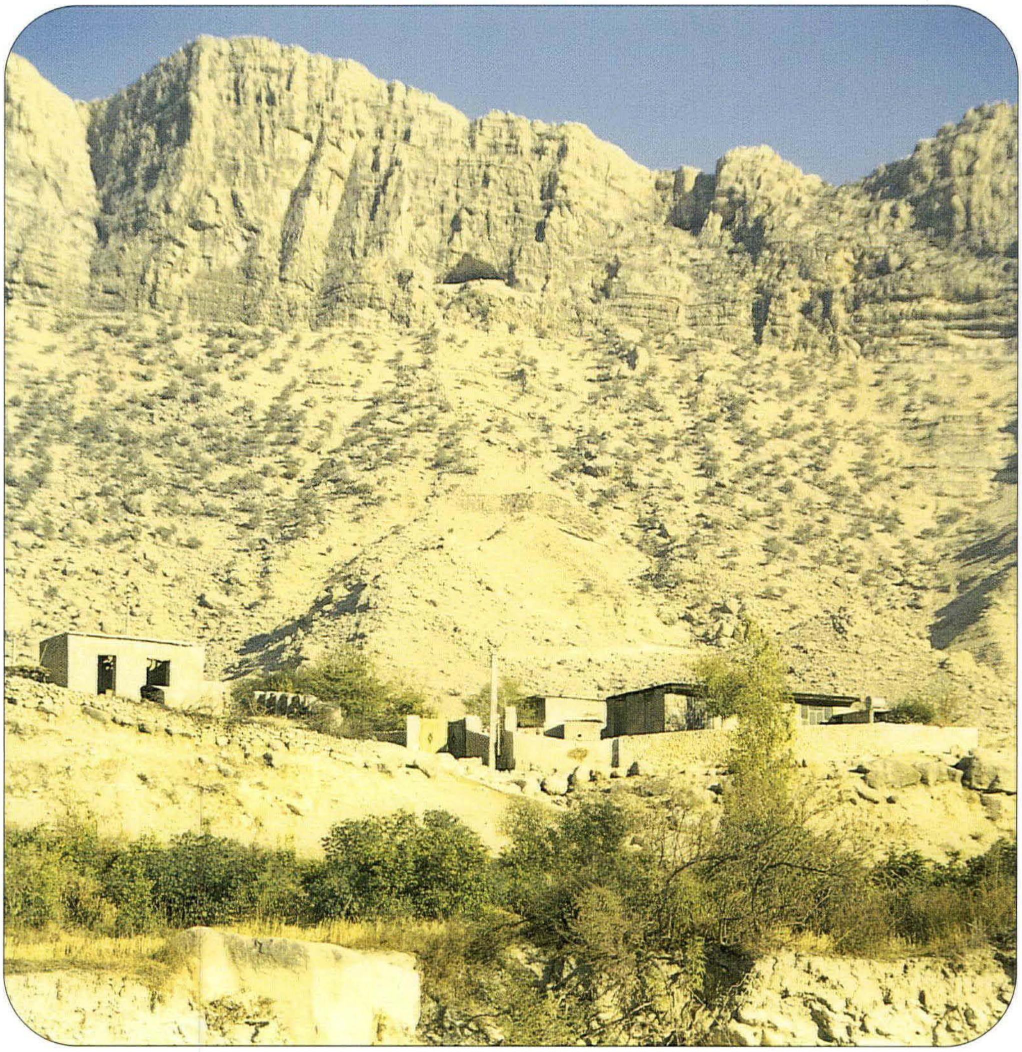
Cave and Karst Science

The Transactions of the British Cave Research Association

BCRA

Volume 24 Number 1 April 1997



Cave and Karst Science

Authors are encouraged to submit articles for publication in the Transactions of the British Cave Research Association under four broad headings:

1. Mainstream Articles
Scientific papers, normally up to 6,000 words, on any aspect of karst/speleological science, including archaeology, biology, chemistry, conservation, geology, geomorphology, history, hydrology and physics. Papers should be of a high standard and will be subject to peer review by two referees.

2. Development Articles
Shorter papers, normally 500-3,000 words, on aspects of karst/speleological science listed above, or more descriptive material such as caving expedition reports and technical articles. These will be reviewed by the editorial board unless the subject matter is outside their fields of expertise, in which case appropriate expert assessment will be sought.

3. Forum
Personal statements of up to 1,000 words on topical issues; discussion of published papers and book reviews. Statements should put forward an argument and make a case, backed-up by examples used as evidence.

4. Abstracts
Authors (or supervisors) of undergraduate or postgraduate dissertations on cave/karst themes are asked to submit abstracts for publication. Please indicate whether the thesis is available on inter-library loan. Abstracts of papers presented at BCRA and related conferences or symposia will also be published.

Manuscripts may be sent to either of the Editors: Dr. D J Lowe, British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK, and Professor J Gunn, Limestone Research Group, Department of Geographical and Environmental Sciences, The University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, UK. Intending authors are welcome to contact the Editors, who will be pleased to advise on manuscript preparation.

Notes for Contributors

These notes are intended to help the authors to prepare their material in the most advantageous way so as to expedite publication and to reduce both their own and editorial labour. It saves a lot of time if the rules below are followed.

All material should be presented in a format as close as possible to that of *Cave and Karst Science* since 1994. Text should be typed double-spaced on one side of the paper only. Subheadings within an article should follow the system used in *Cave and Karst Science*; a system of primary, secondary and if necessary, tertiary subheadings should be clearly indicated.

Abstract: All material should be accompanied by an abstract stating the essential results of the investigation for use by abstracting, library and other services. The abstract may also be published in *Caves and Caving*.

References to previously published work should be given in the standard format used in *Cave and Karst Science*. In the text the statement referred to should be followed by the relevant author's name and date (and page number, if appropriate) in brackets. Thus: (Smith, 1969, p.42). All such references cited in the text should be given in full, in alphabetical order, at the end. Thus: Smith, D.E., 1969. The speleogenesis of the Cavern Hole. Bulletin Yorkshire Caving Assoc., Vol. 7. p.1-63. Books should be cited by the author, date, title, publisher and where published. Periodical titles should be abbreviated in standard style, or, where doubt exists, should be written out in full.

Acknowledgements: Anyone who has given a grant or helped with the investigation, or with the preparation of the article, should be acknowledged briefly. Contributors in universities and other institutions are reminded that grants towards the cost of publication may be available and they should make the appropriate enquiries as early as possible. Expedition budgets should include an element to help publication, and the editor should be informed at the time of submission.

Figures: Line diagrams and drawings must be in black ink on either clean white paper or card, or on tracing paper or such materials as Kodatrace. Anaemic grey ink and pencil will not reproduce! Illustrations should be designed to make maximum use of page space. Maps must have bar scales only. If photo-reduction is contemplated all lines and letters must be large and thick enough to allow for their reduction. Letters must be done by stencil, Letraset or similar methods, not handwritten. Diagrams should be numbered in sequences as figures, and referred to in the text, where necessary, by inserting (Fig. 1) etc. in brackets. A full list of figure captions should be submitted on a separate sheet.

Photographic plates are welcome. They must be good clear black and white prints, with sharp focus and not too much contrast; prints about 15 x 10 cm (6 x 4 inches) are best; if in doubt, a selection may be submitted. They should be numbered in sequence but not referred to in the text, except where essential and then after discussion with one of the Editors. A full list of plate captions, with photographer credits where relevant, should be submitted on a separate sheet.

Tables: These should not be included in the text but should be typed, or clearly handwritten, on separate sheets. They should be numbered in sequence, and a list of captions, if necessary, should be submitted on a separate sheet.

Approximate locations for tables, plates and figures should be marked in pencil in the manuscript margins.

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Speleological expeditions have a moral obligation to produce reports (contractual in the case of recipients of awards from the Ghar Parau Foundation). These should be concise and cover the results of the expedition as soon as possible after the return from overseas, so that later expeditions are informed for their planning. Personal anecdotes should be kept to a minimum, but useful advice such as location of food supplies, medical services, etc. may be included, normally as a series of appendices.

Authors will be provided with 20 reprints of their own contribution, free of charge, for their own private use.

We prefer articles to be submitted on disk if possible, although paper copy is also acceptable. We can read most PC based word processing packages but if in doubt please consult one of the Editors. Apple Mac disks are accepted as a last resort!

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

Cave and Karst Science

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

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Cover photo:
North-western cliff of the Chowgan Valley, Iran
Photo by Dr Ezzatollah Raeisi (see article by Raeisi and Kowsar)
The Dashtak Anticline, one of a series of magnificently exposed fold structures in southern Iran, has been cut through by the Shahpour River, forming cliffs within a thick carbonate sequence above the Chowgan Valley. Viewed from river level, the impressive north-western cliff is made more spectacular by exposing the entrances to Shahpour Cave.

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Cave and Karst Science is published three times a year by the British Cave Research Association and is issued free to all paid up members of the Association.
The 1997 subscription rate to Cave and Karst Science is £16.00 per annum (postage paid).
Individual copies, back issues and details of annual subscriptions to Cave and Karst Science, and of Association membership, can be obtained from the BCRA General Administrator, 20 Woodland Avenue, Westonzoyland, Bridgwater TA7 OLG.
The Association's permanent address is: BCM BCRA, London WC1N 3XX.

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ISSN 1356-191X

EDITORIAL

David Lowe and John Gunn

The last two *Cave and Karst Science* editorials have included discussion of how best to disseminate information about cave and karst science, in its broadest sense. When compared to the minimal feedback that had been received about our own efforts during the previous two years, the correspondence concerning some of the points raised has been encouraging, as well as very interesting. Observations and suggestions continue to arrive, by word of mouth, by letter and by electronic mail, from all over the world. Rather than simply filing these away after either acting upon them or ignoring them, we have decided that we will publish the edited highlights. It might not be possible in the short term to revolutionise the ways that cavers and cave scientists share information, but if interested parties are made aware of how others are thinking, the way may be opened for dramatic - or less dramatic - evolution in the future.

One initiative that fits broadly with at least some of the ideas that were raised in the editorial of Volume 23 Number 2 has already begun. We have agreed to a trial arrangement whereby the abstracts of papers appearing in *Cave and Karst Science* will also be printed in the magazine *Karstologia* and, reciprocally, abstracts from *Karstologia* will appear (in English) in *Cave and Karst Science*. This issue of *Cave and Karst Science* includes the first set of these abstracts, which relate to papers that appeared in the latest issue of *Karstologia* (Number 28). In the future it may be possible to build similar reciprocal agreements with other leading cave and karst publications, providing a means of informing our readership about what is appearing elsewhere.

Arguably for those who maintain an interest in the study of caves and karst, and also for those who are only just beginning to develop such interests, it is important to know what has been written in the past, as well as about what is appearing now. Many past papers remain of great value and/or interest, whether this be scientific or simply historical. In some cases they provide permanent records of observations that have not yet been, or will not be, repeated. Others provide information about earlier ideas that might or might not have stood the test of time, or might have been a step in the evolutionary growth of today's theories. The world of scientific publications includes a wealth of indexes of one sort or another, some available as hard-copy and others via a variety of digital media. A relatively new index, of specific value to those with a broad interest in caves and karst, is the *"Combined Indexes Volume"*, published by the *British Cave Research Association* under the *Cave Science* banner late in 1996. Compiled by Pete Cousins and Graham Mullan, this volume provides a complete index to the 20 volumes of the *Transactions of the British Cave Research Association* that appeared between 1974 and 1994, under the title of *Cave Science* from 1980. Equally important, the volume includes an index to volumes 1 to 15 of the *Transactions of the Cave Research Group of Great Britain*, which were published between 1948 and 1973. Copies of this invaluable index are available from the BCRA Administrator, Bryan Ellis (at the address on the inside back cover), at a cost of £1-00 (BCRA members) or £3-00 (non-members).

A currently topical area of discussion, touched upon in earlier issues, centres upon the definition of "karst". As commonly happens in all branches of science, there seems to have been a resurgence of interest in this topic from several directions more or less simultaneously, only some of which has been reported in *Cave and Karst Science.* Outside the sphere of *Cave and Karst Science,* significant thoughts on the definition of karst in general will be published soon, including ideas developed by the well-known Ukrainian karstologist Alexander Klimchouk. These ideas, together with those of other leading scientists from around the world, should appear later this year, hopefully before the International Speleological Congress, as part of a much broader publication describing the many aspects of *"Gypsum Karst of the World"*. This will form a special edition of the *International Journal of Speleology.* Following publication of a controversial paper on differentiating karst and pseudokarst, written by Charlie Self and Graham Mullan, in *Cave and Karst Science* Volume 23 Number 2, a variety of correspondence and short papers on aspects of the karst definition question, has been received from around the world. The one thing so far lacking in all of this is any feeling of overall "agreement", even about whether or not it really matters! However, it obviously matters to some workers and, even though it will pre-empt the suggestions of Alexander Klimchouk and his colleagues, the contributions that have been received in response to the Self/Mullan paper will hopefully be published in the next issue of *Cave and Karst Science.*

As we were putting the finishing touches to this issue we heard the sad news of the death of one of Britain's best known and respected cave diving scientists, Rob Palmer. Rob was a pioneer of deep, long-duration diving, and was the author of *An Introduction to Technical Diving* (1994). Over the years he was involved in several major exploratory dives in Britain and Ireland, but will probably be best remembered for his innovative work on the tropical sea caves of the Bahamas. Besides writing two books on this fascinating subject (*The Blue Holes of the Bahamas* in 1985 and *Deep into the Blue Holes* in 1989), he edited a special issue of *Cave Science* (Volume 11, Number 1, 1984) entitled *'Bahamas Blue Holes 1981-1982'*. Some of Rob's close colleagues and collaborators have suggested that it would be a fitting memorial to his outstanding contributions to caving and cave science if another Special Issue of *Cave and Karst Science* could be compiled and published to honour his achievements. We are hopeful that this will be possible.

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Transactions of the British Cave Research Association

The development of the Derwent Gorge and its caves at Matlock, Derbyshire: A review

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Abstract: The River Derwent is thought to have been superimposed from the Mio-Pliocene Brassington Formation onto a partly eroded Millstone Grit surface, and thence onto the underlying Carboniferous Limestone. As the limestone was exposed by erosion, a system of phreatic caves developed in the hydrological compartment between two impermeable lava flows. Outwash sediments filling these cave systems appear to relate to an Early Pleistocene glacial episode. Later glaciation(s) yielded firstly a high-level plateau till, and a later terrace till of probable "Wolstonian" age. The Gorge was incised during the interval between these two glacial episodes and uniclinal shift was blocked by the upstanding reef of High Tor. The Gorge today is effectively an elongate nick point in the thalweg of the River Derwent.

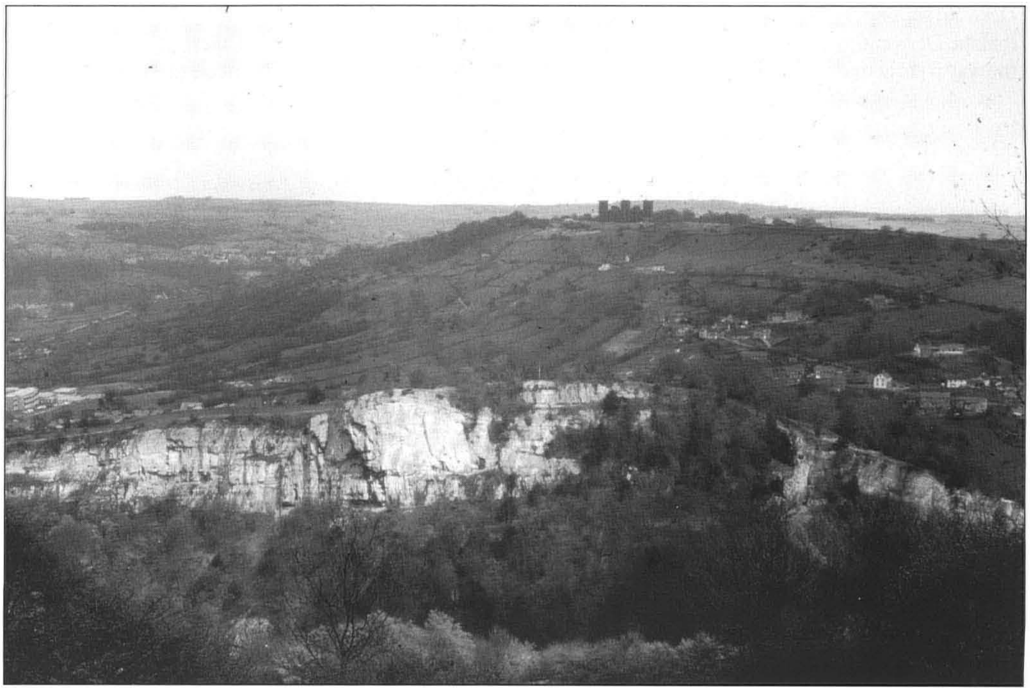
INTRODUCTION

The River Derwent flows southwards through a scenic limestone gorge for 3.5km between Matlock and Cromford. This karstic gorge, incised more than 200m below the surrounding summit levels, is anomalous. The river has a wide floodplain with meanders upstream of the gorge around Darley Dale, and a moderately wide floodplain downstream of Cromford to the south, but the intervening gorge is narrow and the river in this section has a steeper gradient. The River Derwent is at about 92m OD at Matlock and 81m OD at Cromford, giving a fall of 11m in 3.5km. The Gorge has a pattern of incised meanders and is markedly asymmetrical in cross-section. The western slopes are sub-parallel to the dip of the limestones and their interleaved lavas, whilst near-vertical cliffs line the eastern side. Around High Tor these are partly aligned along a mineral vein, but elsewhere the Gorge crosses veins without any distinctive features having formed. The stretches of floodplain to the north and south of the Gorge are floored by Namurian Edale Shales, which are only weakly resistant to erosion. Logically the river should have developed its course to the east of Matlock by staying on the outcrop of the Edale Shales down dip of the Gorge, but instead the river took a different course and has been incised across the anticline that plunges eastwards from Masson Hill. Both the reef structure and the numerous caves within its walls have contributed to the development of this anomalous limestone gorge, though, surprisingly, no comprehensive analysis of its development appears to have been attempted.

The purpose of this contribution is to re-examine the available evidence, and propose a geological history for the Derwent Gorge.

PREVIOUS RESEARCH

Many writers have commented that the Derwent Gorge probably resulted from superimposition from an overlying surface. In the pioneering years of geological science, at a time when the idea of erosional histories was unknown, Whitehurst (1778, 1786) published sections across the Gorge, showing a "gulf" full of angular boulders beneath the river, by which he misinterpreted the depth of what we should now know as bouldery alluvium (Fig.1). Whitehurst thought the two walls of the Gorge had been torn apart and cited evidence that the dip of the strata did not match across the Gorge; in fact it does. John Farey (1808, 1811) realized that former covering strata had been "denudated", not torn apart. Instead he invoked catastrophic upheaval of blocks of country along faults as a partial explanation for the inclined strata. He did not discuss the application of his denudation concept directly to the Derwent Gorge but gave a section to show the continuity of the lower strata across the Gorge and the "denudated" ends of the upper strata on the east side only (Fig.2). White Watson (1813) rebutted Farey's concept of catastrophic upheaval along faults, by pointing out the nature of the "bassets" (outcrops) of successive strata (now known as stratigraphical contacts), some of which were unconformities. He also proposed volcanic causes from within the Earth as the mechanism for uplift.



View eastwards across the Derwent Gorge from Masson Hill. High Tor in the centre with the shale hollow behind and the scarp of the Ashover Grit crowned by Riber Castle.

