable to regain colouration when subjected to epigeal conditions, and conversely, the lack of a labile genetic pigmentary mechanism may explain the epigeans that maintain their colour in darkness.

Mechanisms of Evolutionary Development

A combination of environmental influence, and genetic change leads to evolutionary development, and Vandel (1965) attributed the origin of Cavernicoles to an evolutionary change. His mechanism is called Organicism. Vandel stated that all phyletic lines pass through successive stages: the creation of a new species, its subsequent expansion and diversification, and finally, its specialisation and scenscence resulting in extinction. He stated that Cavernicolous adaptation is an example of regressive evolution occurring in the stage of

scenscence. This mechanism explains how epigeans can pre-adapt metabolically to Cavernicolous life, and also how troglolobiotic fixed depigmentation may occur as well as epigeal fixed colouration. It cannot, however, explain how pigmentary reactions may occur in the lifetime of a single organism, nor the variability of pigmentation observed in many populations.

CAVERNICOLOUS DEPIGMENTARY EVOLUTION

Having analysed suggested depigmentary mechanisms, it is necessary to discuss hypogean evolution, in terms of loss of colour, in order to determine how pigmentary reactions once established in a population, may become fixed within the species.

Evolution may be regarded as the phenotypic and genotypic development of a species in order to adapt to a changing habitat. Environmental influences, in the short term, such as change of light, media and diet constitutions or parasitic occurrence, may be seen to cause reversible phenotypic adaptive changes in an organism. However, in the long term a change in environment leads to a shift in natural selection and consequent genotypic alteration.

The initial phase of cave colonisation is the troglolophilic stage. Such populations are connected with the epigeal form and therefore still belong to the same gene pool. Environmental influences may at this stage affect the individual as shown above. Genetic change may only occur once the surface members of the species are extinct (Sbordoni, 1982) or geographically remote from the cave population (Wilkens, 1979). Most hypogean populations are thus totally isolated and may die out. However, if they survive, a re-organisation of the epigenotype occurs, adapting the colony more closely to its new environment. Features biologically useless in the cave now begin degenerating as is seen by an unusually high variability of features between individuals (Wilkens, 1976) until a stable, final rudimentary state is reached.

Depigmentation of new Cavernicoles will follow the above description of hypogean evolution. Thus, after initial colonisation, environmental influences may affect the pigmentation of an individual but for genetic change to occur in order to produce an heredity, irreversible depigmented state, isolation of the population must occur, such that gene flow is interrupted from epigeal to hypogean populations, and the smaller such a group is, the faster

genetic drift will occur throughout. Such isolation generally occurs as a result of environmental or climatic influences: for example cave floods occur suddenly and act as agents of distribution, maintaining food supplies to caves, and initiating colonisation with troglomorphic epigeal species, as well as moving Cavernicoles throughout the subterranean system. Thus, after the recession of a flood, a population previously distributed throughout a relatively large volume of water may be confined to a small, isolated pond, restricting the gene pool and allowing genetic change to occur at an increased rate. In such a way, subterranean pools may be seen as 'refuges' where a population may evolve and specialise away from the competition of epigeal ecosystems (Hawes, 1947).

SUMMARY: THE PIGMENTARY DEVELOPMENT OF NEW CAVERNICOLES

The aim of this paper was to analyse the pigmentary development of cavernicolous animals within their habitat. Therefore, if such a study may be successful, it should be possible to predict the pigmentary development of a new Cavernicole.

It was shown how pre-adaptation to a Cavernicolous life is necessary if the epigeal organism is to survive in a subterranean environment. Having achieved this, the organism may adopt a troglomorphic existence: living in the cave and yet maintaining a gene flow and possibly alternating habitats, with the epigeal form.

In this troglomorphic state, an organism living within the cave is subjected to hypogean environmental influence, whilst maintaining epigeal metabolism and genotype. At this stage, subterranean factors may affect the phenotype of the animal: if the pigmentation of such an organism is Carotenoid in nature, troglomorphic, reversible depigmentation may occur due to lack of Carotenoids in the hypogean media. Carotenoids present in cave detritus may not be available to many organisms and individuals may assimilate various forms of the pigment, causing colour variation within a population. Such organisms are seen to develop normal colouration upon subjection to the epigeal environment. This is probably due to increased Carotenoid content of the outside media, possibly due to the large presence of algae. Carotenoid-pigmented Amphipods that are reported to remain depigmented even when fed Carotenoid material may only be able to assimilate certain forms of Carotenoid not available under some conditions. Labile Melanin pigmentation may also be affected by the hypogean environment during a troglomorphic existence. Evidence has also been given earlier to show that Melanophore aggregation will produce visible depigmentation and it has been cited how high salt concentrations characteristic of the cave media may induce such an effect. Perhaps this explains labile Melanin pigmentation so often observed in cave Salamanders and subterranean fish populations.

Organisms tolerant to high salt concentrations and not pigmented by labile Carotenoids or Melanins will not be affected phenotypically by the cave environment whilst in such a troglomorphic stage. Such populations will maintain their present form until an external influence isolates a group from the epigeal type. Gene flow between hypogean and epigeal populations is now interrupted. Evidence suggests that animals pigmented by Melanin possess a labile genetic pigmentary mechanism which is seen to break down in the hypogean environment due to lack of selective pressure. Such degeneration is shown as variable colouration within a population. In time, genetic drift will ensure total loss of pigment will spread throughout the population, at a rate proportional to population size. Various mechanisms are seen to break down in this way demonstrating a loss of capability to produce both Melanin and Melanophores.

Observations of epigeal organisms maintaining fixed colouration through generations in a

hypogean environment may be explained by lack of a labile genetic pigmentary mechanism, or by Vandel's mechanism of organicism whereby phylogenetically young species will be unable to perform regressive evolution and will maintain their pigment due to their zoological group being ineluctably led through successive stages of evolution, only able to perform genetic regression on a geological time scale, and only when present in the final stages of speciation.

The pigmentary development of a new cavernicole is thus dependant on its phyletic age and mechanism of pigmentation. Troglomorphic depigmentation may be reversible upon subjection to epigeal conditions, whereas depigmentation via genetic change is troglomorphic adaptation and such organisms will, apart from pigmentary regression, be so adapted to the hypogean environment that subsequent exposure to the epigeal world would mean certain death of the individual. Troglomorphic adaptation may be seen to maintain a form suited to hypogean and specialised epigeal environments; true troglomorphic evolution regresses an individual to a basic, rudimentary form no longer capable of epigeal existence. Such organisms exhibit fixed depigmentation and possibly depict one of the most specialised adaptations of the animal kingdom.

ACKNOWLEDGEMENTS

The author would like to thank Dr. J.P. Margham of Liverpool Polytechnic for helping in the production of this paper, and also Dave Warrington for his assistance. Finally, a special thanks to my wife, Clare, for preparing the manuscript and for her patience with my 'English'. The paper is based on an undergraduate project done at Liverpool Polytechnic.

Editor's note: Readers may like to know that there is a discussion of the subject of regressive evolution in cave animals in the Bulletin of the National Speleological Society, volume 47, no 2, December 1985. This was not available to the present author when he wrote his paper.

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Received February 1988

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The Least Squares Method of Cave Survey Data Reduction based on a Micro Computer

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Abstract: Using the method of least squares to distribute errors in survey loop misclosures has been frequently talked about by people describing ideal systems for survey data reduction, but often it has been thought too complicated to be implemented on anything but a mainframe computer. This paper presents an overview of the least squares method, extensions to the basic method and a brief outline of a program written to demonstrate the technique.

INTRODUCTION

The Least Squares Method (LSM) is the standard technique in Engineering and Science for measuring the distance between two experimental results. Survey data is reduced by this method by assigning misclosure error values to all the legs in a survey so that the sum of the squares of all these errors is the minimum possible value. From this we calculate the optimal values for station positions within the survey.

The LSM has been used in America for cave survey data for a number of years (see Schmidt and Schelleng [1970] for example) but this work does not seem to have been appreciated in Britain. It is hoped that the present paper will go some way towards remedying this omission.

One of the first people in Britain to apply the LSM to cave survey data was Luckwill (1970). His technique unfortunately did not take into account any measure of the number of legs that were 'accountable' for the error, therefore this scheme was little better than the method of fixing individual loops within the survey and fixing other loops to these. Indeed given the complexity of the maths required for the LSM you would be better off using the cruder approach, presented by Irwin and Stenner (1975). Warren (1987) described a method that solves this problem, by counting the number of legs in a traverse so they can be taken into account when solving the equations for a given junction. He also presented a number of axioms that help reduce the volume of data so drastically that the technique becomes usable on a desk top computer. Changes made to this algorithm while coding it for use on just such a computer have led to what we believe is a totally universal LSM for cave survey data reduction.

A value can be obtained for the traverse's accountability to the closure error by assigning each leg a value (standard deviation) relating to its accuracy (e.g. Survey Grade) and changing the simple leg count (used as a measure of the traverse's accountability to the closure error by Warren (1987) to a sum of the legs' accuracy measures. In this way we can define a technique that will cope with all the situations encountered when surveying caves. Points can be fixed to absolute positions and then the survey 'bent' to fit them (e.g. two entrances and a surveyed through trip). Estimated or low accuracy measurements can be made within loops without distorting the accurately surveyed data. In its most general form the algorithm will accept the usual survey data measurements along with their 'Grade', then distribute the error accordingly among the survey legs.

Interesting mathematical asides show that what has been the surveyor's 'Rule of Thumb' for years for distributing errors around simple loops can be justified as a mathematically correct procedure.

Further than this is it is possible to define the region in space in which a station must lie given the errors accumulated from the survey legs. Thus if trying to make contact with an underground

party via a 'mole-phone' or some such device the size of the search area would be known. Equally it could assist in predicting if a connection might be made between two sections of the cave. For example if the survey shows two stations as being 5m apart but with error circles of radius 2m then there may really be only 1m separating the points. (Alternatively there may be 9m!). Hence it is possible to assess a potential dig with best and worse case values.

BASIC RESULTS

This part of the paper gives an outline of the results used by the algorithm in the next part. The rules for reducing survey data by least squares are summarised. Some details of the mathematical derivation were given by Warren (1987); for further details contact the authors.

After all the hard underground surveying work we will have obtained lots of data consisting of 'From Station', 'To Station', 'Length Reading', 'Clino Reading', 'Bearing Reading' for each survey leg. These can be reduced to sets of easting, northing and height changes in the normal way. The method should be in any cave surveying book such as that by Ellis [1976], and is also covered by Warren (1987). These are written as $\delta x, \delta y, \delta z$ standing for easting, northing, height changes respectively. In a similar manner, the position of a survey station is written as (x, y, z) standing for its easting, northing, height coordinates respectively. From now on we just consider the eastings (i.e. δx 's and x 's) since the same rules are applied to the northings and heights (y 's and z 's).

The first step is to break the set of survey stations up into two types - vertex stations and intermediate stations. The intermediate stations lie along the lengths of passage which have no branches attached to them - traverses. The vertex stations lie at the ends of these traverses, and are usually at junctions or passage ends. This is illustrated in fig. 1. Note that we are not excluding the possibility that a vertex station can join only two traverses (like C in fig 1), although we shall see that in such a case we can join the two traverses into a longer one, and treat the vertex station as an intermediate one. We find the vertex station positions by solving a set of simultaneous equations, and the intermediate station positions by distributing the misclosure errors back along the traverses.

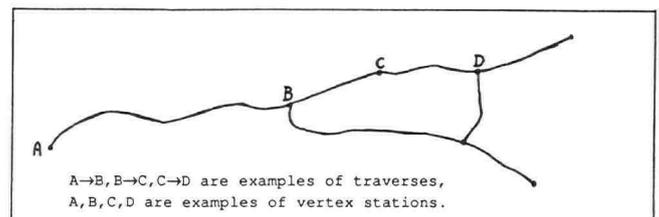


Figure 1 Examples of traverses and vertex stations.