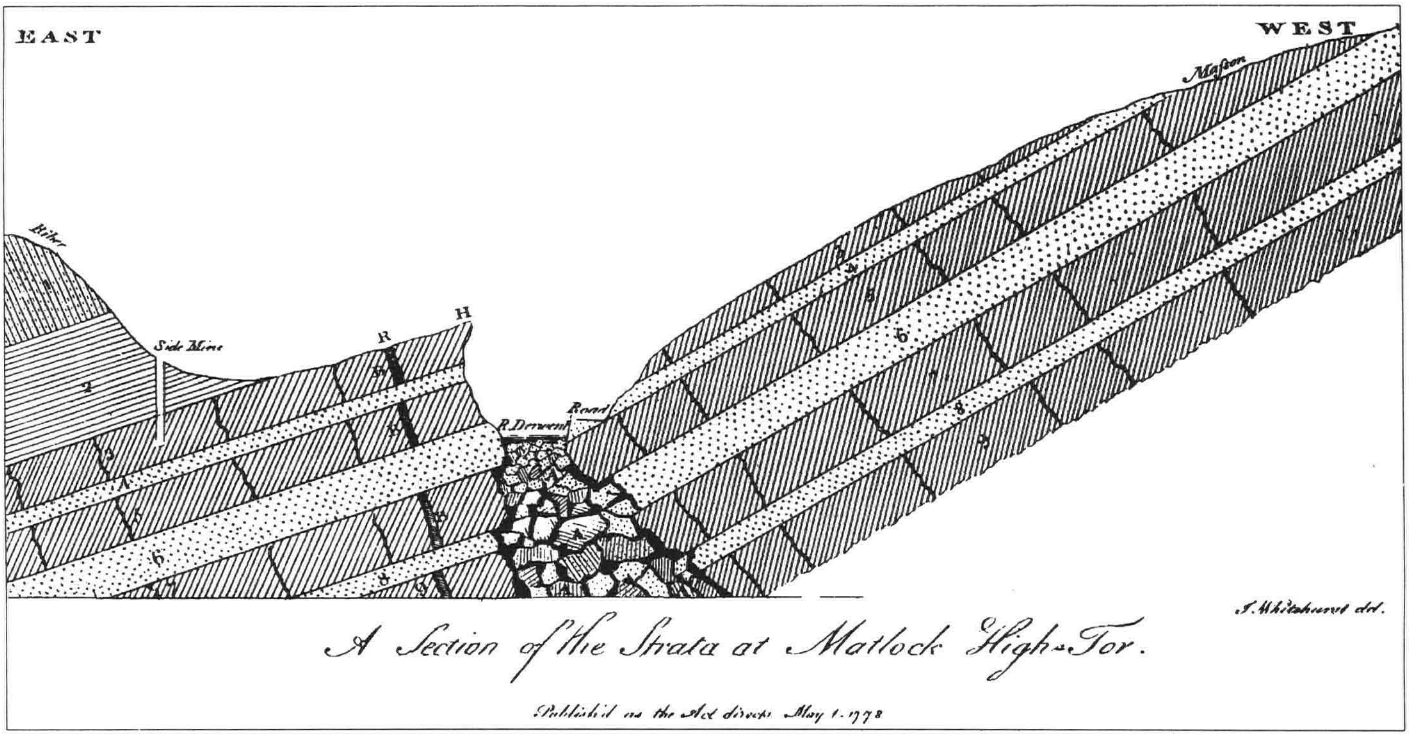


Figure 1. John Whitehurst's (1778) section across the Derwent Gorge, showing different dips on the two sides and the "gulf" full of boulders beneath the river bed. Beds 3, 5, 7 and 9 are limestones; 4, 6 and 8 are lavas. Drawn facing south.

Later writers were more concerned with the whole River Derwent and its possible superimposition from some hypothetical "Upland Surface". In an early Geological Survey Memoir, Green (1887) was of the opinion that the river had been superimposed from a cover of unspecified Mesozoic or Tertiary strata. Fearnsides (1932) thought that the Derwent had been incised from a former cover of Triassic sedimentary rocks, which indeed crop out only some 10-15km to the south and east, though at a lower altitude. Superimposition from a former Triassic cover was again put forward by Kent (1957), who regarded the silica sand deposits around Brassington as Triassic relics related to a surface 1,000ft (about 300m) above sea level. Linton (1951, 1956) examined hypothetical ancient drainage patterns on a theoretical Chalk surface, at a time when working out denudational histories from drainage was very much in vogue. He changed his opinions somewhat between the two publications as to whether the Derwent was a subsequent tributary of a consequent proto-Trent flowing down an eastward-dipping surface or a consequent proto-Derwent superimposed from a southerly-dipping surface. He emphasized that the Derwent's course could not be a "normal subsequent" because of the way it cut across folds such as that at Matlock. Though more concerned with the Ashover area, some 4km ENE of the Derwent Gorge, Clayton (1968) provided small-scale structure and geomorphological maps of much of the Derwent and also suggested that uniclinal shift had been important in places. Doornkamp (1971) noted that the 1,000ft surface was one of planation, as it was present on limestone and Millstone Grit alike. Without discussing the evidence, he suggested that the planation could have been in the Miocene or Pliocene. Though long regarded as Triassic relics, localised pocket deposits of silica sand sediment were shown to be Mio-Pliocene relics and were named the Brassington Formation by Walsh et al (1972). These sediments are largely redeposited Triassic material, but contain fossil plants of Mio-Pliocene age. Walsh et al (1972) deduced that it was very likely that the Brassington Formation once extended over the whole Matlock area as a Mio-Pliocene cover. Today the nearest outcrops of pebbly sands and clays of the Brassington Formation to the Derwent Gorge are found in dissolution/collapse structures some 5km southwest of Cromford (Walsh et al, 1972; Ford, 1977).

In their studies of the terrace sequences along the Derwent Valley, Johnson (1957) and Waters and Johnson (1958) made no deductions

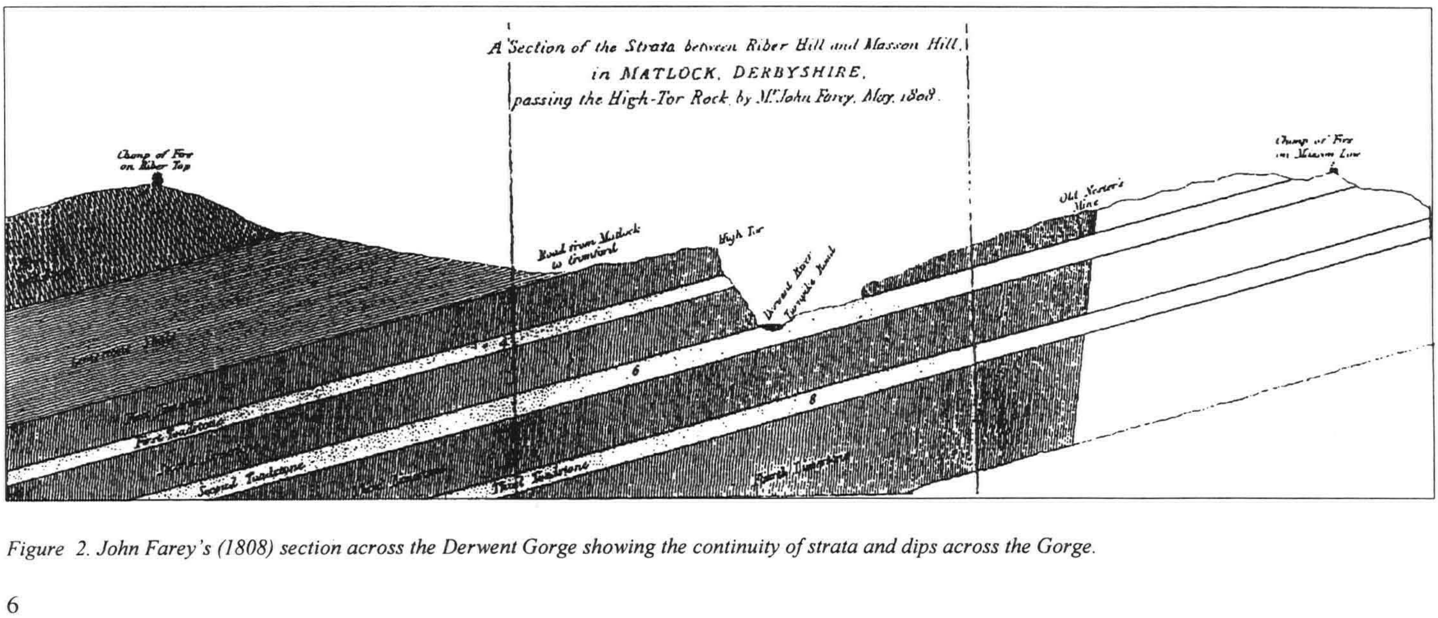
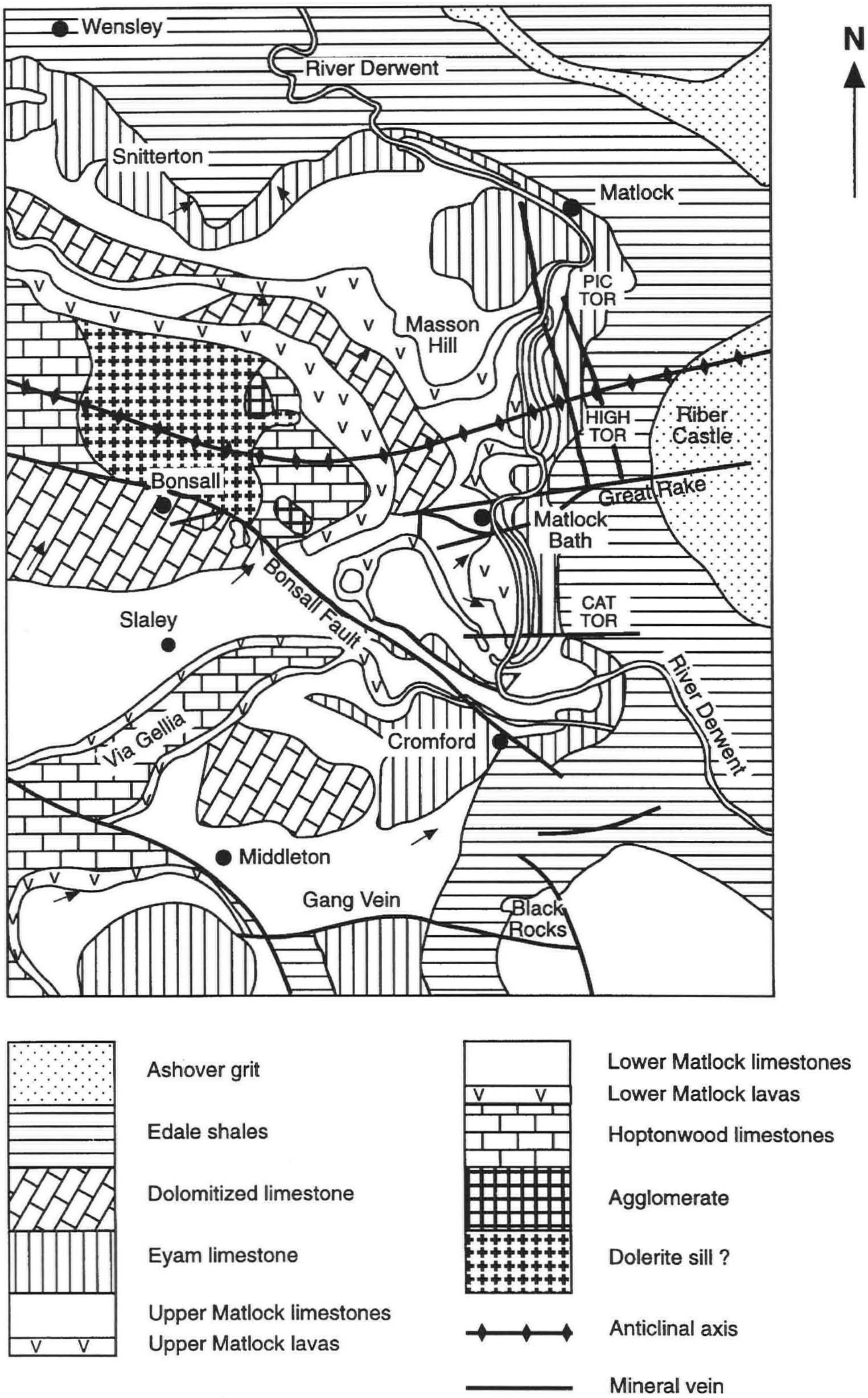


Figure 2. John Farey's (1808) section across the Derwent Gorge showing the continuity of strata and dips across the Gorge.

Figure 3. Geological sketch map of the area around the Derwent Gorge at Matlock.



about the nature of the former cover, but argued the case for vertical downcutting of the Gorge, and noted how in effect it formed a nick-point holding up adjustment of the river's upstream thalweg to deeper incision downstream of Cromford. Doornkamp (1971) argued briefly that vertical incision did not take place until after the development of the 1,000ft planation surface, which might have been early in the Pleistocene. Prior to this there had been a general eastward down-dip migration of the river's course by uniclinal shift as the Millstone Grit escarpments receded. Ford and Burek (1976) suggested that, following vertical downcutting through the Edale Shales, when the river reached the top of the limestone there was uniclinal shift eastwards down-dip. The shift was then blocked by the upstanding reefs in the highest beds of limestone, such as High Tor, trapping the river in a hollow on the limestone surface. Vertical incision into the limestone ensued, yielding the present gorge.

Glacial diversion of drainage was suggested as a mechanism for at least part of the Derwent's course by Wedd (1905, and in Gibson and Wedd, 1913), though it was far from clear whence the river had been diverted or where the glacier lay. An ice blockage in Wensley Dale, north of Masson Hill, was proposed in the discussion, though with no clear evidence as to where it lay. The later Geological Survey Memoir (Smith et al, 1967), however, noted that the drainage pattern must have been established before glaciation, as there is till on terraces only some 50m above river level both upstream and downstream of the Derwent Gorge. Smith et al (1967) also noted that the Gorge is not entirely in limestone but also cuts through two sheets of basaltic lava (known locally as toadstone).

None of the above literature took the cave systems or their sediments into account in looking at the Derwent's anomalous course through the Gorge.

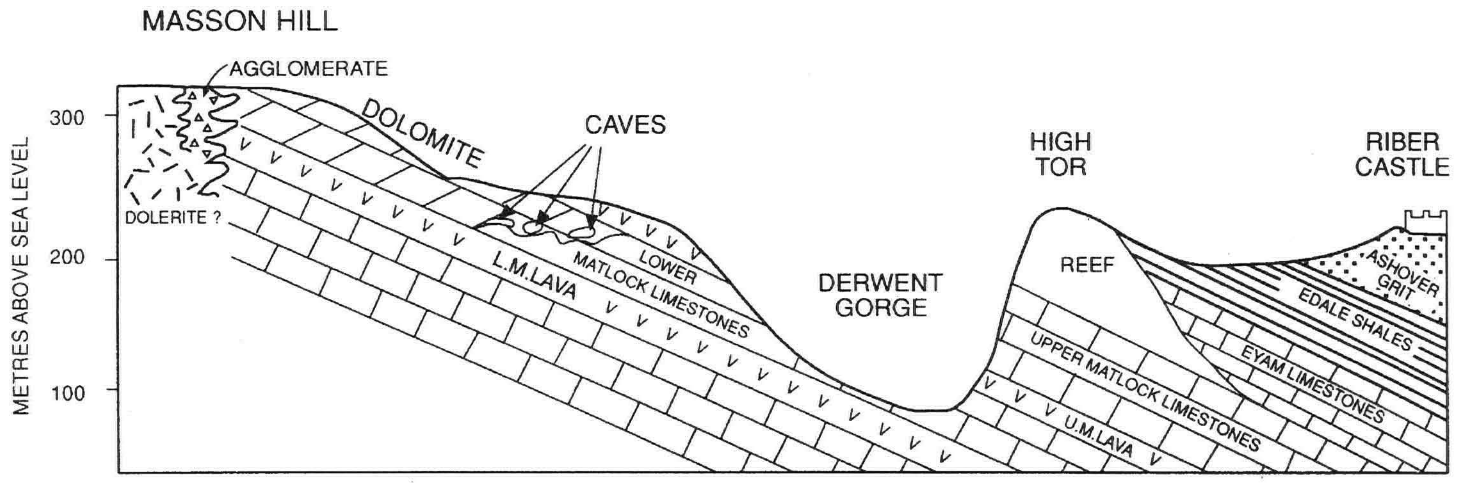


Figure 4. Section across the Derwent Gorge showing the relationships of limestones, a reef, lavas, dolomite and caves. Drawn facing north.

A polyphase evolution, with the final stages requiring a high water table, was recognized by Worley and Nash (1977) in their study of Jug Holes. Noel et al (1984) and Noel (1987) used palaeomagnetic evidence to date sediments in the Masson Cave system and to suggest how the cave systems might have been significant in the early Pleistocene. The caves were developed then by "pirating" a Late Carboniferous hydrothermal palaeokarst (Ford and Worley, 1977; Waltham et al, 1996). They also noted that the caves were in limestones that constituted a hydrological compartment between impervious lavas.

GEOLOGICAL SITUATION

The sequence of Carboniferous strata in the Matlock area has been described by Smith et al (1967) and by Cox and Harrison (1980). It totals some 500m, with the base not exposed. Details of the relevant subdivisions are given in Table 1.

The distribution of rock outcrops is shown in Figure 3, and a diagrammatic section across the Gorge is shown in Figure 4.

The Hoptonwood Limestones (also known as Bee Low Limestones farther north) underlie the whole area but crop out only to the west of the summit of Masson Hill, in the core of the Masson anticline, and in the floor of the Via Gellia valley, 1-2km west of Cromford. The Lower and Upper Matlock limestones together are about 130m thick and they form most of Masson Hill and the walls of the Derwent Gorge. They include two interlayered contemporary basaltic lava flows, each around 50m thick: the Lower Matlock Lava is at the base and the Upper Matlock Lava some 35m higher, overlying the Lower Matlock Limestones. Both the Lower and Upper Matlock limestones are also characterized by sporadic thin "wayboards" - clay-like tuff horizons a few centimetres thick. Both the lavas and the wayboards act as partial aquicludes. Capping the limestone sequence are the Eyam Limestones (previously known as the Cawdor Limestones in this area), cropping out mainly in the highest parts of the cliffs east of the Gorge. They are variable in lithology and their thickness ranges from 30 to 50m. Reefs or mud-mounds, such as High Tor, Pic Tor and Cat Tor, separated by inter-reef bioclastic limestones, are seen to pass laterally into thin muddy limestones and shales in Cawdor Quarry, northwest of Matlock. Some evidence of contemporary palaeokarst surfaces has been found in the Matlock and Eyam limestones in the Wirksworth and Via Gellia areas, and such palaeokarst may well have developed throughout the Matlock area, though now being masked locally by later dolomitization and mineralization.

The summit of Masson Hill is marked by the outcrop of the doleritic Bonsall Sill, about 1km^2 in area. The dolerite appears to be in contact with the Lower Lava, but exposure is sparse. With small patches of agglomerate nearby, the dolerite has usually been regarded as a sill (Smith et al, 1967; Walters and Ineson, 1981) but as its margins are poorly exposed, and boreholes have failed to reach its base at depths of up to 55m, it may well be a plug in the core of a late Dinantian volcano. Whether it represents part

Sub-system	Series	Stage	Rock units
Silesian	Westphalian	Various	Coal Measures
	Namurian	Various	Rough Rock and various thin sandstones and shales Ashover Grit Edale Shales
Dinantian	Viséan	Brigantian	Eyam (=Cawdor) Limestones Upper Matlock Limestones and Dolomite Upper Matlock Lava Lower Matlock Limestones and Dolomite Lower Matlock Lava
		Asbian	Hoptonwood (=Bee Low) Limestones
		older beds not exposed	

Table 1. Geological sequence of Carboniferous strata in the Matlock area.

of a feeder system for the Matlock lavas is also debatable. Some silicification of the limestones is visible adjacent to mineral veins, where they intersect the volcanic rocks.

The lowermost beds of the Millstone Grit Group, the Edale Shales, are greatly reduced in thickness across the Masson anticline. The shales are overlain by the massive coarse-grained deltaic sandstones of the Ashover Grit, followed in turn by a sequence of shales alternating with higher sandstones, including the Chatsworth Grit and Rough Rock. Some 6km east of Matlock the edge of the Coal Measures flanks the eastern margins of the Ashover and Crich anticlines. Beyond the coalfield to the east is the scarp of the Permian Magnesian Limestone and farther east still is the margin of the Triassic Sherwood Sandstone Group. Projection of their current geometry westwards suggests that extensions of both of these divisions could have passed over the Matlock area at one time.

The Carboniferous strata are folded into the Masson anticline, which had started to develop in late Dinantian times, as is shown by facies changes in the Eyam Limestones and by the thinning of the Edale Shales. The axis may then have been horizontal, the present eastward plunge being related to the post-Carboniferous inversion of the Pennine basin. The anticline now plunges eastwards at about 10-15°. Dips on its northern flank are about 20-30° towards the north, swinging round to around 10-15° across the gorge. The southern flank of the anticline is accentuated by a local increase of dip to about 45° towards the south along the Great Rake fault, followed by a slackening to 10-20°, still towards the south. The subsidiary and weaker Upperwood-Willersley anticline plunges eastwards across the gorge south of Matlock Bath. The limestones disappear beneath the Edale Shales southeast of Cromford, but to the southwest the limestone sequence is dropped down by the NW-SE Bonsall Fault system. To the southwest of this is a shallow syncline along the Via Gellia, beyond which the limestones rise again in the Bole Hill anticline between Cromford and Wirksworth.

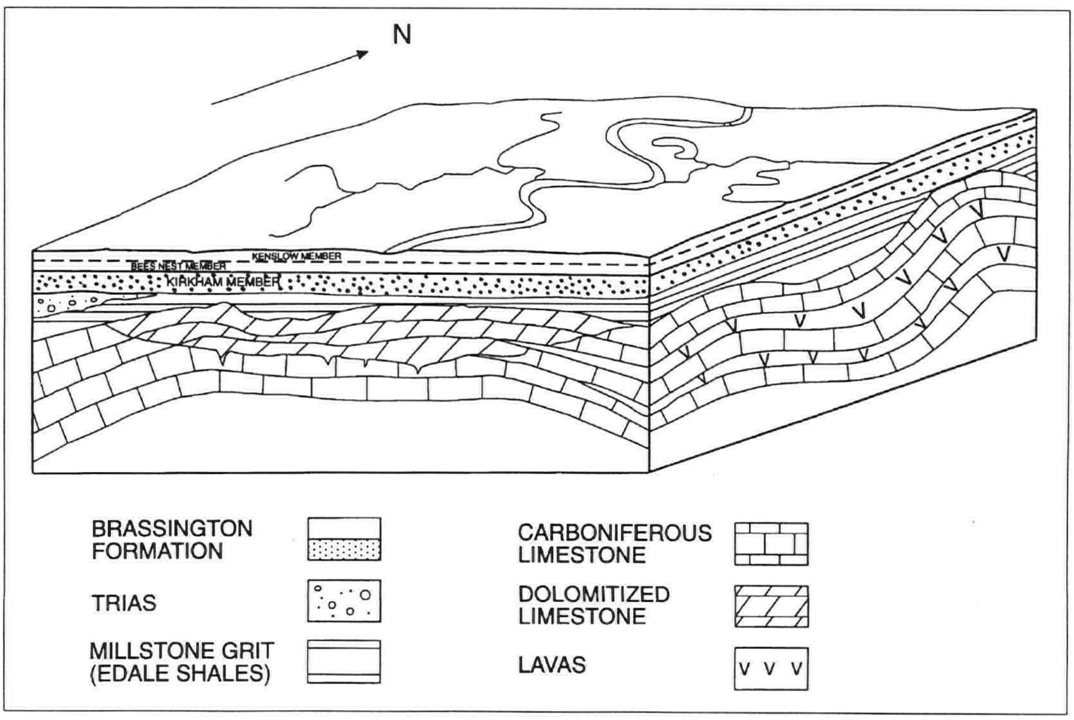
Part of the limestone sequence over some of the area underwent subsequent dolomitization (Cox and Harrison, 1980). The long-accepted concept that this was due to sub-surface penetration of Late Permian brines is now less certain, as dolomitization preceded mineralization and that is now regarded as having climaxed in late Carboniferous times. Dolomitization may thus be due to an early phase of mineralization. Much of the summit area of Masson Hill is composed of partially dolomitized limestones of both the Matlock and Cawdor formations. Down-dip penetration of dolomitization occurs in the Lower Matlock Limestones between the two lavas, but similar penetration down-dip in the Upper Matlock Limestones is less obvious. Both mineralization and caves are concentrated at or near the base of the dolomitized zone (Ford and Worley, 1977; Waltham et al, 1996). Unaltered limestones lie beneath the dolomitized rock wherever the sequence can be seen.

The limestones are host to a swarm of nearly vertical mineral veins containing galena, sphalerite, fluorite, baryte and calcite. There are many small "scrin" veins with NW-SE or NE-SW trends, crossed by major E-W "rakes" and a few N-S veins (Flindall and Hayes, 1972, 1973, 1976; Warriner et al, 1981). There is also a variety of pipe veins filling or lining palaeokarstic cavities, and flat veins along bedding partings, as well as scattered replacement deposits. Pipes, flats and replacements commonly follow wayboard horizons and have a general NW-SE trend. Mineralization is generally regarded as having occurred at about the end of the Carboniferous Period. Some of the pipe veins are effectively fills of a palaeokarst cavity system of Mid to Late Carboniferous age (Ford, 1984).

THE BRASSINGTON FORMATION

Still regarded as Triassic relics at the time of Linton's (1956) and Waters and Johnson's (1958) researches, the significance of this Neogene formation was completely overlooked. Some 5km west of the Derwent Gorge are the easternmost of a series of silica sand pockets, ranging for some 15km in a northwesterly direction towards Parsley Hay. The infillings of sand and clay make up the Brassington Formation, determined as being of Mio-Pliocene age by the fossil plants found in the Kenslow Member (Walsh et al, 1972; Ford, 1977). Though now preserved only in dissolution/collapse structures, the Brassington Formation was once a fluvial sheet lying across the entire limestone plateau and on relics of the Millstone Grit (Fig.5). The sands, and many included purple quartzite pebbles (formerly known as Bunter pebbles), were derived from the Triassic Sherwood Sandstone Group outcrop, which now lies at a lower altitude to the south, and this prompted Walsh et al (1972) to argue that there must have been considerable uplift of the plateau since their deposition, i.e. in Pliocene times. The effect of such uplift would be to accentuate the plunge of the Masson anticline. The sheet of sands and clays probably relates to an ancient river system that flowed eastwards, and it is tempting to regard this as the ancestral river system proposed by Linton (1951, 1956). The dissolution/collapse structures could have developed later, but the cover of till shows that they were formed before the Anglian glaciation. Some hydrological gradient must have been present to effect dissolution in the limestone. Underground flow was perhaps towards springs in fore-runners of the present valleys, perhaps in early Pleistocene times.

Figure 5. Block diagram of the Brassington Formation lying unconformably on folded Edale Shales and Carboniferous Limestone (some dolomitized) and on a relic of the Triassic Sherwood Sandstone Group. A river system drained off the Brassington Formation in Pliocene times (modified from Walsh et al, 1972).



DRAINAGE PATTERN

The Derwent Gorge has the pattern of superimposed incised meanders. An ancestral Derwent may have meandered at high-level, perhaps on the Brassington Formation, but it is the subsequent incision that is significant. When the river flowed on the Millstone Grit, it cut down through the sandstones into the Edale Shales. With scarp retreat of the sandstones the river cut rapidly down into the shales. Over the Masson anticline the shales were thin and the river soon encountered the underlying limestone. Uniclinal shift down the limestone surface was constrained by the projecting High Tor reef and vertical incision ensued. Similar reefs at Cat Tor to the south constrained the southern part of the Gorge. The shale-floored col between Matlock Bath and Cromford stations was developed by two small tributaries; it has subsequently been deepened by landslips at each end (Doornkamp, 1990).

The Derwent was the main drain for melt-water from much of the South Pennines area during each glaciation, so that it had the potential for rapid incision during each waning phase. Comparing the Derwent Gorge with Malham Cove in the North Pennines, ascribed to a jokhulalp-type torrential outpouring of water from melting ice (Waltham et al, 1996), no evidence has been found that the Derwent Gorge was cut by headward retreat along a similar brief but intense cascade system, though it is not impossible that a waterfall phase may have occurred.

The only tributary stream to join the Derwent Gorge is that flowing from the Via Gellia at Cromford. The Via Gellia valley has a relatively small catchment area, even when its function as the focus of a dry valley system of late Pleistocene age is taken into account (Warwick, 1964). Its present day misfit stream rises from springs above lavas around Grangemill, 6km upstream. The River Derwent has a large allogenic catchment area maintaining a steady flow. As the Via Gellia is graded to its junction with the Derwent at Cromford its evolutionary story is clearly related, and periglacial run-off was probably sufficient to maintain a similar rate of downcutting.

GLACIATION

The Pleistocene glacial history of the Peak District has many uncertainties (Jowett and Charlesworth, 1929; Burek, 1977, 1985, 1991). Scattered patches of till in the area around Matlock (Smith et al, 1967; Cox and Harrison, 1980) have not been studied to the level of detail that Burek applied to the Bakewell-Rowsley area (Fig.6). A high-level till is generally found above 300m OD on the plateau at Bonsall Moor and around Brassington to the west of the Derwent Gorge, it also occurs at the same height east of the Gorge on the Millstone Grit country. Low-level till occurs mainly below about 240m OD particularly on fragments of the Hathersage Terrace some 50m above the River Wye at Bakewell, and near Alport-by-Youlgreave (Burek, 1985).

The sandy high-level till west of the Derwent contains abundant chert, derived from insoluble weathering residues, but little limestone, owing to almost complete decalcification. There are also abundant purple quartzite pebbles, originating from the Brassington Formation. Smith et al (1967) still regarded the latter formation as isolated Triassic relics, and suggested a hypothetical former course of the Trent to the north of Matlock to explain the occurrence of the quartzite pebbles. No studies of clast orientation have been reported, and none of the till patches can be related to dated interglacial deposits. The till around the Derwent Gorge is dark and argillaceous, being of Pennine derivation (Posnansky, 1960). No "Chalky Boulder Clay" has been recognized in the Peak District and the Pennine ice sheet did not impinge on the eastern "Chalky" ice sheet until reaching the vicinity of Derby. High-level tills east of the Derwent are, however, dominated by Upper Carboniferous material, though there is still some decalcification. Until detailed petrographic studies are done on all the tills, the ascription of high- and low-level tills to different glaciations must remain uncertain. The currently-recognised differences in composition may be no more than reflections of the available local source materials. Widespread low-level till around the Carsington Reservoir and in the Ecclesbourne valley south of Wirksworth again contains many quartzite pebbles, but this is to be expected as it is down-slope from the Brassington sand pockets. Both high- and low-level tills contain sporadic Lake District erratics.

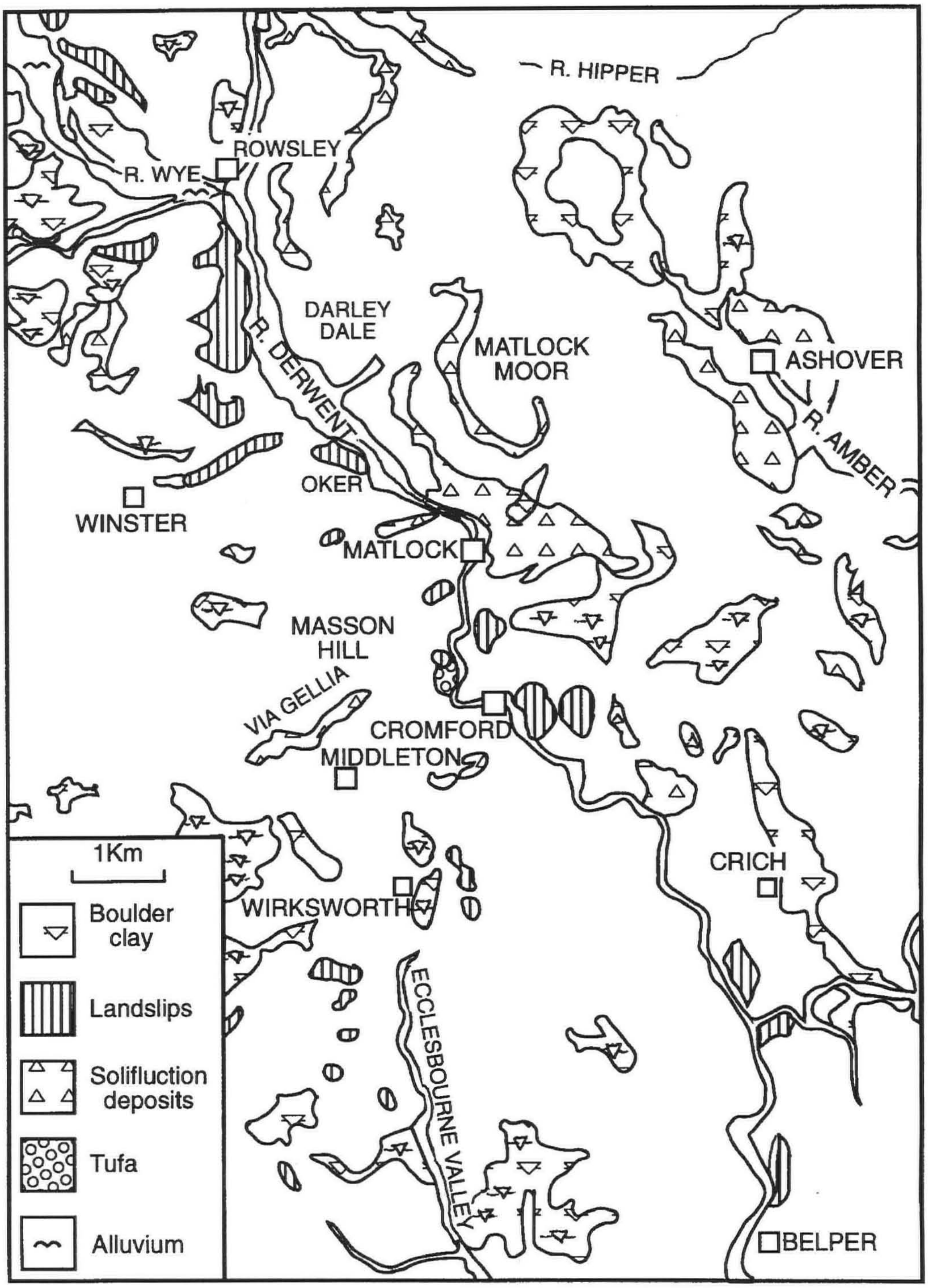
The two tills may indicate two separate glaciations, but definitive dating is not possible at present, nor is correlation with the "standard" East Anglian and Midland Pleistocene successions. The till on the Hathersage Terrace is certainly earlier than the main Devensian advance (i.e. pre-"Wolstonian"), but whether the high plateau till is "Anglian" or older is unknown. Current research in the type area of East Anglia appears to show that the deposits of the "Anglian" and "Wolstonian" glaciations are contemporary there, though the O-18 record indicates two episodes of low sea-level, possibly due to glaciations in the rest of Britain (Bowen et al, 1986). It is possible that what was once regarded as "Wolstonian" would be better assigned to an early Devensian glacial episode. New terms to replace "Anglian" and "Wolstonian" may be necessary, but until they are available it seems desirable to retain their use for the Peak District. What seems certain is that the Peak District was covered twice, possibly more often, by ice sheets moving generally southeastwards from Northwest England. Ice sheets crossed the Peak District in a generally southeasterly direction along the line of the Wye Valley, whose river later became an important tributary to the Derwent. The till on the terrace at Bakewell has continuations at roughly the same height above the Derwent and its wide floodplain around Rowsley (Burek, 1985); an isolated remnant at a higher altitude near Wensley probably belongs to the same till sheet.

The high-level till west of the summit of Masson Hill on the south flank of Blakemoor and on the heights either side of the Hopton Valley south of the Via Gellia are thought to be of Anglian age. However, the Ecclesbourne till sheet at a lower altitude appears to have an equivalent on a terrace east of Duffield in the lower Derwent Valley, and this in turn merges with what has generally been regarded as "Wolstonian" till around Derby (Frost and Smart, 1979). High-level till is present northwest of the Ashover anticline and along the east flank of the Crich anticline some 7km ESE of Cromford; both are "sheltered" from the Derwent Gorge by intervening high ground and may be representative of a separate ice stream moving southwards along the coalfield flank of the Pennines. There are scattered quartzite pebbles, probably derived via a former extent of the Brassington Formation. Patches of this till occur at intervals high on the east side of the Derwent Valley around Belper and east of Duffield. None of these till occurrences gives any direct indication of the extent to which the gorge had been incised at the time of any of the glacial advances. The high-level plateau glaciation could have ridden over a high ice-way along the site of the Gorge, perhaps guided by an early shallow col. The later, "Wolstonian", glaciation, represented by the till at Bakewell, Rowsley and Wensley, indicates that the Gorge had probably been incised to an equivalent depth by that time, i.e. some 50m above present river level. Being confined within the early Gorge the ice was more likely to have been erosive than depositional.

Though Burek (1985) has provided detailed descriptions and analyses of the tills around Bakewell and Alport, no comparable study of the tills around Matlock appears to have been attempted. Until such a study is done, it must remain problematical how many glaciations were responsible. Farther south, where the tills around Derby have been studied, there remain other problems of interpretation (Posnansky, 1960).

The late Devensian glacial limits were away to the north or west of the Peak District so that no ice reached the Derwent catchment then. Periglacial effects included the formation of a formerly widespread sheet of silty drift, with a high loess component, on the limestone plateau (Pigott, 1962). There are scattered remnants on Masson Hill and Bole Hill, but there is little trace of it in the Gorge. Solifluction deposits, commonly known as Head, occur widely on both limestone and Millstone Grit, extending down to river level in places. As far as can be ascertained, the surviving solifluction deposits are all of Devensian or post-glacial age.

Figure 6. Sketch map of Quaternary deposits in the general area of Matlock.



Regrettably, no bone caves are now known in the Derwent Gorge, so no dating of events by this means is possible. The former Boden's Quarry Cave yielded what appears to have been a Devensian fauna, only some 20m above the river (Law, 1878). It was totally quarried away in the long disused Long Tor Quarry and little detail of the deposits or bones has survived. The lack of speleothems in the Matlock caves means that the uranium series dating method cannot be applied.

The River Derwent is the main drain for a large catchment area in North Derbyshire, so that any event causing a fall in base level would have significant effects on its middle course, including the Gorge at Matlock. Incision of the Wye-Derwent river system started well before the formation of the Hathersage Terrace (Johnson, 1957, 1969; Waters and Johnson, 1958; Briggs and Burek, 1985). To what extent periods of incision were controlled by glacial falls of base level or by climatic influences remains uncertain. Further incision of about 50m took place after the Hathersage Terrace was covered by "Wolstonian" till, but a stillstand caused by the "nick-point" of the Matlock Gorge is reflected by the meandering course of the Derwent across the flat Darley Dale area. Downcutting of the Gorge continued during Ipswichian, Devensian and post-glacial times and the younger Hope and Rowsley terraces can be traced through the Gorge into the lower Derwent valley. However, the nick-point at the head of the Ambergate Terrace has not yet migrated upstream into the Darley Dale area: instead it is represented by the steeper gradient through the Derwent Gorge.

Unfortunately no chronological analysis of the terrace sequence has been attempted since Waters and Johnson's (1958) referral to "Older" and "Newer" Drifts, so that various uncertainties remain to be resolved. Indeed Briggs and Burek (1985) cite unpublished work by Redda on C-14 dating of material in the terraces of the Noe valley (tributary to the upper Derwent) which throws doubt upon the correlation of these with the terraces of the middle and lower Derwent.

What appear to be marginal drainage channels lie along the lower slopes of the north flank of Masson Hill around Snitterton. Wedd (in Gibson and

View southwards down the Gorge, taken from an old postcard of c.1900-1910. High Tor on the left with the mineral vein in the cleft. The two Long Tor quarries (hidden in trees today) show the dip of the Lower Matlock Limestones; the prominent partings are clay wayboards. The 1965 landslip destroyed the middle house and damaged the others.

Wedd, 1913) and Smith et al, (1967) thought these originated as channels along the margin of an ice sheet lying in the Darley Dale area, possibly in two episodes when the ice margin was at different heights. Wedd also offered the suggestion that the Derwent Gorge was due to glacial diversion from an earlier course along the shale outcrop, but he did not explain how the diversion came about. Indeed he contradicted himself by saying later in the same publication that the diversion was pre-glacial.

LANDSLIPS

Large landslips are widespread below the Millstone Grit escarpments both upstream and downstream of the Derwent Gorge but only small slips occur in the Gorge itself (Doornkamp, 1990; Taylor, 1966) (Fig.6). These are on the western slopes where the slips are oriented down the dip of the beds. The most recent slip destroyed a house close to the Long Tor quarry in 1965 (Taylor, 1966). The slip-planes appear to be on the weathered tops of the lavas or on clay wayboards, and it is clear that earlier slips could have occurred on such horizons at any time after incision had started. As most of the presently visible landslips come right down to river level they are clearly of post-glacial date. Some, indeed, have been aggravated by quarrying or road construction along the river side.

To the northwest of Matlock, Oker Hill is a highly disturbed mass of Millstone Grit strata that have been partly undermined by the river at the toe (Doornkamp, 1990). Whilst the present situation of Oker Hill has no apparent significance for the evolution of the Derwent Gorge, the writer has heard suggestions that at some stage the whole mass slid off the summit of Masson Hill and down the northern limestone slope. This idea is difficult to accept as there is a marginal channel along the intervening slope, and any such channel would have been filled in by landslide debris.