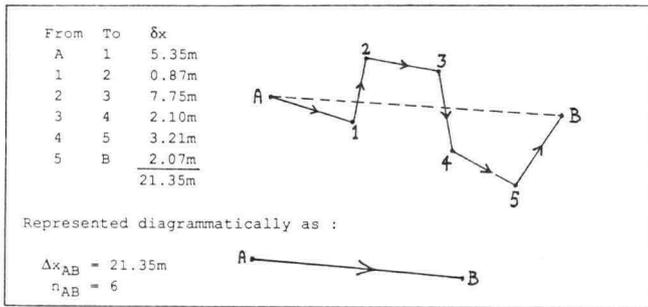


Figure 2 A typical traverse and data.

Before starting we must introduce some more definitions concerned with traverses. Specifically consider a traverse that goes from vertex station A to vertex station B. We can calculate the total displacements in easting, northing and height for the traverse, and we call them Δx_{AB} , Δy_{AB} , Δz_{AB} . Converting all the leg data to point in the same direction along the traverse, these are just the sum of the individual displacements for each leg. We also need the number of legs which we call n_{AB} . This is illustrated in fig 2. Each traverse is completely characterised by the stations it joins, its direction, and the set of data $(\Delta x, \Delta y, \Delta z, n)$.

Due to misclosure errors the measured displacements may not be exactly equal to the displacement $x_B - x_A$. The difference is the total error for the traverse and is given by the symbol Ex , (likewise for Ey and Ez). For example the traverse $A \rightarrow B$ has:

$$Ex_{AB} = x_B - x_A - \Delta x_{AB}$$

Also defined is the error per leg, which is given the symbol ex , (similarly ey and ez). for $A \rightarrow B$ we get:

$$ex_{AB} = Ex_{AB} / n_{AB} = [x_B - x_A - \Delta x_{AB}] / n_{AB}$$

We have to solve the full problem to determine what the vertex station positions are before we can work out what these errors are for any traverse.

Solution of Vertex Station Positions

The least squares solution is obtained by treating the vertex station positions (x_A, x_B, \dots) as variables in the formula for e for each traverse, and writing the following equation for each vertex station:

$$\sum_{\text{entering}} ex - \sum_{\text{leaving}} ex = 0 \quad (1)$$

The sums are over the traverses attached to vertex station in question. In words: Algebraic sum of ex 's attached to this station is zero.

Equations (1) are simultaneous equations in the vertex station positions. There is one equation for each vertex station, but they are not all independent. We must discard one and give a supplementary equation to fix the position of the survey in space. This will normally take the form of giving a specific value to the position of some vertex station, for example the entrance. Note that this station must be included among the

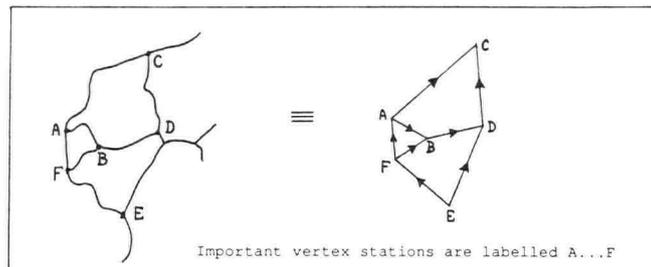


Figure 3 First example network.

From	To	Δx	n	$x_{To} - x_{From}$	Ex	ex
A	B	21.35m	6	21.61m	0.26m	0.0437m
F	A	9.77	7	9.85	0.08	0.0118
F	B	31.98	7	31.46	-0.51	-0.0736
B	D	31.77	7	31.56	-0.21	-0.0299
E	F	-27.02	13	-27.82	-0.80	-0.0618
E	D	34.09	18	35.20	1.11	0.0618
A	C	58.21	16	57.70	-0.51	-0.0319
D	C	4.11	13	4.53	0.42	0.0319

These columns are the data. These columns are worked out from the answers.

Table 1 - Traverse data and results for first example network.

Positions	Displacements	Error to be added
$x_A = -17.97m$	$\delta x_{A1} = 5.35m$	0.0437m
$x_1 = -12.58m$	$\delta x_{12} = 0.87m$	"
$x_2 = -11.66m$	$\delta x_{23} = 7.75m$	"
$x_3 = -3.87m$	$\delta x_{34} = 2.10m$	"
$x_4 = -1.73m$	$\delta x_{45} = 3.21m$	"
$x_5 = 1.53m$	$\delta x_5 = 2.07m$	"
$x_B = 3.64m$		

Table 2 - Errors are distributed back along a traverse

From	To	Δx	n	$x_{To} - x_{From}$	Ex	ex
A	B	3.45m	5	3.35m	-0.10m	-0.0193m
B	C	12.71	5	12.48	-0.23	-0.0462
B	C	12.29	7	12.48	0.19	0.0270
C	D	13.00	6	12.88	-0.12	-0.0193
A	D	28.37	18	28.72	0.35	0.0193

Table 3 - Traverse data and results for second example network.

vertex stations. The solution of (1) and the supplementary equation gives us the positions of the vertex stations.

The best way to illustrate this is to do an example. Suppose we had the network shown in fig 3, and had already worked out the data for the traverses which is shown in the first half of table 1. We can ignore those sections that do not form part of a loop. Note that traverse $A \rightarrow B$ is the one we used before (fig 2). For each vertex we are told to write an equation like (1). We get the following:

$$\begin{aligned} \text{For A: } & (x_A - x_F - 9.77) / 7 - (x_B - x_A - 21.35) / 6 - (x_C - x_A - 58.21) / 16 = 0 \\ \text{For B: } & (x_B - x_F - 31.98) / 7 + (x_B - x_A - 21.35) / 6 - (x_D - x_B - 31.77) / 7 = 0 \\ \text{For C: } & (x_C - x_A - 58.21) / 16 + (x_C - x_D - 4.11) / 13 = 0 \\ \text{For D: } & (x_D - x_B - 31.77) / 7 + (x_D - x_E - 34.09) / 18 - (x_C - x_D - 4.11) / 13 = 0 \\ \text{For E: } & - (x_F - x_E + 27.02) / 13 - (x_D - x_E - 34.09) / 18 = 0 \\ \text{For F: } & (x_F - x_E + 27.02) / 13 - (x_A - x_F - 9.77) / 7 - (x_B - x_F - 31.98) / 7 = 0 \end{aligned}$$

We must fix the position of one station - let us fix station E to be at the origin. We then discard the penultimate equation above, replacing it with the following:

$$\text{For E: } x_E = 0.00$$

We solve the equations (using a computer, although this example is just about manageable by hand) to get the complete solution.

$$\begin{aligned} x_A &= -17.97m & x_D &= 35.20m \\ x_B &= 3.64m & x_E &= 0.00m \\ x_C &= 39.73m & x_F &= -27.82m \end{aligned}$$

These answers are put back into the last three columns of table 3 above. The Ex and ex for each section is worked out, allowing us to distribute the errors along each section as will be illustrated next.