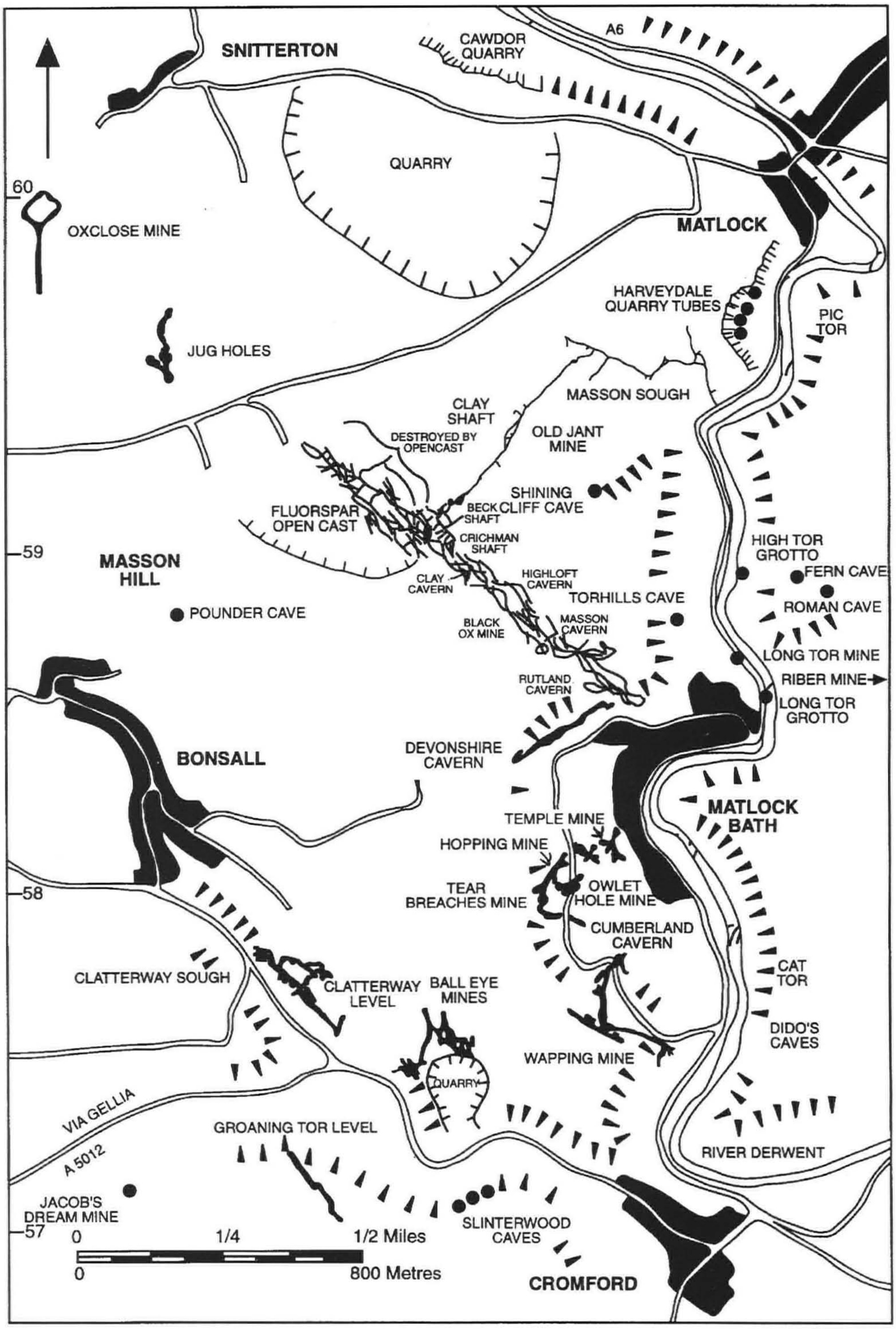
TUFA

A large sheet of tufa extends for about 700m along the western side of the Gorge at Matlock Bath. It is fed from weakly thermal springs of meteoric waters that have circulated deeply within the limestones. The present deposit is clearly younger than the Gorge itself, but whether there were earlier equivalents is unknown. A borehole to the base of the tufa deposits might reveal dateable material.

THE CAVES

Most of the caves in or around the Derwent Gorge (Fig.7) were found by lead miners tunnelling into the hillsides (Flindall and Hayes, 1976; Ford, 1977; Ford and Worley, 1977; Warriner et al, 1981; Waltham et al, 1996). The caves range in altitude from close to the summit of Masson Hill at more than 300m OD almost down to river level just below 100m OD. In many cases it is difficult to distinguish wholly man-made mine workings from caves enlarged by mining operations. The caves are largely phreatic cavities developed from a pre-existing hydrothermal karst system. Following a mid-Carboniferous palaeokarst episode a hydrothermal mineral suite of galena, sphalerite, fluorite, baryte and calcite lined many of the cavities. Later, probably in Late Tertiary and Quaternary times, phreatic dissolution enlarged the hydrothermal cavities. There is little evidence of vadose modification. Both the mineralization and most of the caves are within the hydrological compartment of Lower Matlock Limestones between the two lavas. The tourist "caves" are largely mines that have intersected such caves. Many of the caves have passages ending in sections entirely filled with bedded sands, silts and clays, so that the full extent of the caves is unknown. These sediments are present in the whole range of altitudes. Phreatic dissolution caves have been recognized over

Figure 7. Sketch map of the cave systems in the Matlock area.



a length of around 2km and have a depth range approaching 200m, but continuity between them all cannot be proved owing to mining activities and sediment fills.

On the northern flank of Masson Hill several cave-cum-mine complexes are oriented down the northerly dip of the Lower Matlock Limestones; these include Jug Holes (Worley and Nash, 1977), Oxclose Mine, Tearsall and Brightgate Caverns. They are again largely mines that have intersected phreatic dissolution caverns, and there is little vadose modification. They are not obviously related to the evolution of the Masson caves or of the Derwent Gorge, but they must have been developed at a time of high water-table, before drainage by the downcutting of the river Derwent. They are thus possibly synchronous with the Masson caves. Several have deposits of glutinous mud that seems to be composed largely of in-washed loess.

Masson Caverns trend southeast for over a kilometre from near the summit of Masson Hill. They lie within the Lower Matlock Limestones, between the two lavas. Great Masson Cavern itself is a large phreatic dissolution chamber: it was once filled with sediments and was cleaned out by 14th/15th-century lead miners who extracted colluvial lead ore material. High Loft Cavern is a similar-sized chamber on the same NW-SE fracture system discovered by lead miners in the 18th century. Nearby the Clay Cavern contains bedded glaciofluvial sediments. Several other chambers in the Crichman sector of workings have similar deposits (Flindall and Hayes, 1976; Noel et al, 1984). Former extensions at the northwest end of the cave-cum-mine system were removed by fluorspar opencast workings close to the summit of Masson Hill. These workings intersected and destroyed several other sediment-filled caverns at altitudes of c.250-300m OD. At right-angles to Masson Caverns, Gentlewomen's Pipe extended northeastwards almost down to river level, and had

Aerial view of the Derwent Gorge. Reproduced by kind permission of Engineering Surveys Limited, Maidenhead.

sediment-filled caverns in the part known as Old Jant Mine. The sediments therein are at a similar altitude, c.240m OD (i.e. about 140m above river level), and palaeomagnetic studies indicate a date of deposition around the Brunhes-Matuyama reversal, i.e. 730,000 years ago (Noel et al, 1984; Noel, 1987). Later re-assessments place this reversal at about 780,000 years ago (see Waltham et al, 1996). Sedimentological studies (Noel et al, 1984) indicate a glacial outwash origin, as yet the only evidence of glaciation at this date in Britain.

The less extensive Rutland Cavern also lies between the two lavas, which have been intersected in the mine workings. The large chambers within include phreatic dissolution caverns from which any sediment fills have been totally removed by the lead miners (Flindall and Hayes, 1976). The underlying Lower Nestus Pipe appears to have had similar caverns and sediments, but it is no longer accessible for study. A parallel Bacon Pipe has not been seen since mining days (Flindall and Hayes, 1976).

Devonshire Cavern, a sloping system with a significant altitudinal range, follows the trend of Coalpit Rake within the Lower Matlock Limestones and has considerable evidence of mineral linings of hydrothermal cavities with adjacent replacements in steeply dipping limestones. It also has relics of a sediment fill in dissolution-widened bedding planes.

The Royal Mine - Hopping Pipe complex, which includes the former Tear Breeches and Speedwell Mines (Flindall and Hayes, 1973), includes short sections of phreatic caverns, though any sedimentary fills were long ago cleaned out by the lead and fluorspar miners.

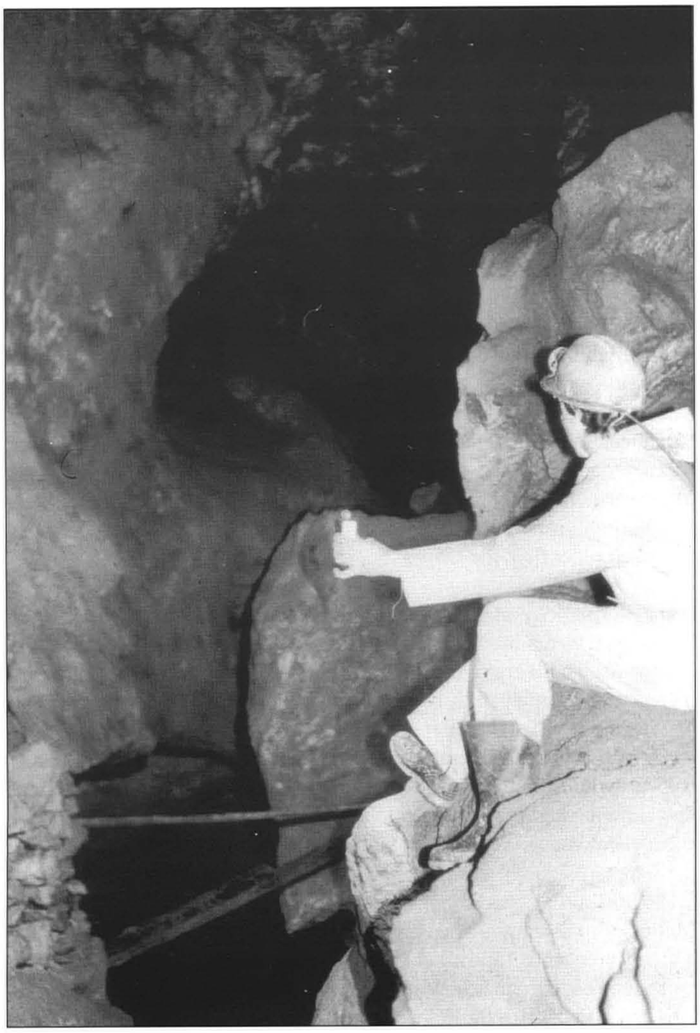
Temple Mine, worked for fluorspar in the 1920s, has several sections of sediment totally filling ancient phreatic caverns, again within the Lower Matlock Limestones. These are only about 30m above river level, so whether they were contemporary with the much higher Masson Cavern sediments is not known.

The Cumberland Cavern - Wapping Mine system again has natural caverns in the Lower Matlock Limestones, though there is little sedimentary fill left (Findall and Hayes, 1972).

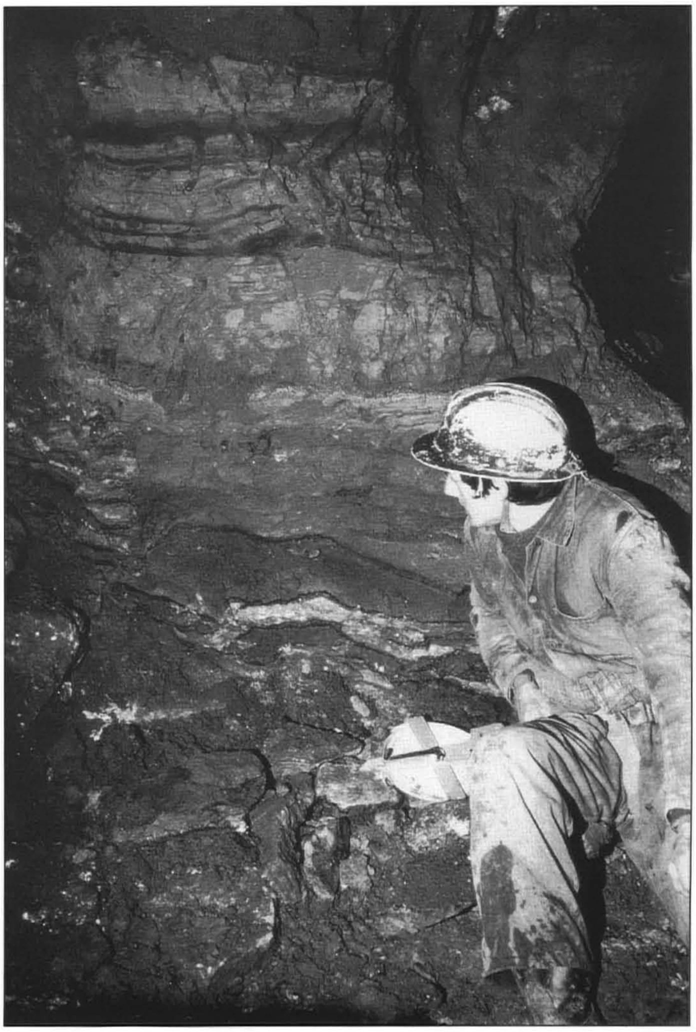
The Harveydale Quarry caves are low phreatic tubes developed along bedding planes some 50-60m above river level. Some of them have small immature vadose trenches. They appear to have originated by seepage from the Seven Rakes mineral vein down a prominent bedding plane. Whether they have any relationship to the older caves is not clear.

Ball Eye Mine and Cavern (Hurt, 1970) in the Via Gellia valley, now partly quarried away, included large phreatic chambers one of which at high level yielded a fossil elephant skull (Buckland, 1823) of unknown species and date. There are limited sedimentary fills in the lower levels but it is not clear whether these are due to relatively recent flooding rather than ancient Pleistocene deposition.

No caves of any significance have been located within the Upper Matlock Limestones, though a few dissolution cavities were found in mine workings east of the Gorge. Some of these are in the Fern and Roman "Caves" (roofless vein workings behind High Tor), the High Tor Grotto close to river level, and Riber Mine farther down-dip to the east. Dido's



The phreatic dissolution cavern in High Loft Mine, Masson Caverns.



Glacio-fluvial sedimentary fill in Clay Cavern, Masson Caverns.

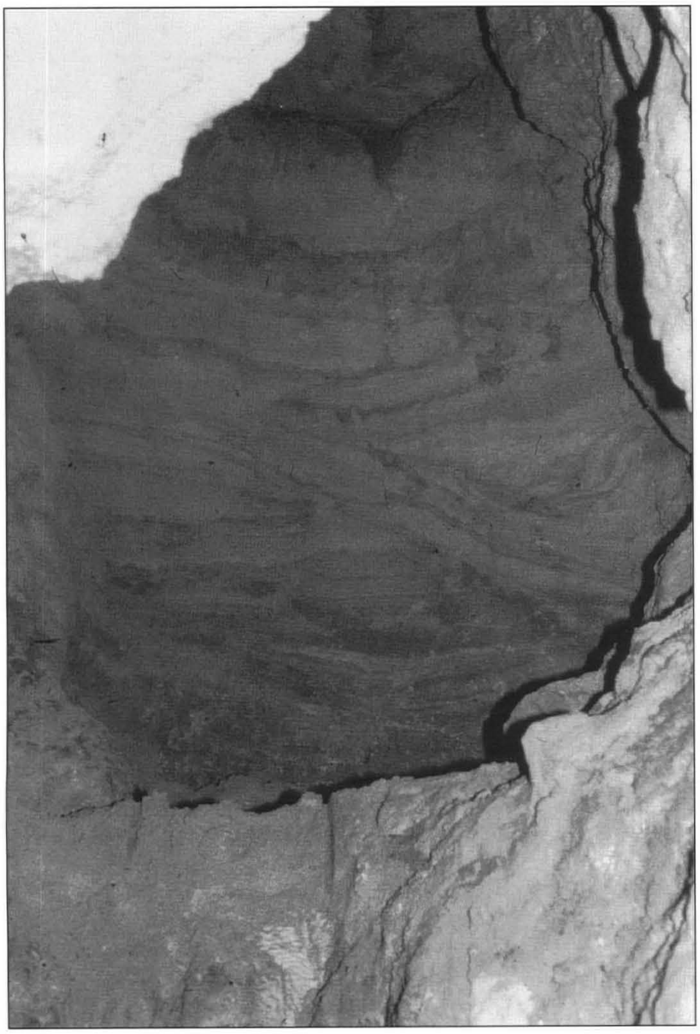
Cave, farther south, is similarly within vein fissures, with only limited evidence of phreatic dissolution. These mines are all in fractures and no pipe vein cavities were developed around the base of dolomitization, of which there is little trace east of the Gorge.

The sedimentary fills in the caves consist of laminated sands with scattered small pebbles, silts and clays, with surface textures on sand grains showing evidence of both glacial and fluvial transport and thus probably of glacial outwash origin (Noel et al, 1984). Local channel-fills within the sediment sequences suggest episodes of scouring, but otherwise the rapid changes of grain size probably represent no more than brief episodes of quiescence or spate during phases of glacial outwash. Clasts of derived wall rock, particularly of mineral vein fragments, occur mainly in the basal layers, but are also scattered through the deposits owing to dissolutional detachment from pipe-vein walls. Lumps of galena were sufficiently common in some caverns to stimulate the miners into removing all the fill, to extract the lead ore during dressing on the surface.

DISCUSSION

Until the question of how many glaciations occurred is answered, part of the story of the Derwent Gorge must remain uncertain, but it does seem that there was a plateau glacial phase (described here as Anglian) followed later by a terrace episode (described here as "Wolstonian"), as shown by contrasts in maturity and mineralogy (Burek, 1991). During each glacial advance and retreat vast quantities of melt-water must have been released in the South Pennines and the Derwent was the main drain. It was during such high run-off episodes that the main incision took place. The evidence of the sediment-filled caves suggests that there was no more than a very shallow valley along the line of the Gorge, at that early stage. The run-off from later glaciations incised the Derwent Valley deeply south of Cromford, but the resistance of the limestone retarded the rate of incision and maintained the Gorge as an elongate nick-point.

The cave systems throw additional light on the evolution of the Derwent Gorge. While phreatic dissolution is obvious, there is little sign of vadose modification (Ford and Worley, 1977). Most of the caves are within the hydrological compartment of the Lower Matlock Limestones between the two lava aquicludes and close to the base of dolomitization. There is very little evidence of comparable sediment-filled phreatic cave systems in the Upper Matlock Limestones, though most of these limestones have been stripped from the western slopes and any such caves would have been destroyed. The known caves thus demonstrate the possibility of slow phreatic transmission of water from north to south through the Lower Matlock Limestones of the Masson and Upperwood-Willersley anticlines after at least the highest part of the anticline had been stripped bare of the shale cover, i.e. before the Gorge had been incised enough to lower the water table. Continuity between the various sediment-filled cave systems cannot yet be proved, but a complex up-and-down phreatic drainage is a distinct possibility. The occurrence of phreatic caves at all altitudes from the summit down to about 30m above river level demonstrates the possibility of deep circulation with a meteoric input somewhere north of the summit; the corollary is that there must have been a resurgence near this altitude somewhere around Cromford, perhaps with water rising along the Bonsall Fault. A crag with several small caves close to Cromford crossroads may be a relic of such a resurgence. It is possible that there were hydrological systems in both the Lower and Upper Matlock Limestones,



Glacio-fluvial fill in a small phreatic cavern in Temple Mine.

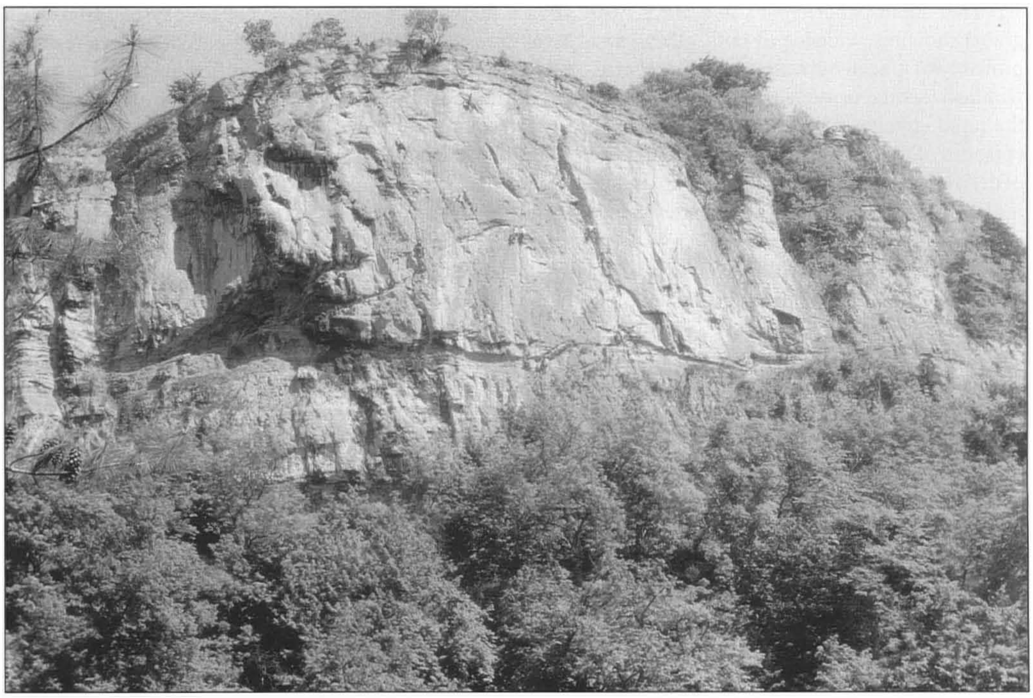
The sedimentary fills in the Masson Hill caves were deposited in phreatic dissolution cavities by streams that at times flowed strongly enough to carry sand and even a few pebbles, but at others were quiet enough for mud to be deposited. Local scouring suggests episodes of energetic flow, but all this could occur under epiphreatic conditions rather than vadose. As noted above, the fills of at least Old Jant Mine and Masson Cavern (Noel et al, 1984) have been dated at about 730,000 years (now revised to 780,000) and their textures indicate a glacial outwash origin. Though some pollen was found, no record has been published. As yet this is the only indication of a glacial phase at this date, during the early Pleistocene of Britain. The fills cannot be related to any of the surface tills and it seems likely that they represent separate events. The fills are also mostly higher than any of the terraces, so no relationship can be established there. Unfortunately, as yet the palaeomagnetism of most of the other fills has not been studied, so there is no direct proof that they are all of early Pleistocene age, though their lithological similarities suggest that all the fills are contemporary. The phreatic dissolutional development of the caves must obviously have been earlier than the fills, perhaps as far back as 1 million years. A corollary of this argument is that the cave systems are much older than the Gorge.