Solution of Intermediate Stations Positions

Once the vertex station positions have been calculated, it remains to find the positions of the intermediate stations. This is simply done by distributing the misclosure errors back along the traverses. For example, the traverse $A \rightarrow B$ in fig 2 includes intermediate stations 1, 2, etc .., and we would write:

$$\begin{aligned} x_1 &= x_A + \delta x_{A1} + ex_{AB} \\ x_2 &= x_1 + \delta x_{12} + ex_{AB} \\ \text{etc...} \end{aligned}$$

We now have the positions of all the survey stations, and have solved the problem. This method we call the e method.

As an example consider the original traverse A→B shown in fig 2. We already know Δx_{AB} is 21.35m and we have just worked out x_A and x_B to be -17.97m and 3.64m respectively. Hence

$$e_{x_{AB}} = [3.64 - (-17.97) - 21.35]/6 = 0.0437m$$

We can now calculate the positions of stations 1.5 and this is shown in Table 2. The computer algorithm in the next part of the paper does both these steps automatically, without the user needing to break the survey up into traverses.

Notes on the above method

The e values for the traverses give us a check on the validity of the leg data. If the e values are large compared with what we would expect from the survey grade, we can check the data has been correctly input - no legs have been inverted or other errors made. Note that the e values have to be calculated in any case to distribute the errors back along the traverses. One advantage of a computer program is that if we identify some erroneous data we can correct it and run the program again very easily and quickly.

Numbers are kept to four or more places of decimals during the calculation to avoid rounding errors, which might otherwise be larger than the misclosure errors we are trying to distribute. In the last three columns of tables 1 and 3 the figures are rounded to the desired degree of accuracy, and may not tally exactly. The values for misclosure error per leg are given to four places of decimals, again to avoid rounding errors when distributing the misclosures along the traverses.

Looking at equations (1) in detail we see that there are two cases when the reduction of the data is simplified.

Reduction Type 1 - The misclosure error for a traverse that does not form part of a loop is zero, and the position of an intermediate station is found just by adding the individual leg displacements onto the position of the vertex station at the start of the traverse. This is of course just what we would expect.

Reduction Type 2 - For a traverse that forms a simple closed loop, namely both ends are joined to the same vertex station, the e value is found straight from the leg data, and does not involve the position of the vertex station. In this case we find the intermediate station positions by distributing the error around the loop. This justifies what has always been practised by cave surveyors.

We can reduce the volume of data dropping traverses which satisfy the above conditions, and putting them back in again after the positions of the remaining vertex stations have been found.

The volume of data can be further reduced by making use of the following two replacement theorems which can be proved from equations (1).

Replacement Theorem 1 - Two traverses joined at a vertex station, which has no other traverses attached, can be treated as a single traverse. The vertex station becomes an intermediate station whose position is calculated just as for any other

intermediate station. Thus if A→B and B→C shown in fig 4 have $\Delta x_{AB}, n_{AB}$ and $\Delta x_{BC}, n_{BC}$ respectively, we can replace them with a single traverse A→C with $\Delta x_{AC}, n_{AC}$ given by

$$\begin{aligned} \Delta x_{AC} &= \Delta x_{AB} + \Delta x_{BC} \\ n_{AC} &= n_{AB} + n_{BC} \end{aligned} \tag{2a}$$

Station B has a position given by

$$x_B = x_A + \Delta x_{AB} + n_{AB} \cdot e_{x_{AC}} \tag{2b}$$

It has become an intermediate station.

Replacement Theorem 2 - Two different traverses which join the same two vertex stations can be treated as a single traverse joining the two vertex stations. Thus if stations A and B shown in fig 5 are joined by two traverses 1,2 with $\Delta x_1, n_1$ and $\Delta x_2, n_2$ respectively, we can replace them by a single traverse with $\Delta x, n$ given by

$$\begin{aligned} 1/n &= 1/n_1 + 1/n_2 \\ \Delta x/n &= \Delta x_1/n_1 + \Delta x_2/n_2 \end{aligned} \tag{3}$$

Obviously we can apply these replacement theorems (together with the two types of reduction) recursively to treat quite complex networks.

As an illustration of the use of the replacement theorems, consider the simple network in fig 6, together with the data for the traverses. Replacement Theorem 2 tells us we can replace the two routes from B and C by a single one with $\Delta x, n$ given by:

$$\begin{aligned} 1/n &= 1/5 + 1/7 && \text{or } n = 2.92 \\ \Delta x/n &= 12.71/5 + 12.29/7 && \text{or } \Delta x = 12.54m \end{aligned}$$

Now we have the second network shown in fig 6. Using Replacement Theorem 1 on the three traverses A→B, B→C, C→D, we have a second route A→D with $\Delta x, n$ given by

$$\begin{aligned} n &= 5 + 2.92 + 6 && = 13.92 \\ \Delta x &= 3.45 + 12.54 + 13.00 && = 28.99m \end{aligned}$$

We get the third network in fig 6, and can apply Replacement Theorem 2 a second time to get a single route A→D (fourth network).

$$\begin{aligned} 1/n &= 1/18 + 1/13.92 && \text{or } n = 7.85 \\ \Delta x/n &= 28.37/18 + 28.99/13.92 && \text{or } \Delta x = 28.72m \end{aligned}$$

We have done all the replacement we can and have in fact solved the problem. We can now go back and calculate the positions of the stations. Let's take A to be at the origin: $x_A = 0.00m$. Then from the last result obtained $x_D = 28.72m$. The fractional error from A→D along the route containing B and C is

$$e_{x_{A(BC)D}} = [28.72 - 28.99] / 13.92 = -0.0193m$$

Hence for B and C we get

$$\begin{aligned} x_B &= x_A + \Delta x_{AB} + n_{AB} \cdot e_{x_{AC}} \\ &= 0.00 + 3.45 + 5 \times -0.0193 = 3.35m \end{aligned}$$

$$\begin{aligned} x_C &= x_B + \Delta x_{BC} + n_{BC} \cdot e_{x_{AC}} \\ &= 3.35 + 12.54 + 2.92 \times -0.0193 = 15.83m \end{aligned}$$

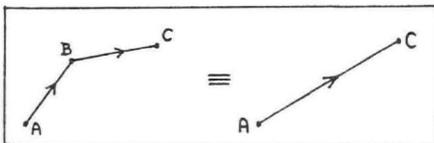


Figure 4 Replacement Theorem 1.

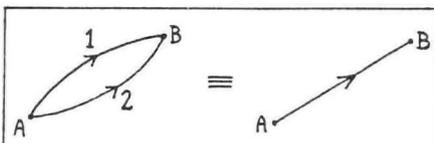


Figure 5 Replacement Theorem 2.

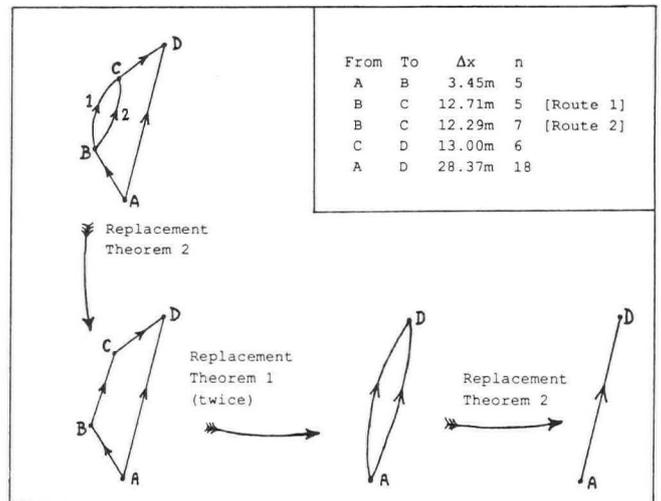


Figure 6 Second example network and its method of solution.

In summary therefore

$$x_A = 0.00m \quad x_B = 3.35m \quad x_C = 15.83m \quad x_D = 28.72m$$

We can calculate the errors back along the various traverses and these are shown in Table 3. Note that in the above work, we used fractional values of n exactly as we use integer values. We could now go on to distribute the errors along the traverses as before.

This set of results enables some networks to be reduced by hand, without trial and error. They are suitable for networks where we have the problem of what to substitute in place of smaller loops on larger loops, and how to distribute the misclosure errors back across these smaller loops. In networks which are not in this simple form, we must resort to equations (1) to solve the problem.

FURTHER RESULTS

Statistical Treatment

There is a justification for least squares based on statistics, which follows from a few assumptions. Firstly we assume that the measurements we make - the leg data - are independent random variables. Secondly we assume they are normally distributed, centred on the true value, and with a standard deviation which represents somehow the accuracy of the measurement. All systematic errors such as compass corrections etc. are supposed to have been taken care of when working out the easting, northing and height changes from the leg data. If we restrict the legs to have the standard deviation, namely they are surveyed to the same standard, then our previous treatment can be applied.

We can be more general and allow the legs to have different standard deviations, in other words the legs are not all surveyed to the same standard. This modifies our equations, but the same breakdown of the survey into traverses is possible. Each traverse is specified as before, except for replacing n by σ^2 , the sum of the squares of the standard deviations for the individual legs. The total error Ex is as before, but the fractional error ex is defined with σ^2 replacing n . It is no longer an error per leg, rather a quantity that measures this error in terms of standard deviation. Traverses are characterised by the stations they join, their direction, and now (x, y, z, σ^2) .

For example the traverse A→B (fig 2) would have a fractional error ex given by the following (σ_{A1} is the standard deviation for the leg A→1, etc.):

$$ex_{AB} = [x_B - x_A - \Delta x_{AB}] / \sigma_{AB}^2$$

where

$$\sigma_{AB}^2 = \sigma_{A1}^2 + \sigma_{12}^2 + \dots + \sigma_{5B}^2$$

We still use the e method, but with the new e in the equations. The error is now distributed back along the traverse weighted appropriately with the square of the standard deviation of the leg in question. Using the previous example shown in fig 2 we would now write:

$$x_1 = x_A + \delta x_{A1} + \sigma_{A1}^2 \cdot ex_{AB}$$
$$x_2 = x_1 + \delta x_{12} + \sigma_{12}^2 \cdot ex_{AB} \quad (4)$$

etc...

The replacement theorems generalise in a similar manner, with σ^2 replacing n in eqns 2a, 2b, 3. This generalised 'e' method means we can now solve completely general networks with different bits surveyed to different standards.

Including Constraints

By this we mean the cave has one or more entrances whose positions are known very accurately, or a part of the cave has been surveyed to a very high degree of accuracy. There are two methods. Firstly we could give the accurate part of the survey a very low standard deviation, so that the rest of the network is bent

onto that part. For more than one entrance, we would have extra legs connecting the entrances, with very low standard deviations, to achieve the desired effect.

For the purist who doesn't like this fix, we can introduce proper constraints into the problem from the start. If they are followed through the algebra, the result is quite simple. If we have a number of fixed stations, we make sure they are treated as vertex stations, and discard the 'e' equations for these stations in (1), replacing them with the constraint equations. (This is just like the way we put the position of the basis station in to fix the survey in space.) The simultaneous equations constraints are now solved exactly as before, but the fixed stations are guaranteed to be at the correct positions, and errors caused by the constraints are distributed according to least squares. The first method is the one used in the algorithm.