The morphology of the caves suggests slow phreatic water movement but the sediments indicate an energetic flow regime to yield the glacial sediments. These are two distinct phases of the caves' evolution, early meteoric phreatic dissolution and later glacial inwash. Sediment inwash could have been fast enough under a melt-water regime to preclude vadose modification and considerable quantities of melt-water could be expected from the whole South Pennine area when the ice margin was near Matlock. Once the ice had melted the catchment area would be minimal and no subsequent vadose scouring could be expected.

The position of the presently known caves and their fills in the Lower Matlock Limestones on the west side of the Gorge, with the necessity for a high water-table, followed by infill by glacial outwash, proves that the Gorge had not been incised to any great depth in the early Pleistocene. The caves and their fills are higher than any of the terraces but, of course, phreatic circulation could penetrate down-dip well below the water-table, at least as deep as the base of dolomitization. The Edale Shale cover probably extended part way up the west side of the Gorge, forming a roof over part of the phreatic system. The proto-Derwent was thus still flowing on shales. Only at a later date was the river's course incised sufficiently to meet the limestone, when the resistance of the limestone and the presence of shale interbeds in the Eyam Limestones resulted in uniclinal

but the upper system has largely been removed by the erosion of the western slopes. The cave systems demonstrate that the water-table was at or near the summit of Masson Hill during the phreatic dissolution phase, so that there could not have been much of a Derwent Gorge at that time.

The resistant High Tor reef that blocked uniclinal shift.



shift down the plunging axial region of the anticline. The shift was blocked by the upwardly projecting reefs, such as High Tor, and the river was then incised vertically into the limestones. Incision was probably most effective during later periglacial phases when the sediment-filled caves were frozen and thus not available for flow-through. The substantial run-off of the River Derwent was sufficient to maintain a surface course without the involvement of underground capture. A parallel example is the Avon Gorge at Bristol.

The absence of till and the minimal remnants of terraces within the Gorge mean that a full sequence of events cannot be deduced, but the failure of the river to exploit the caves described above suggests that the critical time of early incision was under periglacial conditions with both caves and their fills frozen solid. At least one, and probably two, ice sheets overrode the area, but till is restricted to patches at high level west of Masson Hill and to remnants of the Hathersage Terrace both up- and downstream of the Gorge, so that the full story of glaciation cannot yet be deciphered.

So far, no evidence has been brought forward to argue that the Gorge was fashioned or even trimmed by an ice tongue passing through. Nor has any evidence been produced to suggest that the Gorge was the site of a waterfall and that it has resulted from waterfall retreat. However, the till-covered terraces correlate sufficiently well up- and downstream to indicate that ice must have passed through at the time the Hathersage Terrace was formed, i.e. during the "Wolstonian". Thus the main period of incision must have been since 780,000 years ago and before the "Wolstonian" glaciation. The higher terrace sequence upstream has been correlated tentatively with "Older" Drifts (presumably Anglian) by Waters and Johnson (1958) and with some pre-"Wolstonian" stages by Burek (1977).

CONCLUSIONS

Several events have helped to prepare the ground for subsequent events, some as far back as the Carboniferous. Firstly, contemporary palaeokarst surfaces within the limestone succession provided potential inception horizons. Secondly, the folding of the Masson anticline raised the limestone massif in Mid-to-Late Carboniferous times. Later, hydrothermal karst producing mineral-lined cavities at or near the base of dolomitization. Thus a system of weaknesses that would favour speleogenesis and gorge incision was available at an early stage (Fig.8).

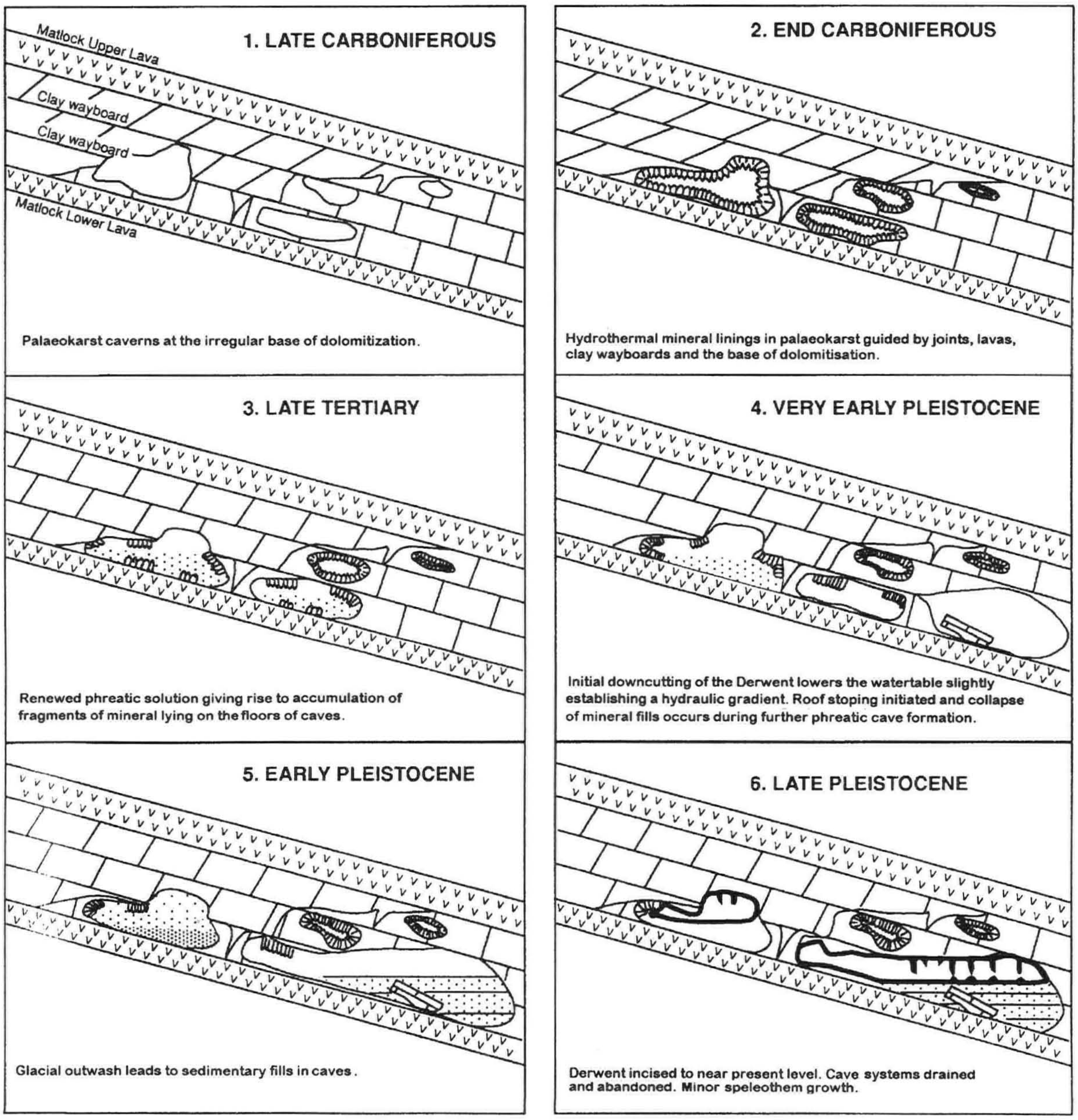


Figure 8. Strip-cartoon diagram to show the evolution of the Matlock caves (modified from Ford and Worley 1977).

The proposed existence of a former cover of Jurassic and Cretaceous strata over the Peak District must be viewed with suspicion, owing to the lack of relics beneath the Mio-Pliocene Brassington Formation. In the absence of such a cover the hypothetical course of a proto-Trent and its tributary Derwent on a Cretaceous surface across the Peak District as proposed by Linton (1951, 1956) must be replaced by an ancestral river course on the Brassington Formation.

The Mio-Pliocene Brassington Formation once covered much of the southern Peak District, both Carboniferous Limestone and Millstone Grit, as argued by Walsh et al, (1972). Today it is preserved only in dissolution/collapse "pockets". Largely derived from a retreating Triassic escarpment, the fluvial sheets of the Brassington Formation probably fed firstly northwards and then eastwards into a river system draining towards the North Sea. Such a system would have included forerunners of both the rivers Trent and Derwent.

Later Pliocene uplift of the southern Pennines led to the erosion of most of the Brassington Formation and to the superimposition of the proto-Derwent onto the remaining Millstone Grit cover on the limestone. With the concomitant depression of the Triassic rocks into a trough along the Middle Trent Valley the Derwent evolved into a subsequent tributary flowing southwards, largely along the strike of the Edale Shales. Its incision resulted in the Derwent crossing several folds in the Millstone Grit, as well as the Masson anticline in limestones and lavas.

By Early Pleistocene times, perhaps around 1 million years ago, much of the Millstone Grit cover had been eroded away, leaving the limestone plateau exposed, but without any incised valleys. The crest of the Masson Hill anticline was trimmed off, exposing the dolerite mass flanked by the upper parts of the limestone hydrological compartments between the lavas. Percolation through the dolomites and mineral-lined cavities led to the development of a phreatic dissolution cavern network transmitting water through the anticline. The site of the Gorge was no more than a gentle col on the shales at this stage, with the River Derwent flowing across it.

Still within Early Pleistocene times, by about 780,000 years ago, an early glacial advance impinged on the Peak District. Whether it extended further to the south or not is unknown, but when the ice limit was around Masson Hill, outwash sediments poured into the phreatic caves and choked them to the roof. No vadose scouring or deepening of the caves followed in the presently accessible caves, perhaps because of permafrost conditions. If equivalent sediment-filled phreatic caves were also extensive in the Upper Matlock Limestones hydrological compartment they might have been more easily available to vadose scouring along the site of the present Gorge, but no evidence of such a system is available at present.

In Mid Pleistocene times, under interglacial climatic conditions, the proto-Derwent was still flowing on the Edale Shales along the present line of the Gorge and gradually migrating eastwards down-dip, owing to uniclinal shift. As the removal of the shales cut down to the limestone the upward-projecting reefs, such as those in the cliffs between High Tor and Pic Tor, blocked further uniclinal shift, and incision thereafter was vertical. The southern section of the Derwent Gorge was also incised because of upstanding reefs in Cat Tor. With the drainage of a large catchment area the river through the Gorge was energetic, and down-cutting was rapid, particularly during periglacial phases.

A pre-Anglian glaciation is represented by the outwash sediment fills in the cave systems, and is dated by the Brunhes-Matuyama reversal at 780,000 years.

Later the "Anglian" glaciers swept over the Matlock area and left till at high level on both Carboniferous Limestone and Millstone Grit uplands on either side of the future Gorge.

The later "Wolstonian" (i.e. post-Hoxnian) was marked by an ice tongue following a Derwent Valley system with its floor about 50m above present river level. The Gorge had apparently been incised to such a depth during the preceding Hoxnian interglacial. The till on the terraces up- and downstream demonstrates that the glacier was mobile down to that level. However, the Gorge is likely to have had a nearly static ice plug with the moving ice riding over it on a shear plane near Gorge-lip level. Within the confines of the Gorge the ice was static and little till deposition occurred; any till that was deposited was rapidly eroded during the succeeding fluvial phases. The drainage of the hydrological compartments with the lack of any substantial catchments meant that the phreatic caves and their fills were by-passed and abandoned without vadose modification.

The "Wolstonian" (probably Early Devensian) glaciation was the last to reach the Matlock area and the Derwent was incised a further 50m during the succeeding Ipswichian, Devensian and post-glacial periods.

The above sequence of events demonstrates that the Derwent Gorge at Matlock has resulted essentially from superimposition of a drainage pattern from the Mio-Pliocene Brassington Formation on to a shale-covered limestone anticline extending eastwards from Masson Hill. Uniclinal shift down the shale/limestone surface was blocked by the upstanding reef of High Tor, and vertical incision followed. The high-level Anglian till demonstrates that the Gorge was no more than a shallow col then. Incision was most effective in the periglacial phases after the Anglian glaciation, i.e. in early and late "Wolstonian" times, when run-off was high. Palaeokarst developments, together with dolomitization and mineralization of the Upper Matlock Limestones, may have provided weaknesses favouring incision into the limestone at that stratigraphical level. The comparable cave systems within the Lower Matlock Limestones played little part in the evolution of the Derwent Gorge but the outwash sediments preserved within them demonstrate that the onset of glaciation was earlier than proven elsewhere in most of Britain. Correlation with one or other of the early cold-phase Crag deposits in East Anglia is not yet possible, nor is correlation with the ocean-floor sedimentary record of oxygen isotope variations due to climatic changes.

ACKNOWLEDGMENTS

Thanks are due to Drs C V Burek and A C Waltham for their critical reading of an early version. Thanks also to Lawrence Coogan for drafting the diagrams.

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CAVE AND KARST SCIENCE Vol. 24, No.1, April 1997
Transactions of the British Cave Research Association

An unusual seawrack-dependent fauna in a Manx seacave

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Abstract: Langness Seacave (Langness peninsula, Isle of Man) contains an invertebrate faunal assemblage dominated by cavernicoles (troglophiles) yet dependant upon marine driftweed as the primary source of food. The biospeleological significance of this unusual site is discussed, and arguments are offered for the possible subterranean nature of two species Itunella tenuiremis *(Copepoda: Canthocamptidae) and* Trechus fulvus *(Coleoptera: Carabidae).*

INTRODUCTION

Langness Seacave is located on the Castletown Bay coast of the Langness peninsula, Isle of Man (NGR SC282.656) (Fig. 1). The cave was found by the present author during a biospeleological reconnaissance in April 1994. Its existence had not been previously reported in the literature. It is 35m. in length, and partly tidal (see Fig. 2), and it was observed that decomposing marine seawrack, deposited inside the cave by storms, was associated with a rich cavernicolous invertebrate fauna. The site was visited several times between Spring 1994 and Autumn 1995 in order to collect representative invertebrate faunal samples, and to observe any seasonal changes. The collections have been identified by specialist taxonomists: where this has not yet been possible no attempt has been made to assign specific identifications. Reynolds (1996) reported that both of the two earthworms occurring in the cave are species commonly recorded from British caves. The present paper describes the cave, lists and describes the invertebrate fauna and discusses the biospeleological significance of this unusual site. In addition evidence is adduced from the site, and other published records, that the marine or brackish water copepod *Itunella tenuiremis* is primarily interstitial, and in support of the possible cavernicolous nature of a carabid beetle *Trechus fulvus*.

DESCRIPTION OF THE CAVE

The cave is in the Carboniferous age Langness Conglomerate. This member (formerly called the "Basement Conglomerate") underlies the Castletown Limestone which is exposed in cliff sections nearby and which forms much of the southern portion of Langness peninsula. The conglomerate is composed of rounded water-worn pebbles, mainly of slate and quartzite, cemented by non-calcareous matrix coloured reddish by iron oxide. Where exposed in coastal sections this rock is usually highly dissected by erosion along joints and veins, resulting in collapsed ground, sea caves, natural arches, narrow embayments and similar geomorphological features.

The cave was formed by marine action in an inclined joint (or fault), clearly visible from the seaward, and which continues beyond the actual cave mouth as a deep, narrow gully nearly 10 m deep at its inner (eastern) end. Langness Seacave was possibly, though not certainly, modified during mediaeval or prehistoric times by the mining activity which was extensive and widespread on Man (P. Gillman pers. comm. 1995). From the mouth of the cave, the passage inclines gently upwards, becoming steadily lower and narrower until intersecting a cross passage which has

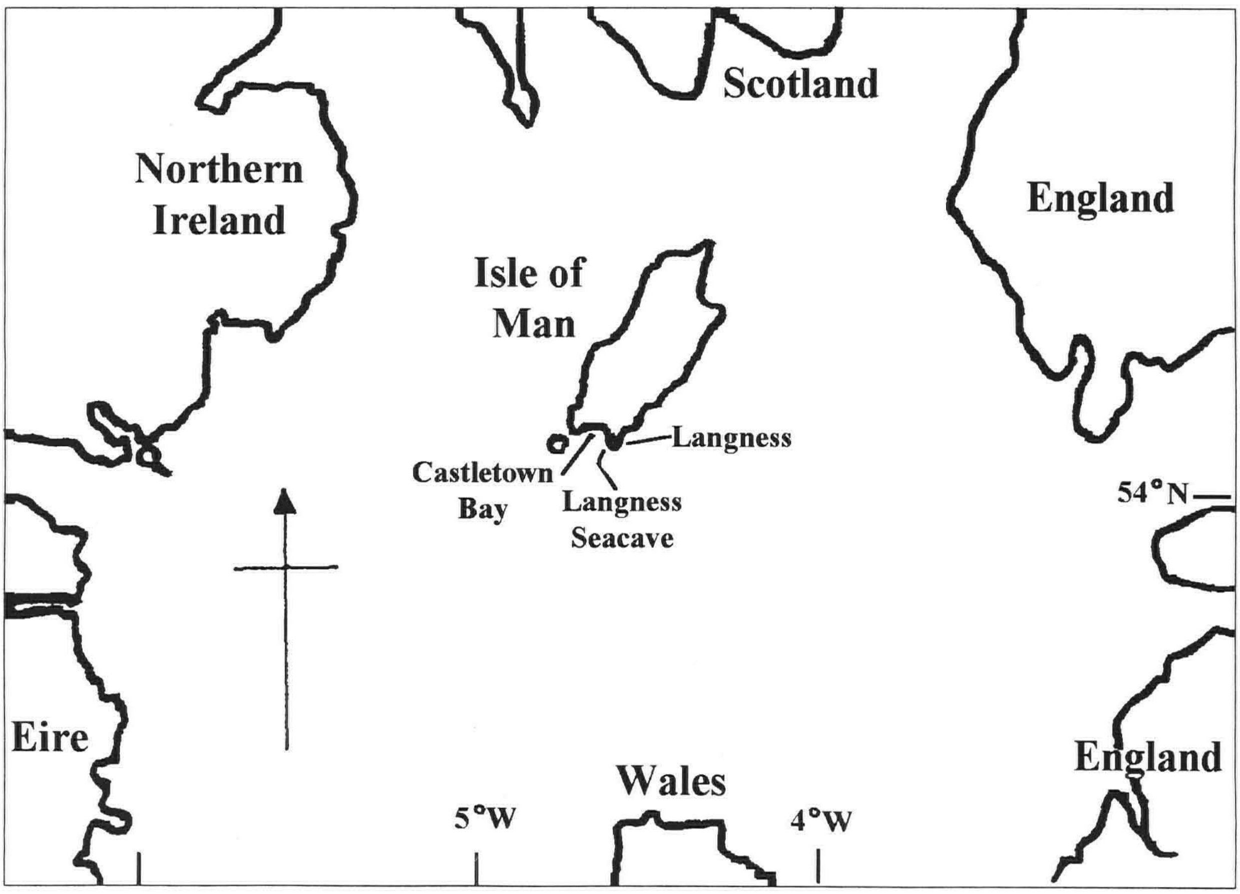


Figure 1. Area map to show the location of the Isle of Man and Langness Seacave.