A further use

We can get some idea of the statistical relationship between any two stations in the network if we use the generalised e method above. In other words we could estimate the separation, and standard deviation of the separation, for two distant stations (distant in the network that is, not necessarily in space). This is done by introducing a fictitious traverse between the two (of the wrong length), and measuring how the network adjusts to the error introduced. This could be useful where we suspect the two stations separated by lots of passage are really quite close. It would give an error bound on our hopes of a connection! We will not take these fascinating ideas here.

COMPUTATIONAL ASPECTS

Having seen the mathematics involved we have to convert this to a usable computer algorithm in order for it to be any use to any but the keenest mathematicians. The arithmetic required by the technique is drastically reduced, thanks to the extensive rules for reducing the size of the problem (refer to reduction and replacement theorems). The processing power of the computer is therefore less important than would have been the case. The task lends itself very neatly to a recursive solution based on a linked list describing the survey being reduced. These factors determine the computer resources required to solve the task, namely a big memory and a language that can dynamically allocate these memory resources. Luckily this presents no problem for the latest generation of home computers where machines with 0.5 MByte memories sell for under £400. We have implemented this software and tested it with 1000 leg surveys in Pascal on an IBM PC clone which is fairly typical of the power and memory available on modern home computers.

An important factor in the program is the ability to cope with the variability that surveys have: there must be no restriction on number of legs in a traverse or the number of traverses in a

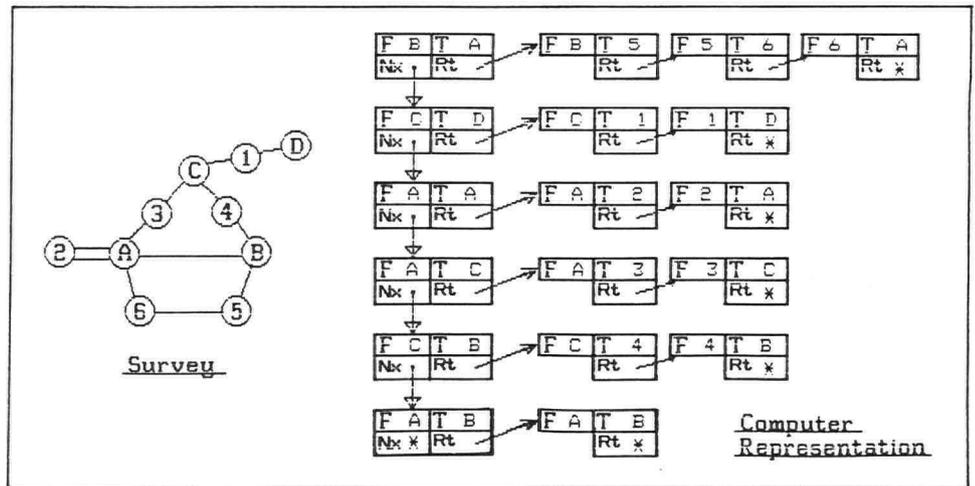
```
a station =
name :name of the station
x,y,z :position in space if known
next :pointer to another station (or Nil if it is the last one)

a leg =
from,to :pointers to stations
δx,δy,δz :Measured difference between to and from
acc :Measure of leg's accuracy (Grade)
next :pointer to another leg

a traverse =
from,to :pointers to stations that are the termini of
the traverse
route :pointer to a list of legs describing the traverse
Δx,Δy,Δz :sum of leg differences between to and from
acc :Measure of traverse's accuracy (Grade)
next :pointer to another traverse
```

Figure 7 Typical data structures to describe all surveys.

Figure 8 A typical survey and how it is represented in the computer.



survey. To do this without having massive redundancy, and thus wasting memory space, memory allocation must be done dynamically. List structures lend themselves well to this sort of implementation and have the flexibility to cope with the reshaping of the survey as the reduction axioms are applied. Using a simple set of structures such as those shown below (Fig 7) we can describe any survey with any number of stations/legs/traverses so long as the total memory required is less than the available space. One such survey and its representation may look like Fig 8.

Once we have the whole survey represented as a list of traverses, application of the reduction axioms becomes easy to implement recursively. An efficient solution to the problem is thus obtained. Route information is unused by this algorithm, so the new legs it creates while reducing the data can have a nil route to minimise the memory and processing requirements. Station positions along the route can be calculated iteratively once this algorithm has terminated, reducing memory demands further. In fact the memory requirements of this algorithm are very low as only pointers to the removed traverses need be stored between recursive steps and only one parameter is required (or type of pointer).

The sketch algorithm in fig 9 will take a survey described using the above data structure and fix the x, y, z position of the ends of all the traverses. Note that a type 1 traverse fits the criteria for Reduction Type 1, and a type 2 fits Reduction Type 2. Similarly type 3 traverses fit Replacement Theorem 1 and type 4 fit Replacement Theorem 2. All that now remains to be done is to fix the positions of the intermediate stations in the traverses. This is of course

```

Solve (Survey) : {
  If (Survey has just 1 traverse) : { Fix termini from Δx,Δy,Δz }
  If (Survey has type 1 traverse) : { Remove it;
    Solve (remaining survey);
    Replace it;
    Fix terminus from Δx,Δy,Δz }
  If (Survey has type 2 traverse) : { Remove it;
    Solve (remaining survey);
    Replace it }
  If (Survey has type 3 traverses) : { Remove them;
    Make new traverse [eqn 2a];
    Solve (remaining survey
      + new traverse);
    Remove new traverse;
    Replace old ones;
    Fix junction [eqn 2b] }
  If (Survey has type 4 traverses) : { Remove them;
    Make new traverse [eqn 3];
    Solve (remaining survey
      + new traverse);
    Remove new traverse;
    Replace old ones }
  Survey cannot be reduced so solve using simultaneous
  equations [eqn 1] }