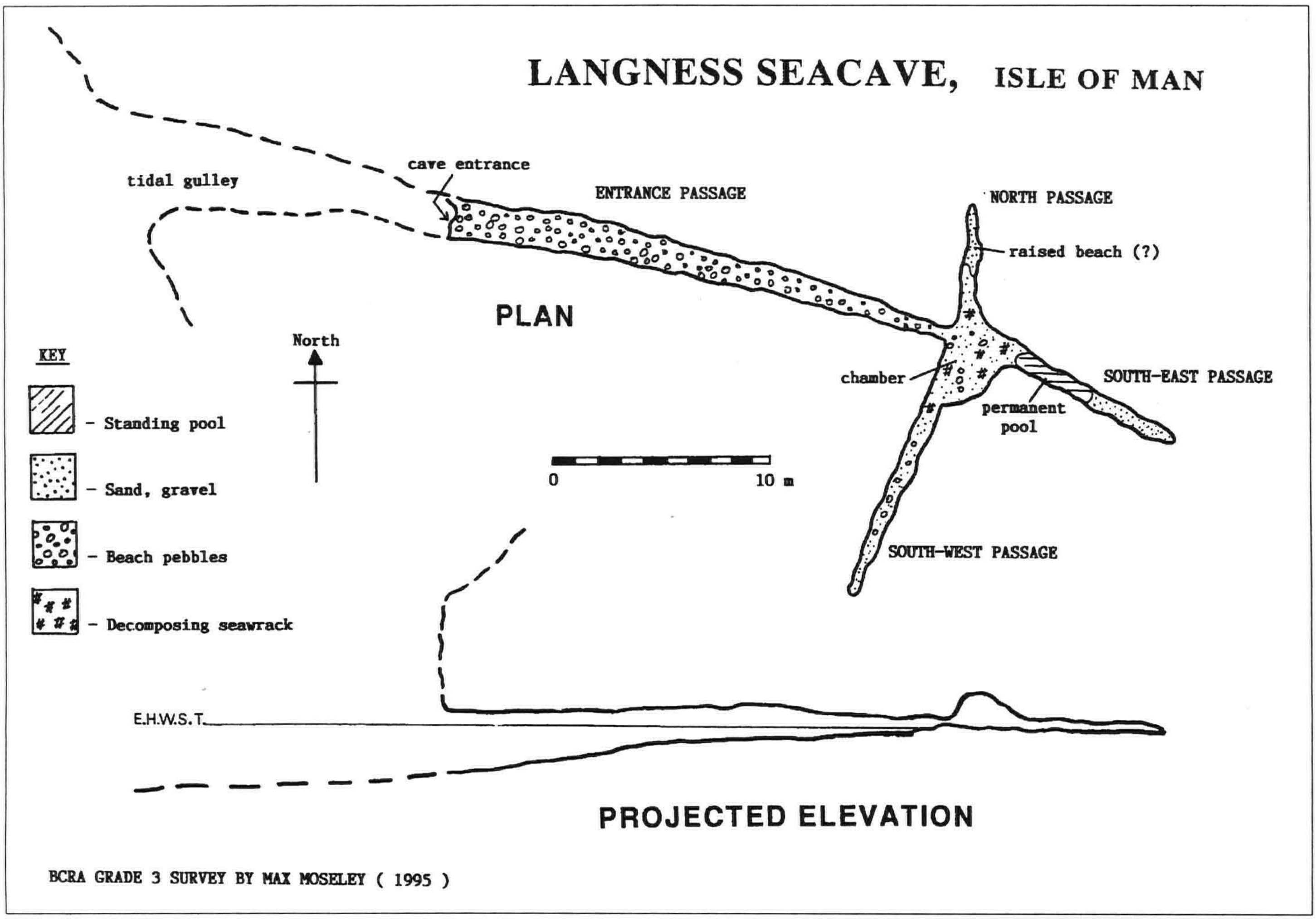


Figure 2. Plan and projected elevation of the Langness Seacave, Langness, Isle of Man.

formed along a vein of softer rock within the conglomerate: this vein is clearly visible in North Passage. A small chamber has formed at the intersection.

The cave is tidal. Extreme High Water Spring Tides (E.H.W.S.T.) reach the end of the entrance passage, just in front of the chamber. Under high water storm conditions the sea can enter further, carrying marine flotsam and driftweed with it, and, due to the constricted nature of the entrance to the chamber, this material is deposited and remains in the chamber. There is the remnant of a probable raised beach at the end of North Passage, evidence that the cave was formed when the sea level was higher than today. Low water mark is several hundred metres away from the cave, the intervening shore comprising a wide stable pebble beach with rock outcrops.

The floor of the tidal Entrance Passage is composed of pebbles, and is contiguous with the outside pebble beach. Further inside the cave the floor is covered by thick deposits of mixed sand, gravel and pebbles. Within the chamber and immediately adjacent areas these have been sorted by storm action into an upper layer of pebbles and coarse gravel, grading downwards into coarse gravel and sand which is reached at a depth of 10-15cm. Driftwood, marine flotsam and driftweed litter the surface, at various stages of decomposition depending on the season (See 'Cave Habitat' below). Fragments and decomposition products of the driftweed penetrate throughout the floor deposits.

All drainage on the Langness peninsula is subterranean though no solution caves are reported in the limestone and there are no major springs. A very small intermittent spring emerges from the conglomerate near the cliff top just south of Langness Seacave, and others may exist. There is no stream in the cave, but freshwater percolation is visible as roof drips throughout the year (except under extreme drought conditions, which are rare on the Isle of Man) and interstitial water is always present under the floor. Even towards the end of the exceptional drought during the summer of 1995, interstitial water was present at a depth of 15 cm in the chamber. The water table here is normally closer to the surface and sometimes forms shallow pools. There is a permanent pool in South-east Passage.

RESULTS

The Cave Habitat

The chamber is at the limit of visible daylight, but the cave is too small to have any true 'deep cave' constant temperature zone. Mean annual temperature is approximately 11°C., and the relative humidity within the cave is 90%-100%. Cave water pH is 7.0- 7.1[1] . Salinity is variable because of intermittent ingress of seawater (approximately 34 ‰ salinity) during winter storms, and continuous flushing by freshwater seepage. Normally it is low : interstitial water in the chamber on 19.XI.95 was only 5 ‰.

Apart from scattered pieces of driftwood, the only significant external food input into the cave is a seasonal deposition of seawrack. The entrance is situated in a small cove which acts as a 'catch cove' and strand lines of fresh driftweed begin to accumulate here as early as July. The driftweed or 'seawrack' is composed almost entirely of marine Phaeophycean algae: mostly Laminariales ('kelp', *Laminaria* spp.) with lesser amounts of

[1] The pool became slightly acidic (pH 6.7) towards the end of an extended drought in 1995.

Entrance of Langness Seacave, looking due east, 11 October, 1995. Note the accumulations of seawrack, deposited on the upper shore during the equinoctal high tides in late September.

Fucales ('Rockweed', *Ascophyllum nodusum* and *Fucus* spp.). Heavy drifts are deposited in the entrance passage of the cave by the equinoctial Spring Tides in late September, and immediately begin to decompose in the humid conditions. These are redeposited within the chamber during gales: this may happen at any time from September onwards. Once deposited inside the chamber, decomposition proceeds rapidly and is well advanced by spring. By May-June-July the cave floor is covered by a layer of well-rotted weed. Carbon dioxide levels at this time can be so high that it becomes difficult to work in the chamber.

The cave is thus subject to an annual seasonal cycle resulting from an influx of saline seawater and deposition of new driftweed in the autumn and winter, followed by flushing of the seawater and decomposition of the weed through the rest of the winter, spring and summer.

The Invertebrate Fauna

The invertebrate fauna is listed in the accompanying table (Table 1). There are no bats or other vertebrates.

The cave floor supports a rich and abundant invertebrate fauna. Population densities of microdrile oligochaetes, copepods, larval and pupating diptera, acari and collembola are high, and this meiofauna in turn supports substantial populations of predatory mesofauna (*Porrhomma convexum, Trechus fulvus* and *Quedius mesomelinus*). The two earthworm species are occasional, but appear to be established as are also the three recorded species of terrestrial isopod. The cave floor has three distinguishable ecological niches: the subsurface interstitial water, the pebble-gravel-sand layer above this, and surface debris (driftwood, seawrack holdfasts, etc.): species lists for each are given in the table.

The permanent pool in South-east Passage contains established populations of copepods (*Paracyclops fimbriatus, Itunella tenuiremis*) and dytiscid beetles (*Hydroporus obsoletus, Agabus guttatus*). The pool-surface association comprises two entomobryid collembola (*Heteromurus nitidus, Tomoceros minor*) and two or more unidentified mites.

The parietal ('threshold') and cave wall associations are impoverished in this cave. Metidid spiders, abundant elsewhere in the thresholds of Manx caves and mines (unpublished), are absent. The fauna consists of a few diptera (unidentified) and occasional individual strays from the cave floor (e.g. *Trechus fulvus* and *Philoscia muscorum*).

No troglobites (obligate cavernicoles) were found[2]. The fauna is, however, predominantly cavernicolous: of the seventeen taxa that have been authoritatively identified to species, thirteen (76%) are generally recognised to be troglophiles in British caves, and most of these (eleven species) are common or abundant in the cave (see Table 1).

The other faunal component is maritime, but it consists of only four species (24% of the total)[3] and two of these, the sub-maritime *Cercyon depressus* and *Strigamia maritima*, are rare, each being represented in the collections only by single individuals. Only the remaining two species are abundant and are undoubtedly established members of the cave's fauna. *Trechus fulvus* is a coastal beetle, usually found under stones near high water mark, near to freshwater springs or seepages (Luff, pers. comm. 1995) whilst *Itunella tenuiremis* is a considered to be a marine and esturine species. However, even these two species may be cavernicolous in Britain (see below). The absence inside the cave of the marine herbivores commonly found in or under decaying seaweed on the shore (e.g. *Marinogammarus* spp.) may also be noted.

***Itunella tenuiremis* (T.Scott) (Copepoda: Canthocamptidae).**

A poorly known species. It has been found in marine plankton tows off the Isle of Man (Bruce et al., 1963) as well as off the west of Scotland (Hogg, pers. comm., 1995), but it is probable that it is only an adventitious member of the plankton: Lang (1948) reports it as a brackish water species collected in Scotland and in Sweden. In Langness Cave it is abundant, being found in every sample taken from the floor deposits, in the pool, and even on the surface of damp driftwood and other debris. There is no doubt that it is a permanent member of the fauna at this locality, and its occurrence in this subterranean habitat suggests that it may primarily be a member of the subterranean littoral interstitial fauna. The related species *Itunella muelleri* (Gagnern) is distributed both in brackish water and in subterranean groundwater in Europe (Illies, 1967), and it is not unlikely that *tenuiremis* is also in the process of evolving into a subterranean species. The Family Canthocamptidae contains a number of troglobites e.g. *Spelaeocamptus*, and it is believed that many subterranean harpacticoids have colonised this habitat by active migration from the sea through brackish environments. They have a high degree of salinity tolerance.

[2] Jefferson (1976) suggested that *Hydroporus obsoletus* could just possibly be a troglobite, but this has not been established.

[3] It is anticipated that some of the oligochaetes and the dipterids will prove to be species normally found in decaying driftweed, but confirmation of this must await specific identification.

Table 1. Invertebrate fauna list, Langness Seacave.

TABLE: LANGNESS SEACAVE - INVERTEBRATE FAUNA LIST.

A = Parietal; B = on damp driftwood lying on floor; C = collected from floor deposit sample taken above the above water table; D = collected from interstitial water in the floor deposits; E = permanent pool; F = collected on pool surface.

" + " = occasional. " ++ " = common or abundant.

Species marked " * " are considered troglophiles in British and Irish caves; underlined = sub-maritime, coastal, marine or esturine; (T) = nominally terrestrial; (A) = nominally aquatic.

				A	B	C	D	E	F
OLIGOCHAETA									
	Enchytraidae	Sp(p) indet.			+	++	++		
	Tubificidae	Sp(p) indet.				+	+		
	Naiidae	Sp(p) indet.				+	+		
	Lumbricidae	* *E iseniella tetrahedra* (Savigny)	(T)			+			
		**Lumbricus rubellus* Hoffmeister	(T)			+			
COPEPODA									
	Canthocamptidae	*Itunella tenuiremis* (T.Scott)	(A)		++	++	++	++	
	Cyclopidae	* *Paracyclops fimbriatus* (Fischer)	(A)			++	++	++	
		* *Diacyclops bisetosus* (Rehberg)	(A)			++	++		
ISOPODA									
	Trichoniscidae	* *Trichoniscus pusillus* (Brandt)	(T)		+				
	Oniscidae	* *Oniscus asellus* (L.)	(T)		+				
		* *Philoscia muscorum* (Scop.)	(T)	+	+				
COLLEMBOLA									
	Entomobryidae	* *Heteromurus nitidus* (Templeton)	(T)		++	++			++
		**Tomocerous minor* (Lubbock)	(T)		++	++			++
	Poduridae	Sp. indet.			+				
COLEOPTERA									
	Dytiscidae	* *Hydroporus obsoletus* Aubé	(A)					++	
		**Agabus guttatus* (Paykull)	(A)					++	
	Carabidae	*Trechus fulvus* Dejean	(T)	+	++	++			
	Staphylinidae	* *Quedius mesomelinus* Marsham	(T)		+	++			
	Hydrophilidae	*Cercyon depressus* Stevens	(T)		+				
DIPTERA		Spp. indet. (+ larvae & pupae)		++	++	++	++		+
	Culicidae	*Culex* sp.	(T)	+					
ARANEA									
	Liniphyiidae	* *Porrhoma convexum* (Westring)	(T)		++	++			
OPILIONES									
	Phalangidae	? *Mitopus morio* (Fabricius)(imm.)	(T)		+				
ACARI		Spp. indet.			++	++			++
CHILOPODA									
	Dignathodontidae	*Strigamia maritima*	(T)			+			

Trechus fulvus **Dejean (Coleoptera: Carabidae)**

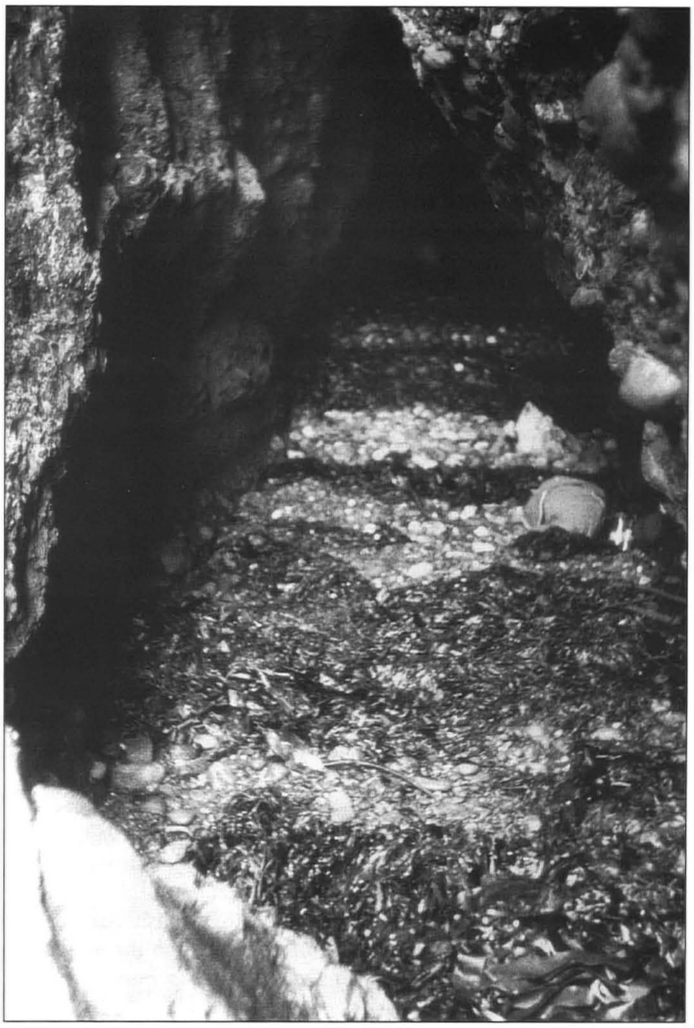
A coastal species found on both sandy and rocky coasts , living under stones near the high water mark, near to freshwater springs or seepages. It has a Lusitanian distribution from southern Norway to Spain including both Britain and Ireland. (Luff, pers. comm., 1995). Cavernicolous populations are reported from Spain, there are several records of adults from caves and mines in the British Isles (Devon, Lancashire, Isle of Man), and the only known specimen of a larva of this species (Luff, pers. comm.,1997) was collected from the dark zone of a mine near the Lancashire coast (Moseley, 1970, as "?*Trechus* sp. larva"). This species thus appears to be a troglophile in Britain, found in caves on or near the coast in the west of the country. It may also be anticipated in suitable underground sites within its known surface geographical distribution, particularly on the south and south-east coasts of England.

DISCUSSION

The absence of troglobites was anticipated. The Isle of Man was extensively glaciated and survival of preglacial cave fauna is improbable.

The cavernicolous nature of the fauna however is rather curious: one might expect to find a sub-maritime fauna similar to that found on the shore, in and under the decaying driftweed of the tidal strand. Certainly, the environmental conditions in the cave are close to those of a typical cave: low light levels, damped seasonal and diurnal temperature variations, high humidity, elevated carbon dioxide levels, and low salinity. The mean annual temperature is comfortably within the normal range for British caves where cave temperatures range from about 13°C in the south-west to about 7°C in the north (Jefferson, 1976, p.365), and elevated carbon dioxide is now recognised as an important characteristic of the subterranean environment (Howarth, 1983, p. 372). However, these conditions also largely apply to the supralittoral habitat beneath driftweed strandlines on the shore, and seasonal salinity variations together with a food web based upon decomposing marine macrophytes are hardly characteristic of most caves. Without further ecological evidence any attempt to explain dominance of the fauna by cavernicoles can be nothing more than speculation.

As a glance at the table will show, terrestrial and aquatic, marine and non-marine, species exist in close association. This is particularly true of the meiofauna: there does seem to be a separate faunal component of active terrestrial mesofauna that tends to be found on wet driftwood and under debris on the cave floor (coleoptera, isopoda and opilionids). The phenomenon of normally terrestrial and aquatic species occurring together is not new and has been widely reported in caves (e.g. Hawes, 1947, p. 89).



Entrance passage, Langness Seacave, 11 October 1995. Note the strandlines of seawrack which had been recently deposited during equinoctal high tides. Fronds and stipes of Laminaria can be distinguished. The floor of the passage is composed of beach pebbles.

The most remarkable example observed in Langness cave was the nominally aquatic *Itunella tenuiremis* occurring as seething masses, easily visible to the naked eye, on the surface of damp driftwood. All the copepods are also found together with terrestrial air breathing dipteran larvae and other nominally terrestrial meiofauna.

Entrance of Langness Seacave. This photograph was taken on 19 October, 1995, one week after the previous two photographs. An onshore gale had left thick deposits of seawrack in front of and inside the cave.

In Langness Seacave however we find the more unusual phenomenon of esturine (aquatic) and sub-maritime (terrestrial) invertebrates living side by side with freshwater and terrestrial organisms. The pool fauna consists of freshwater aquatic beetles, freshwater copepods and a marine/esturine harpacticoid copepod. The latter is also found throughout the floor deposits closely associated with both terrestrial and freshwater fauna. The sub-maritime terrestrial arthropods were found in floor samples together with most of the other nominally terrestrial and aquatic species listed in the table.

CONCLUSION

Is the seawrack-dependent cavernicolous invertebrate fauna of Langness Seacave an interesting, but unimportant, anomaly? In view of the fact that a marine origin is now widely accepted for a number of aquatic subterranean invertebrates (Coineau and Boutin, 1992, p.428), the presence in the cave of (a) a cavernicolous fauna dependant upon a marine food source and of (b) maritime invertebrates closely associated with entirely non-marine forms, is suggestive. There is also Chapman's (1979) report of a rich cavernicolous fauna associated with tidal mud in Otter Hole (Chepstow, Wales): the fact that we now know of two instances of this type of habitat means that it may be more common and widespread than has been recognised. Taken together, all these facts raise the possibility that some subterranean species may have evolved from marine ancestral stocks by initially colonising such food-rich subterranean habitats, rather than the food-poor interstitial habitat that has been proposed, and is probably the case, for many other species (e.g. Jefferson, 1976, Coineau and Boutin, 1992). It has been widely assumed that the cave habitat is food-poor (e.g. Poulson and White, 1969) but, as pointed out by Howarth (1983, p. 372) this may not always be so, and it is thus not entirely unreasonable to suggest this alternative evolutionary route. More examples of cavernicolous faunas in tidal sea caves will be required in order to establish whether such habitats are in fact of evolutionary significance but, in the meantime, Chapman's (1993 p.50) dictum "*In short, the fauna of sea caves is unremarkable*" may prove to have been premature.

ACKNOWLEDGEMENTS

I am especially grateful to Penny Gillman (Isle of Man Bat Group) who provided transportation and helped with the fieldwork in 1994-95. Thanks are also due to Dr. Larch Garrad and Jim Rogers (both of the Manx Museum and National Trust, Douglas, Isle of Man) for providing working space and assistance, and to Dr. Paul Wood (Huddersfield University, England) for reviewing the MS. The following specialists very kindly gave of their time to identify the collections:- P. Barnett (Millport Marine Biological Station, Scotland); D. Bilton (University of Oxford, England); K. Christiansen (Grinnell College, Iowa); P. Hillyard (B.M.[N.H.]); A. Karaytug (B.M.[N.H.]); M. Luff (University of Newcastle-upon-Tyne, England); M. Hogg (Millport, Scotland); J. Reynolds (Ontario, Canada); and J. Wright (St. Helens, England).

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CAVE AND KARST SCIENCE Vol. 24, No.1, April 1997
Transactions of the British Cave Research Association

Development of Shapour Cave, Southern Iran

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Abstract: Shahpour Cave is located on the north-western cliff of the Chowgan Valley, within the Dashtak Anticline, southern Iran. It is a single anastomotic tiered cave that has formed within the karstic Asmari Formation. At the initial stage of subaerial exposure of the Asmari Formation, the Shahpour River started entrenching the Chowgan Valley, and leakage from Shahpour River, through joint and bedding plane fissures, enlarged Shahpour Cave. The cave morphology, the stratigraphical setting and the direction of the hydraulic gradient support the proposed development model.