```

Figure 9 Sketch algorithm for reducing survey data.

```

Passage data collected
Determined traverses and Routes
Reduction type 1
Removing :C-D Acc =2.0 Route = C-1 1-D
Reduction type 2
Removing :A-A Acc =2.0 Route = A-2 2-A
Replacement type 1
Removing :A-C Acc =2.0 Route = A-3 3-C
Removing :C-B Acc =2.0 Route = C-4 4-B
Adding :A-B Acc =4.0
Replacement type 2
Removing :A-B Acc =1.0 Route = A-B
Removing :A-B Acc =4.0
Adding :A-B Acc =0.8
Replacement type 1
Removing :A-B Acc =0.8
Removing :B-A Acc =3.0 Route = B-5 5-6 6-A
Adding :A-A Acc =3.8
Only one traverse. Fix ends.
Removed :A-A
Replacing :B-A
Replacing :A-B
Removed :A-B
Replacing :A-B
Replacing :A-B
Removed :A-B
Replacing :C-B
Replacing :A-C
Replacing :A-A
Replacing :C-D
Calculated Coordinates of Junctions and Ends
Calculated Coordinates of Mid-Passage Stations

```

Figure 10 Output of the program when reducing the example survey.

trivial (given eqn 4) now that we know the positions of the ends and the measured x, y, z's together with their grades. Fig 10 shows the program's output while reducing the example survey.

If you reach a point in reducing the survey where the network cannot be reduced then you are left with no option but to solve the network as a set of simultaneous equations. Again the above structure gives fast access to the information required to build the relevant equations. All the information is held in the traverse nodes so there is no need to search the routes for information. There are many (well documented) ways to solve linear equations on digital computers so all we can do here is point the reader to other work describing such techniques. Given a full survey with no 'hanging' branches the equations obtained must be solvable (i.e. have a real solution), hence any simple algorithm such as described in great detail by Bunday [1984] will do. Alternatively the method we employed involves a network that does not require the set of equations to be solvable, it is described by Press et al [1986]. Here a method of successively

approximating the solutions is described until the square of the error is minimised. As mentioned the memory requirements of this algorithm are low thus enabling large surveys to be reduced in modest computers. The reduction axioms dramatically speed up the computation, our implementation reduces thousand leg surveys in under a minute on an IBM PC clone.

DISCUSSION

The above method as described solves the majority of cases encountered while surveying caves. Outlined below are two cases which the basic method doesn't cater for, they can be accommodated in the general framework.

An enhancement of the program involves the handling of gross errors. Supposing the surveyor missed out a digit in one of the bearing readings making 270 degrees 70 or 27, this would lead to a gross error. The blind algorithm described here is not capable of dealing with such a situation and will distort the whole survey to compensate for the huge misclosure. Obviously such a mistake will be instantly recognisable on the skeleton diagram as it will not match the surveyor's diagram in the note book, the mistake edited in the data file and the points re-computed. However if the mistake is in the 'Length' reading such errors are less easy to recognise. It would of course be a simple task for the computer to question any traverses in which the value of 'e' exceeded a certain limit, say two times the standard deviation.

As it stands the method described above treats all three displacements for each leg as having the same standard deviation. This may not always be the case - for example in a canal passage the gradient readings will be accurate, whereas the compass bearings and length measurements will be to the normal accuracy. This can be overcome by having a separate standard deviation for each leg displacement (x, y, z).

CONCLUSIONS

We have demonstrated that the LSM is capable of reducing any conceivable cave survey data irrespective of grade to give an optimal set of station locations. Whether the survey has been paced or measured with theodolite, mole-phone or even satellite the data can be used without impairing the accuracy of other readings. Since we have also shown that this reduction can be performed by a microcomputer there should be no need now to resort to anything less than a full least squares reduction of your survey data.

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Received March 1988

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Forum

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

THE SEDIMENTOLOGY AND PALYNOLOGY OF SOME POSTGLACIAL DEPOSITS FROM MARBLE ARCH CAVE, CO. FERMANAGH: SOME COMMENTS

Stephen J. GALE and Christopher O. HUNT

Jones' and McKeever's (1987) work on sediments from Marble Arch Cave, County Fermanagh represents a useful addition to the literature on the subject, as well as a further contribution to work in the field of cave palynology. Nevertheless, their assertion that 'The literature on palynological studies (in the cave environment) is remarkably scarce...' (Jones and McKeever, 1987, 4) indicates a lack of familiarity with the considerable amount of work which has been published on this topic. Since much of this work may also be unfamiliar to readers of Cave Science, we have appended a short bibliography of the more important of the >150 papers on cave palynology which are at present known to us.

Although pollen counts from caves are often low, this is more likely to reflect low pollen influxes and dilution by mineral sediment rather than any effect of '...the aggressive cave environment...' (Jones and McKeever, 1987, 4). Much of our experience would suggest that caves are very suitable for the preservation of pollen (Hunt and Gale, 1986). Consideration of the pollen spectra presented by Jones and McKeever (1987) suggests that they have not been biased by the differential destruction of grains that tends to occur in highly oxidising and microbially active environments (Bottema, 1975). In these cases assemblages tend to be dominated by taxa such as *Compositae*, *Pinus* and fern spores, all of which seem to have especially resistant exines (Havinga, 1967, 1971; Bottema, 1975). We should therefore regard the data presented by Jones and McKeever (1987) as a relatively reliable reflection of the pollen influx to Marble Arch Cave, within the limitations of the very low counts made.

Palynology is a valuable but still underused tool for the investigation of cave sediment sequences. We are glad to see it brought to the attention of the readers of Cave Science.

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Received April 1988

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CARLSBAD CAVERN, NEW MEXICO

Trevor D Ford

Until the discoveries of some fairly large chambers in Sarawak and elsewhere, Carlsbad Cavern had long enjoyed the label of "The Largest Cavern in the World" (it would, however, fit three times into Sarawak Chamber). Even though many thousands of visitors go through Carlsbad every year, and several detailed studies have been published, it has remained something of an enigma in its origin and evolution in view of the very limited range of branch passages and owing to its extensive gypsum deposits.