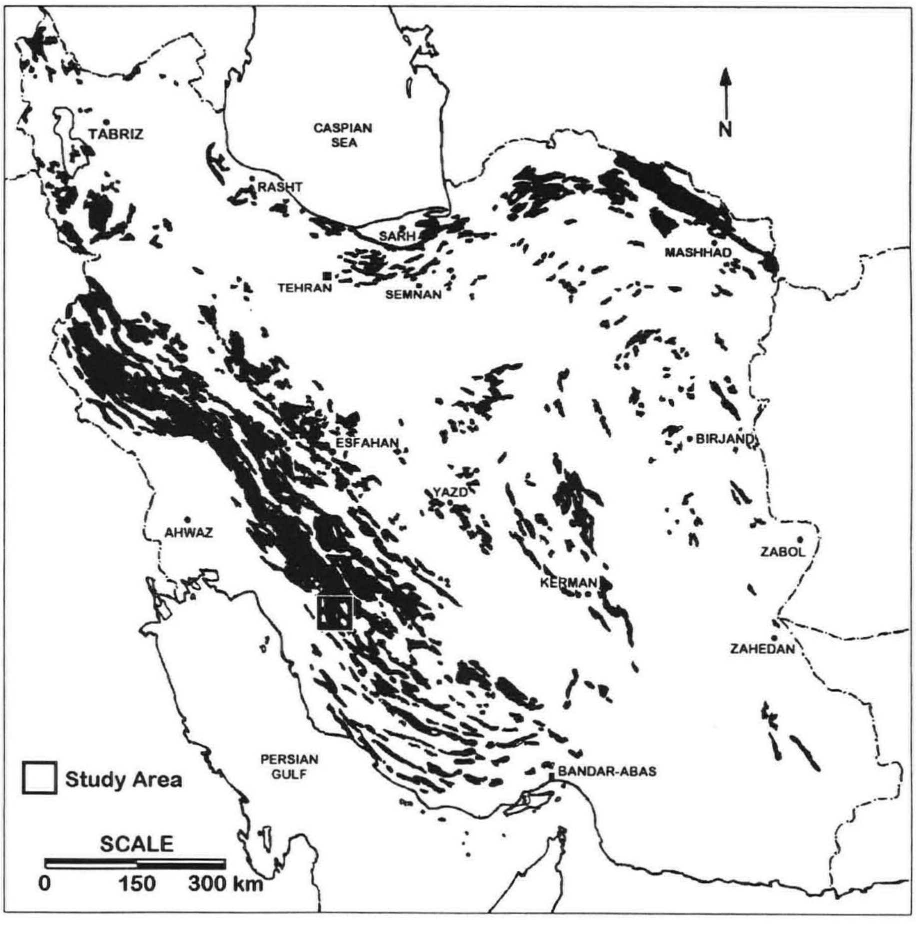
INTRODUCTION

Variables affecting cave development include precipitation, temperature, carbon dioxide levels, relief, tectonic setting, thickness of soluble rocks, and stratigraphical and lithological setting (White, 1988). The diversity of these variables and their interactions account for the diversity of cave patterns. Broad reviews of these variables have been presented by Jennings (1985), White (1988), and Ford and William (1989). Palmer (1991) focused on the origin of cave patterns by dividing them into two broad classes: branchwork caves and maze caves. Branchwork caves consist of passages that join as tributaries. Maze caves comprise fragments of interconnected maze passages. Within maze caves, four distinct subclasses (network caves, anastomotic caves, spongework caves and ramiform caves) can be recognised. Network caves are angular grids of intersecting fissures formed by the widening of nearly all available major fractures. Anastomotic caves consist of curvilinear tubes that intersect in a braided pattern with many closed loops. Spongework caves comprise interconnected dissolution cavities of varied size in a seemingly random three-dimensional pattern. Ramiform caves consist of irregular rooms and galleries that wander three dimensionally, with branches extending outward from the main areas of development. Many single passage caves are merely rudimentary forms of the types described above.

When branchwork caves are forming, each first order branch serves as a conduit for water fed by an essentially discrete recharge source. Water converges into higher-order passages that become fewer and generally larger in the downstream direction. According to existing models, anastomotic mazes are produced only by sources that fluctuate greatly in discharge, whereas network and spongework caves form under a broad range of settings, including flood water, diffuse recharge, and hypogenic conditions. Ramiform caves are almost all hypogenic. The classification described by Palmer (1991) provides an indication of the factors that have influenced cave development. Lowe (1992b) reviewed the history of cave development theories by references to the work of a selection of authors and assessed the continuing validity of traditional ideas when compared with a modern inception horizon hypothesis of limestone cavern origin.

Karstified carbonate rocks crop out on about 11% of Iran's land area (Fig. 1). This value increases to about 23% in the south central region of Iran. In this semi-arid region the extensive karstified area provides a valuable water resource. There has been no extensive speleological research in the south of Iran, especially on cave development mechanisms, and most of the speleological studies have been limited to cave mapping (Marefat, 1994; Judson, 1972).

Figures 1. Distribution map of karstic carbonate formation outcrops in Iran (The ages of the formations are Oligocene, Miocene, Eocene, Cretaceous and Jurassic).



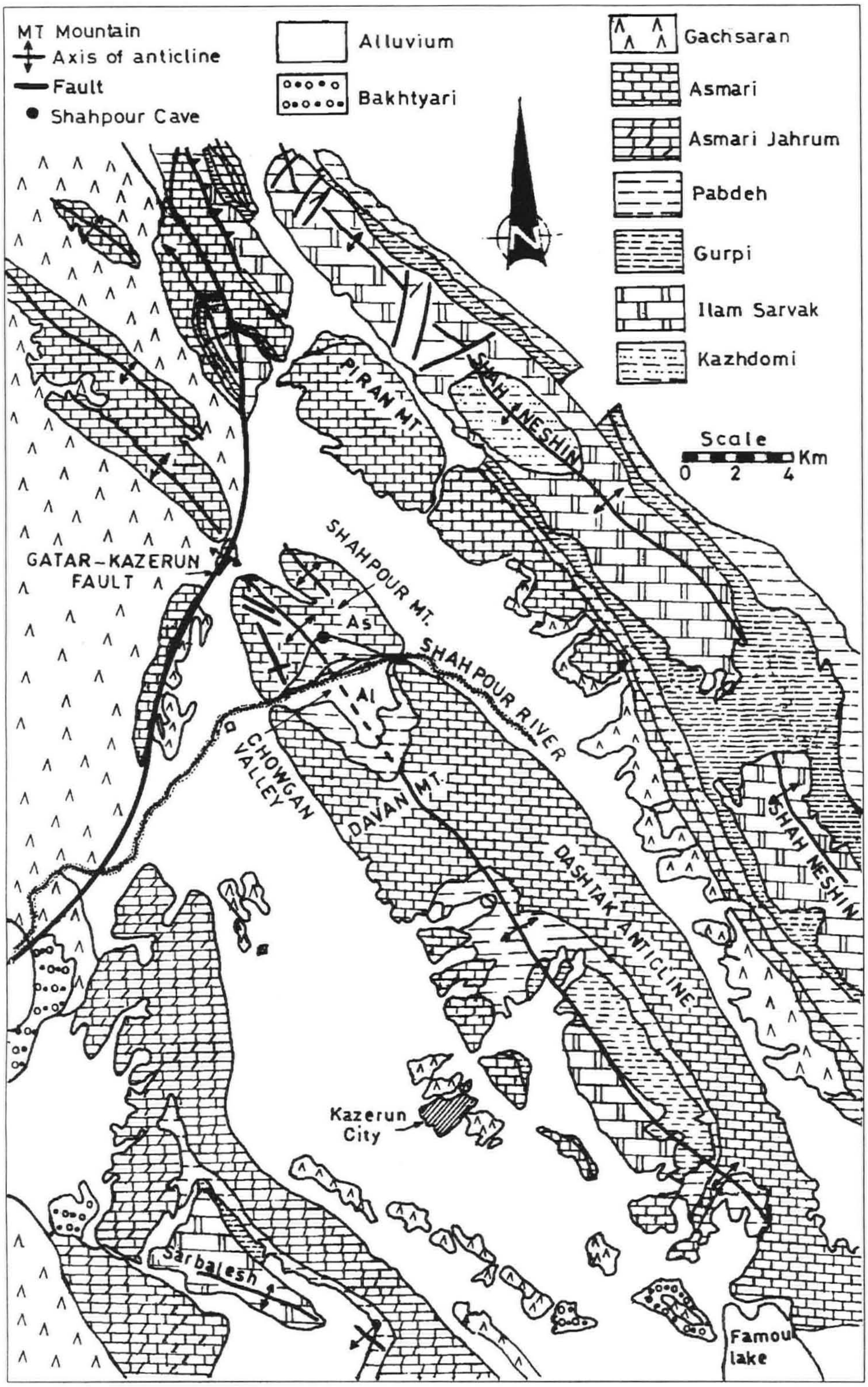


Figure 2. Geological map of the study area showing Shahpour Cave, the Chowgan Valley, the Shahpour River and the Dashtak Anticline.

Shahpour Cave is one of the archaeological and tourist attractions of southern Iran. Millanovic and Aghili (1990) proposed a cave origin model in which Shahpour Cave was formed by the action of diffuse recharge. As the base level lowered, new caves were created at lower levels, and high level conduits were abandoned. But the proposed model does not satisfy the morphological and hydrological conditions displayed at Shahpour Cave. This study examines the morphological characteristics and suggests a probable genesis for Shahpour Cave.

HYDROGEOLOGICAL SETTING

The study area is within the Zagros Mountain Range of southern Iran. Stratigraphical and structural characteristics of the Zagros sedimentary sequence were described in detail by James and Wynd (1965) and Falcon (1974), and simplified details are presented in Fig. 2. Formations of interest, in ascending order of age, consist of the Cretaceous Sarvak Limestone, Cretaceous Gurpi Shales and Marls, Tertiary Pabdeh Shales and Marls, Tertiary Jahrum Dolomite, Tertiary Asmari Limestone, Tertiary Gachsaran Anhydrite and Marl, Tertiary Mishan Marl, Tertiary Aghajari Sandstone and Quaternary Bakhtyari Conglomerate. The 314m-thick Asmari Formation is a well-jointed limestone with shelly intercalations at the type section. It lies disconformably on the Jahrum Formation or conformably on the Pabdeh Formation. The Jahrum Formation at the type section comprises a lower 35m of massive dolomite overlain by 288m of massive dolomitic limestone. The 798m-thick Pabdeh Formation is mostly shales and marls, with its upper part is composed mainly of thin bands of argillaceous limestone interbedded with shales. Contacts between the Pabdeh Formation and the Jahrum Formation or Asmari Formation are conformable and transitional.

Tectonically, the area falls within zone three (simply folded belt) of the Zagros orogeny (Falcon 1974), and overall the main folds follow the general NW-SE Zagros trend. Considerable karstification occurred in the Sarvak, Asmari and Jahrum formations (Raeisi and Moore, 1993; Raeisi et al, 1993; Raeisi and Karami, 1996) and many karst springs are found at the local base of erosion, especially at the contact between the carbonate units and the shaley formations that overlie and underlie them.

The Dashtak Anticline parallels the general trend of the Zagros Mountain Range (Fig. 2), and is best displayed by the outcrop of the Asmari Formation. Though exposed in a limited area at the foot of the Dashtak Anticline, the overlying Gachsaran Formation is mostly buried under the neighbouring plains. Drilling of the Dashtak Anticline by the Iranian Oil Company revealed 442m, 425m and 425m of the Asmari, Pabdeh and Gurpi formations respectively. Significant tectonic features include several faults and master joints, most of which are parallel to the anticlinal axis. A prominent morphological feature is the Chowgan Valley, which is cut normal to the Dashtak Anticline, such that the Pabdeh-Gurpi formations are exposed in the valley floor and the Asmari-Jahrum formations form two vertical cliffs. The Shahpour River flows through the Chowgan Valley (Fig. 2), which divides the mass of the Dashtak Anticline into Shahpour Mountain and Davan Mountain. Probably the valley is a tectonically-guided feature; development of the Gatar-Kazerun Fault near the NW plunge of the Dashtak Anticline may have also caused a major fracture along the Chowgan Valley (Mohab Ghods Consulting Engineering, 1990). Originally the Shahpour River was superimposed on the Asmari Formation (Oberlander, 1965), flowing along the major available fracture, but later erosion and karstification developed the Chowgan Valley. Shahpour Cave is located on the north-western flank of the Dashtak Anticline (Fig. 2). The main entrance is located on the north-western cliff of the Chowgan Valley, 200m below the ridge, and 1320m and 500m above mean sea level and the valley bottom respectively.

Stratigraphy around the cave entrance was studied by means of 31 rock specimens, which revealed that Shahpour Cave is formed entirely within the Asmari Formation. The contact between the Asmari and Jahrum formations lies 15m below the main entrance; the Jahrum Formation is some 20m thick and its transitional contact with the Pabdeh Formation is marked by an increase in marls and microfossils such as *Miscellanea minata* and *Globigerina triloculinoides*. Index fossils of the Asmari Formation and the Jahrum Formation are *Nummulites intermedius* Fichteli and *Sistanites iranica*, respectively. Dominant textures in the Asmari Formation are micrite and microsparite, and various porosities, such as intraparticle, moldic, shelter, fracture, cavern and vug have been observed. Biomicrite is the most common texture in the Jahrum Formation.

The most prominent karst features are various karren forms, dry valleys, caves and springs. Dry valleys are observed on the flanks of the Dashtak Anticline, where deep valleys with vertical walls have formed on the steep slopes. Caves are known on the north-western cliff of the Chowgan Valley and several springs emerge at the foot of the Dashtak Anticline, but no sinkholes, shafts or pits have yet been found.

The local climate is semi-arid and characterised by winter and early summer showers, with a mean annual precipitation and temperature of 498mm and 18.2°C respectively.

CAVE PATTERNS

Plan and profile maps of Shahpour Cave (Figs. 3 and 4) were prepared by standard cave survey methods, the length and direction of traverse lines being measured by tape and Brunton compass or theodolite, respectively. The cave consists of four major passages (Shahpour Avenue, Stalactite Gallery, Sunlight Passage and Ghosts Avenue), three chambers (Big Dome, Bat Chamber, and Pearl Chamber), two main entrances (Shahpour Entrance and Sunlight Entrance) and seven minor passages (Fig. 3). The total cave length using projected map length, continuous linear development and discontinuous linear development is 736m, 1229m, and 815m respectively. The length of the longest continuous passage is 320m by projected map length, 372m by continuous linear development and 350m by discontinuous linear development. Profiles along the main passages are presented in Fig. 4.

From the Sunlight Entrance, which is 40m higher than the Shahpour Entrance, the ceiling and floor both slope downwards towards the end of the cave. Sunlight Passage is part of the upper level of Shahpour Cave. The semi-elliptical Sunlight Entrance (6m maximum height and 30m maximum width) is located on the north-western Chowgan Cliff, such that the cave is not easily accessible by this entrance. Sunlight Passage is 83m long, 20m wide and 5m high on average, and has a slope of 29°. The sun completely lights the passage. The main passage ends abruptly, but it is connected to Ghosts Avenue via Wind Passage, which is located on the left wall, 15m from the end of Sunlight Passage. Large and small breakdown blocks, gravel, cobbles and sand are present on the floor and other significant cave features include condensation corrosion features, one column, and massive breakdown.

Shahpour Entrance is also semi-elliptical, reaching 45m wide at its greatest point, and 20m at its greatest height. It is reached by a 230-step man-made staircase outside the cave. Shahpour Avenue extends northwards

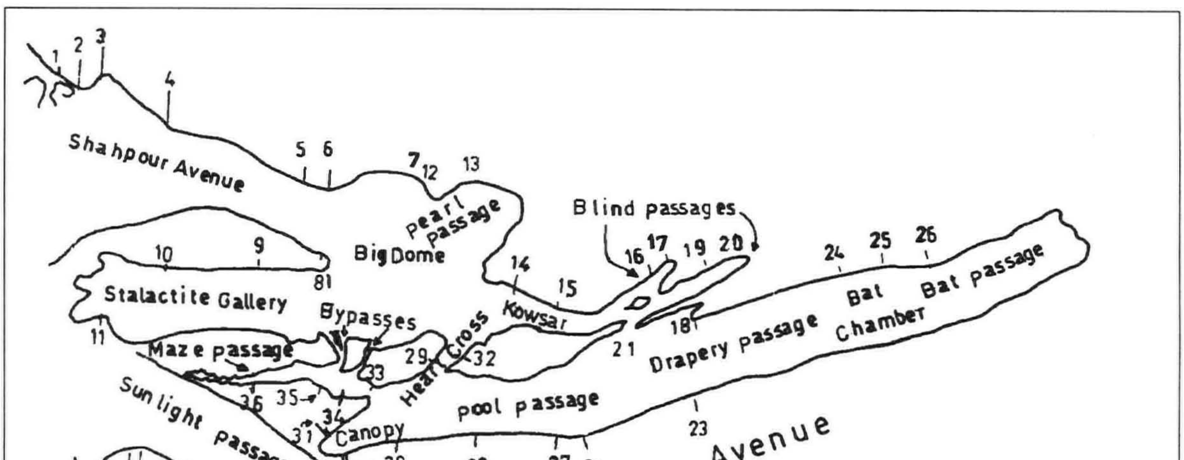


Figure 3. Plan of Shahpour Cave.

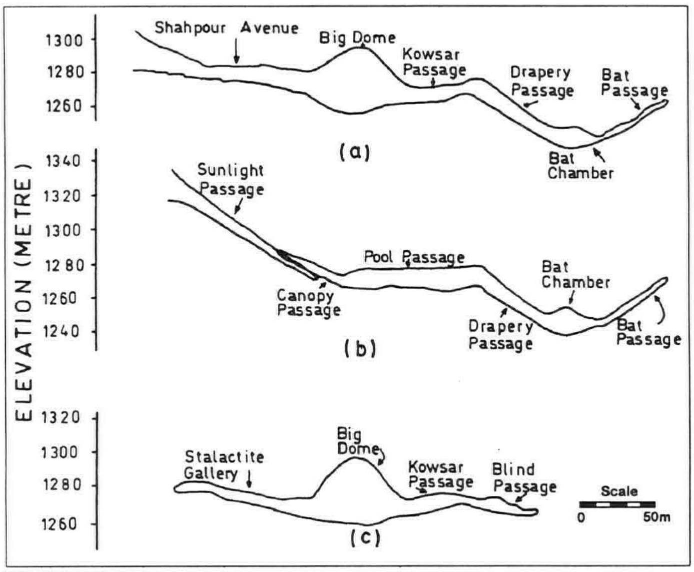


Figure 4. Profile of Shahpour Cave along (a) Shahpour Avenue, Big Dome and Ghosts Avenue (Canopy Passage, Pool Passage, Drapery Passage, Bat Chamber and Bat Passage) (b) Sunlight Passage and Ghosts Avenue (c) Stalactite Gallery, Big Dome, Kowsar Passage and Blind Passage.

and is 100m long, 20 to 50m wide, with a ceiling that ranges from 6 to 30m high. The natural form of this passage has been modified by humans during an extensive occupational history. The natural downward slope of the floor has been altered to a stair-step pattern along the first 60m of its length. A 6m-high statue of Shahpour, the second king of the Sasani Kingdom (241 AD to 271 AD), is located 25m from the Shahpour Entrance and the remains of Sasani carvings are present on both walls of the cave.

Shahpour Avenue leads into the Big Dome, up to 39m high and 40m in diameter, with a total volume of 57000m^3. A stream sinks in the bottom of its steeply sloping, bowl-like floor. The Big Dome has probably been enlarged by ceiling breakdown. Pearl Chamber, Stalactite Gallery, Kowsar Passage, Heart Passage and three minor passages radiate from the Big Dome, all standing at least 5m above the Big Dome floor. The north-west aligned dead-end Pearl Chamber has a maximum diameter of 23m and maximum height of 13m. Stalactite Gallery extends 80m towards the south, with a maximum height and width of 11m and 34m respectively. The abruptly dead-ended Stalactite Gallery is parallel to Shahpour Avenue but at a lower level. The dead-end wall is confirmed as bedrock because it forms part of the Chowgan north-western cliffs.

The Big Dome is connected to Ghosts Avenue via Kowsar Passage, Heart Passage and By-passes 1, 2 and 3, the small total cross-section of which, when compared with the other main passages, indicates that they may be diversion conduits. Kowsar Passage, which leads into blind passages and, from the right wall, into Drapery Passage, is 30m long, with a maximum width of 7m and a maximum height of 10m. The upslope of its floor reduces the height near Blind Passage. Rimstone dams and man-made pools are found on the floor. The dead-ended blind passages 1 and 2 are 10 and 20m long respectively, and they have irregular cross-sections. Heart Passage is 10m long, with a maximum width of 5m and maximum height of 3.5m. By-passes 1, 2 and 3 also have irregular cross-sections.

Ghosts Avenue extends north-west and is 240m long. On the basis of slope variations it can be divided into five sections: Canopy Passage, Pool Passage, Drapery Passage, Bat Chamber and Bat Passage. The steeply sloping Canopy Passage has a length of 30m, maximum width of 15m and maximum height of 6m. This passage comes to a dead-end to the south-east, and is connected to Sunlight Passage via Wind Passage, which is located on the right-hand wall. Wind Passage is a 13m-long crawl of irregular cross-section, passing through breakdown blocks. From the left wall of Canopy Passage, Maze Passage extends nearly 50m to the south, passing through and being terminated by breakdown blocks. It seems that Sunlight Passage was connected to Canopy Passage via Maze Passage before the latter's breakdown. The massive breakdown around Wind and Maze passages implies that Sunlight Passage and Ghosts Avenue were connected and probably formed the upper level of the cave.