Theories of its origin include that of Bretz (1949) who regarded the vast caverns as due to pre-Pleistocene phreatic solution in an earlier erosion cycle, with the gypsum being derived from Permian strata in the adjacent basin by some unspecified process involving back-up of ponded waters in a Pleistocene vadose zone. Queen (1973) and Queen et al (1977) took an entirely different view, involving wholesale replacement of the Permian reef limestone host by gypsum and solution then removing some of the gypsum to leave the present caverns. Jagnow (1977, 1979) partly followed Bretz's phreatic model but added sulphuric acid derived from adjacent shale pyrite as a solution agent, and thus got his gypsum as a byproduct. Davis (1979) following Egemeier (1973) hypothesised that hydrogen-sulphide-bearing waters via thermal springs reacted with oxygenated waters to produce sulphuric acid which attacked the limestone. Davis suggested that the hydrogen sulphide was derived from adjacent oilfield waters in the nearby Delaware Basin.

In an excellent new monograph "Geology of Carlsbad Cavern and other caves in the Guadalupe Mountains, New Mexico and Texas", Carol Hill (author of *Cave Minerals*) has thoroughly discussed all the evidence and has obviously done a much more thorough examination of all parts of the

caverns than previous writers. Her theory invokes three separate solution stages ranging in date from late Permian to Pliocene. These can be related to different parts of the cavern complex and to special features such as solution breccias, sandstone dyke infills of fissures, alterations to clay minerals, the presence of native sulphur, and to gravel and silt fills of some passages. She has incorporated recent work on uranium-series and electron spin resonance dating and isotope distinction of different sources and generations of calcite "spar" crystals and gypsum. The operation of various processes is related to the regional geology and to denudation in Plio-Pleistocene times, and some comment is made on climatic changes and their implications. Her theory supports some aspects from both Jagnow and Davis in requiring hydrogen sulphide, derived from adjacent oilfield water and gas as an agent both in solution and in the generation of the gypsum and sulphur deposits. She goes further in suggesting that the processes may be related in some circumstances to the origin of "Mississippi-Valley-type" lead-zinc ore deposits, though only future research will decide whether this is realistic. This suggestion raises the question of whether the same process can be in any way responsible for some of our Pennine mineral vein caves. A corollary of her theory is that there may well be other as yet undiscovered Carlsbad Caverns around, either in comparable reef limestone complexes on the margins of oilfield basins, or, more specifically in the Guadalupe Mountains themselves since the known caverns there have only been revealed by chance breaching in the present erosion cycle. She draws attention to two possible comparative caves generated by such processes in Italy and Russia, but there may well be more that have not so far been recognised as having had their genesis in part by acidic attack through hydrogen sulphide in oilfield waters. This also implies that there may be as yet unknown caves deep in the subsurface in oilfield regions still full of oil, and awaiting discovery.

Carol Hill's monograph is beautifully produced with some 30 colour photos and 131 black and white photos and diagrams, plus a wad of 9 folding surveys in the back. Apart from a detailed description of the caves there is a large section on speleothems and cave minerals with analyses of growth mechanisms rarely seen elsewhere. There is a comprehensive bibliography. This book should be on every thinking caver's bookshelf.

Details: Carol Hill "Geology of Carlsbad Cavern and other caves in the Guadalupe Mountains, New Mexico and Texas", 150 pages. Published as Bulletin 117 New Mexico Bureau of Mines and Mineral Resources. Obtainable at US \$15 plus \$5 postage and handling from Louis Devlin, Publications office, New Mexico Bureau of Mines, Campus Station, Socorro, New Mexico 87801, U.S.A.

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PALEOKARST

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Review of *Paleokarst* edited by N.P. James and P.W. Choquette, published by Springer-Verlag, New York, Berlin, London, Heidelberg etc. 1987, 416 pages, and 217 illustrations. ISBN 3-540-96563-7. £53.00.

Paleokarst is a convenient collective term for any features of limestones terranes arising from processes operating in the distant geological past, and not directly related to the present erosion cycle. This compendium book of 18 contributions arose out of the symposium entitled "Paleokarst systems and unconformities - characteristics and significance" convened by the Society of Economic Paleontologists and Mineralogists at Golden, Colorado, in 1985. This brought together for the first time geographers and speleologists studying modern karst regimes, petrologists and geochemists unravelling the details of limestone diagenesis, economic geologists concerned with ore-deposits in subsurface paleokarst and petroleum geologists concerned with the locations of oilfields in "unusual" limestone accumulations related to paleokarst.

The book is in two parts: the first looks at the processes operating today which could produce paleokarstic features, whilst the second is a set of case histories. The first part includes an updated overview from Derek Ford of the origin and nature of solutional cave systems; valuable as this is, it focuses on the caves, while surface landforms and karstic landscapes are discussed only as a basis for the spelean diagnosis. Sangster's chapter on breccia-hosted lead-zinc deposits in carbonate rocks will serve to demonstrate the need to look at our Pennine mineral deposits more thoroughly in the context of karst processes (as has been done recently at Castleton by Butcher and Hedges, 1987). How many of our Pennine cave systems have their origins in ancient ore-deposit-forming paleokarstic processes? The chapter on Neptunian dikes and fissure fills by Pete Smart, Rob Palmer, Fiona Whitaker and Paul Wright takes the results of the studies of the Bahamas Blue Holes and puts them into a paleokarstic scenario, and it raises the question of just how much or how many of our caves, particularly those near coastlines ancient and modern, owe at least part of their form to Blue Hole processes in the past involving enhanced solution at the interfaces between fresh and salt water?

The second half of the book is a set of case-histories arranged in stratigraphic order, with examples drawn from Precambrian to Cretaceous situations. Whilst most of the case-histories are in North America, examples include Southern Spain, and South Wales. Paul Wright's work here has demonstrated that we ignore karstic erosion surfaces in the Carboniferous of South Wales at our peril if we try to explain all the features of Welsh caves by modern processes only.

The production of this book is of the high quality (and price) we expect from Springer-Verlag. If you can afford it, it will be an investment and I feel we shall hear a lot more about paleokarst in years to come.

REFERENCE

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Research Funds and Grants

THE JEFF JEFFERSON RESEARCH FUND

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

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

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

GHAR PARAU FOUNDATION EXPEDITION AWARDS

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

SPORTS COUNCIL GRANT-AID IN SUPPORT OF CAVING EXPEDITIONS ABROAD

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

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

THE E.K. TRATMAN AWARD

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