Canopy Passage leads into the horizontal Pool Passage, which is 65m long, with an average height of 7m and a maximum width of 25m. A pool with a maximum depth of 70cm completely covers the north part of this passage during the wet season. Pool Passage leads into the 45m-long Drapery Passage, which extends steeply downslope at 35°. The steep slope of Drapery Passage changes to the bowl-like floor of Bat Chamber, which is 15m long and 23m in maximum diameter, with a dome-like ceiling that is 15m high. A stream sinks into the bottom of the chamber. Beyond the chamber is the steeply up-sloping Bat Passage, which comes to a dead-end to the north. The terminal portion of this passage has a reduced cross-section, with many columns and abundant flowstone. Many bats are found in Bat Chamber and Bat Passage.

Various types of deposits cover the floors of all the passages, so only the upper part of the cross-sections could be mapped (Fig. 5). Semi-elliptical or semi-circular cross-sections in most of the main passages indicate that the cave developed under phreatic conditions. The entrance of Sunlight Passage is semi-elliptical, but the rest of its cross-section is rectangular due to massive breakdown. Details of speleothem and speleogen distribution in the cave are shown in Fig. 6. It contains a variety of carbonate and sulphate speleothems, among which are stalactites, stalagmites, soda straws, columns, draperies, flowstone, rimstone dams, moonmilk, corals, pearls and gypsum crusts. Dissolutional sculpting, including wall and ceiling pockets, etchpits, condensation corrosion features and joint determined wall cavities, is also observed in the cave. Two streams sink at the bottom of the bowl-like floors of the Big Dome and Bat Chamber. Clay, silt, sand, gravel, boulders, breakdown bedrock, fallen speleothems and bat guano are the most abundant cave interior deposits.

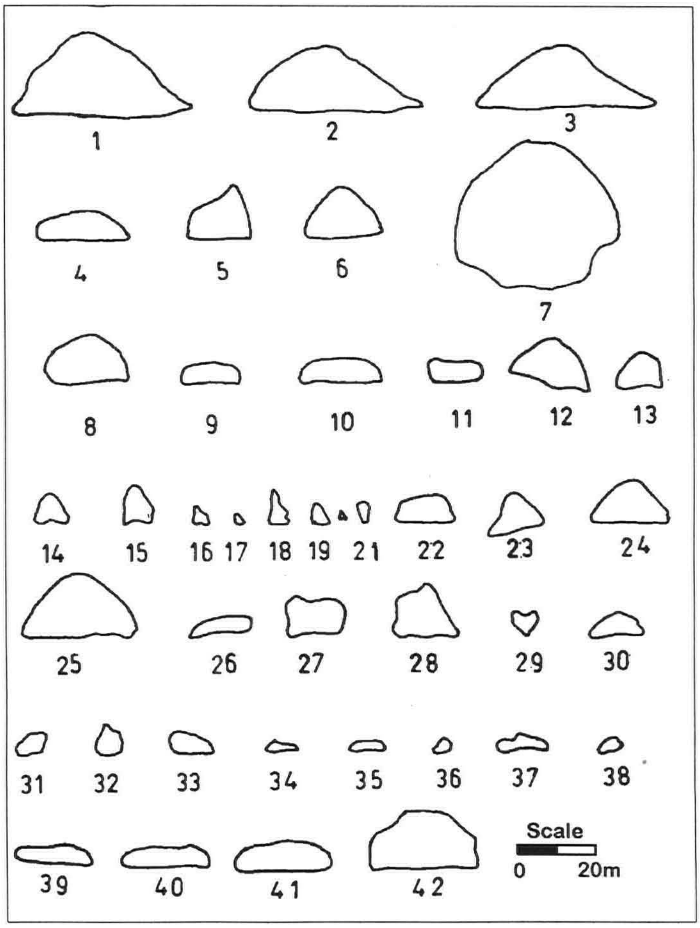


Figure 5. Cross-sections of Shahpour Cave (The numbers indicate the location of cross-sections on Figure 3).

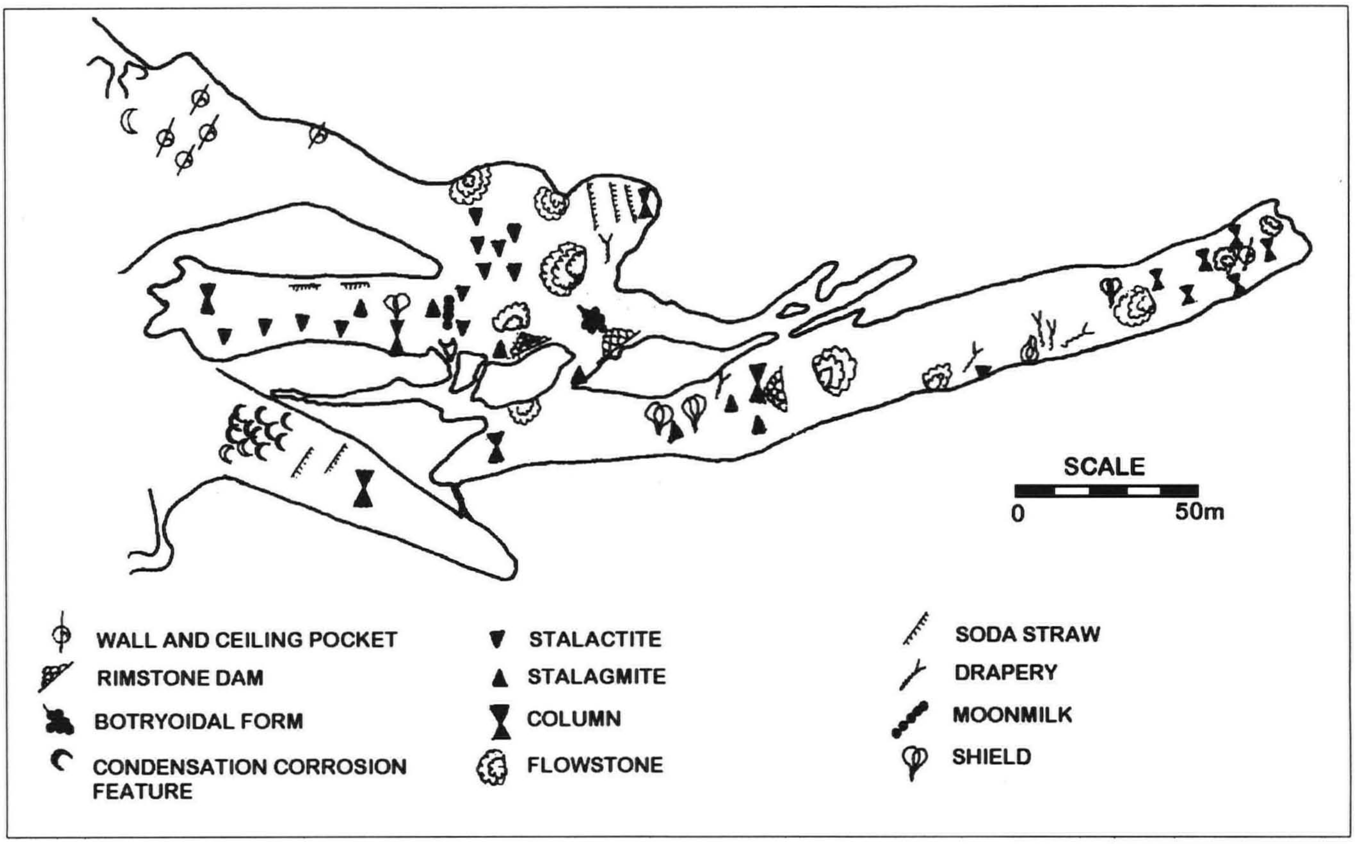


Figure 6. Speleothem and speleogen locations in Shahpour Cave.

CLASSIFICATION OF SHAHPOUR CAVE

Shahpour Cave is a single anastomotic tiered cave. Sunlight Passage and Ghosts Avenue constitute the higher level cave (Fig. 4). At present Sunlight Passage is connected to Canopy Passage by the narrow Wind Passage (Fig. 3). Maze Passage lies within broken blocks, revealing that the connection between Sunlight and Canopy passages was extensive. Almost identical steep slopes in Sunlight and Canopy passages confirm an extensive connection. The second level may have been conceived at the same time as the first level, during the earliest stages of cave development along different guiding horizons (Lowe, 1992a). As the water table and the level of the Shahpour River dropped, the second level developed its present form. The second level comprises Shahpour Avenue, Big Dome and Ghosts Avenue. Lower level passages (Shahpour Avenue and Big Dome) connected with upper level passages (Ghosts Avenue) through constricted features such as Bypasses 1, 2 and 3, Heart Passage and Kowsar Passage. Abrupt dead-ends in Stalactite Gallery and Blind Passages may be back-flood features. Each level could be considered as a single cave. The uniform width of the cave along its path implies that the cave is anastomotic.

Semi-elliptical cross-section 65m into the Shahpour Avenue. It indicates that the cave developed under phreatic conditions.

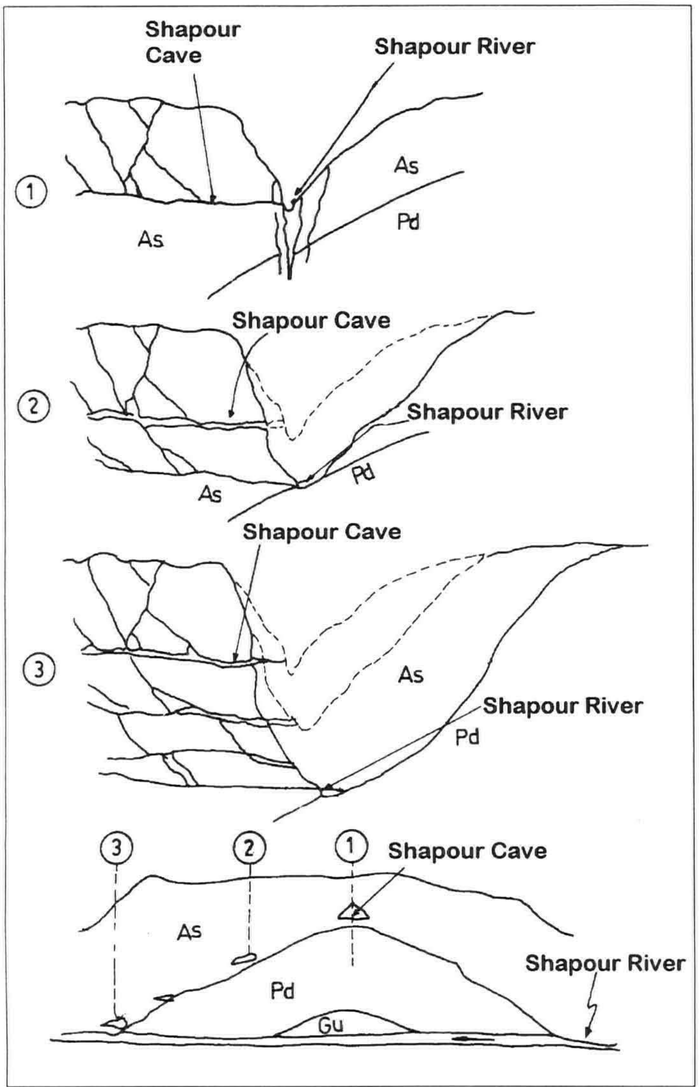


Figure 7. Model for the origin of Shahpour Cave proposed by Millanovic and Aghili (1990).

DISCUSSIONS AND CONCLUSIONS

According to an earlier model for the origin of Shahpour Cave (Millanovic and Aghili, 1990), the cave was formed by the action of diffuse recharge on the catchment. The Sunlight and Shahpour entrances were thought to be sites of emergence and, hence, Shahpour Cave was believed to have fed water to the Shahpour River. As base level lowered, new caves were excavated at lower levels (Fig. 7). However, the exposed limestone above Shahpour Cave is not horizontal (as illustrated in the proposed model), but it dips steeply near the plunge of the Dashtak Anticline (Fig. 8). In addition, as the cave lies on the north-western flank of the Dashtak Anticline, its catchment area would have been only 3km^2 if the Shahpour Entrance was an outlet for groundwater flow. If the Sunlight Entrance was the outlet the catchment area would have been even less than 3km^2. Development of so large a cave in such a small catchment area appears unlikely. Recharge water flows only into joints and the soil, as there are no known sinkholes or shafts in the Dashtak Anticline. The water loses its aggressivity as it passes through a thick aquifer above the Shahpour Cave, with its cover of soil and its narrow joint system. Therefore the significance of the diffuse recharge to cave development must be limited. Currently the electrical conductivity of cave drip water ranges from 353 to 443 micromhos/cm, implying that water entering the cave is almost fully saturated.

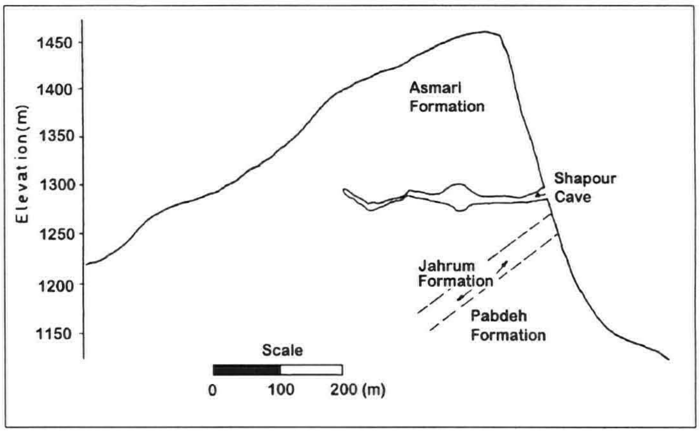


Figure 8. Profiles of Shahpour Mountain and Shahpour Cave.

An alternative model proposed here is that Shahpour Cave was enlarged from pre-existing proto-conduits by recharge from the Shahpour River. Initially the Asmari Formation was exposed only around the axis of the Dashtak Anticline and base level, the contact between the Gachsaran and Asmari formation, was higher than at present. The Shahpour River was superimposed upon the Asmari Formation, entrenching the Shahpour Valley (Fig. 9). Leakage from the Shahpour River into dissolutionally enlarged joint and bedding plane fissures (perhaps the inception horizons of Lowe, 1992a) built a ground-water mound and thus a hydraulic head across the aquifer, resulting in the enlargement of the upper level caves. The general direction of flow was imposed by the elevation of the steeply dipping Pabdeh Formation strata that underlie the Asmari Formation, such that flow was from the Shahpour River towards Shahpour Mountain, not towards Davan Mountain (Fig. 9). Total possible vertical flow was restricted to the thickness of the Asmari-Jahrum formations. Water flowed through Sunlight Passage and Ghosts Avenue, from an early course of the Shahpour River. As base level (the contact between the Asmari and Gachsaran formations) dropped, and the Shahpour River cut down in the Chowgan Valley, the second level of the cave was enlarged and the higher level caves were abandoned. The second level cave consists of Shahpour and Ghosts avenues.

Shahpour Cave may be the remains of a longer cave that extended to the contemporary location of the Shahpour River at the time of cave development. The cave terminates in up-dip directions, ending at Bat Passage, and the water outlet may lie on the flank of Shahpour Mountain, 100m away from the end of Bat Passages (Fig. 8). If the upslope of Bat Passage continues to the surface the postulated outlet may have been filled by talus or transported sediment on the steep slope of the northern flank of Shahpour Mountain, or by cave collapse (White, 1987). The thickness of limestone above the proposed outlet would be least along the line of Shahpour Cave (Fig. 8), corresponding to the epikarst. High dissolution rates in the epikarst could reduce ceiling stability, resulting in cave outlet collapse. Less probable alternative outlets are the current Big Dome and Bat Chamber sinkholes. The proposed model is justified as follows:

1. There are no known caves on the south-eastern cliff of the Chowgan Valley, but there are many caves on the north-western cliff (Fig. 10). The catchment area of the south-eastern cliff area, at an elevation and location similar to Shahpour Cave, is larger than the Shahpour Cave catchment area (Fig. 9). Surface karst and epikarst above the two cliffs are similar. Therefore, if Shahpour and the other caves on the north-western cliff were formed by diffuse recharge on the appropriate catchment area, similar processes should have developed caves on the south-eastern cliff. Lack of caves on the south-eastern cliff implies that the north-western cliff caves were enlarged by leakage from the superimposed Shahpour River. The steep dip of the Pabdeh Formation prevents flow of water towards the south-eastern cliff (Fig. 9).

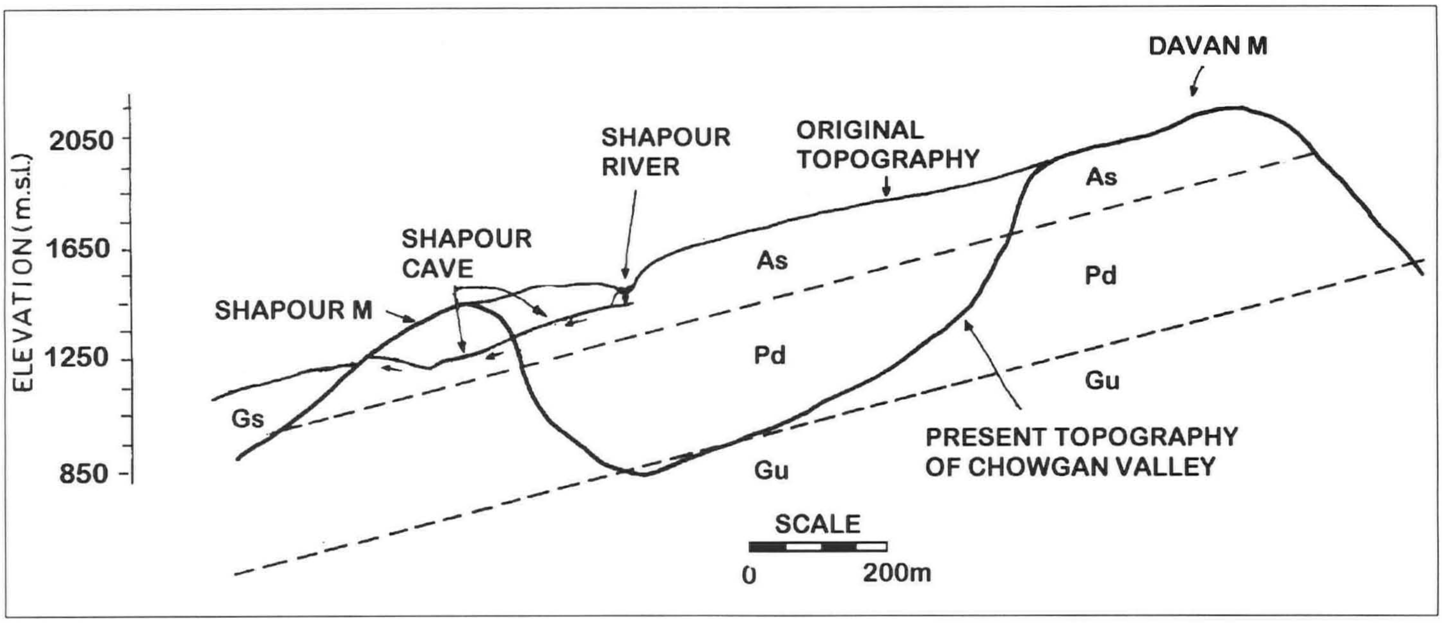


Figure 9. Proposed model of the development of Shahpour Cave.

2. Shahpour Cave is a single passage cave with a very large cross-sectional area at each level. If the cave was developed by infiltration water from the related catchment area, it would necessarily have numerous branches.

3. Shahpour Cave is a single anastomotic cave at each level. Palmer (1991) states that anastomotic mazes are formed by run-off that enters the soluble rocks either as sinking streams or as bank storage along entrenched rivers during floods, providing that hydraulic gradients are steep enough to achieve uniform passage enlargement along many alternative flow routes. Such mazes are produced only by water sources that fluctuate greatly in discharge. Palmer (1991) concludes that flood water forms include injection features and diversion conduits. Injection features, such as dissolution pockets and dead-end passages are formed by bank storage adjacent to flood-prone passages or surface rivers. Diversion conduits transmit flood water around passage constrictions. Many caves contain a combination of both. The dissolution pockets at Shahpour Avenue, dead-end passages such as Stalactite Gallery and Blind Passages, diversion conduits such as Heart Passage, Kowsar Passage and Bypasses 1, 2 and 3 show the effects of flood water. As the flow dropped to the Shahpour Avenue level, constriction between Big Dome and Ghosts Avenue caused water to pond upstream, forming dissolution pockets and dead-end passages.

4. Condensation corrosion features are formed when water vapour condensation occurs under conditions of lowering air temperature. Such features cannot be formed at the entrance, where air temperatures are similar to the adjacent outside atmosphere. This suggests that Sunlight Passage must be part of a longer passage that once continued towards the Shahpour River. If Sunlight Passage maintains the observed slope trend, the catchment area of Shahpour Cave would be even less than $3km^2$.

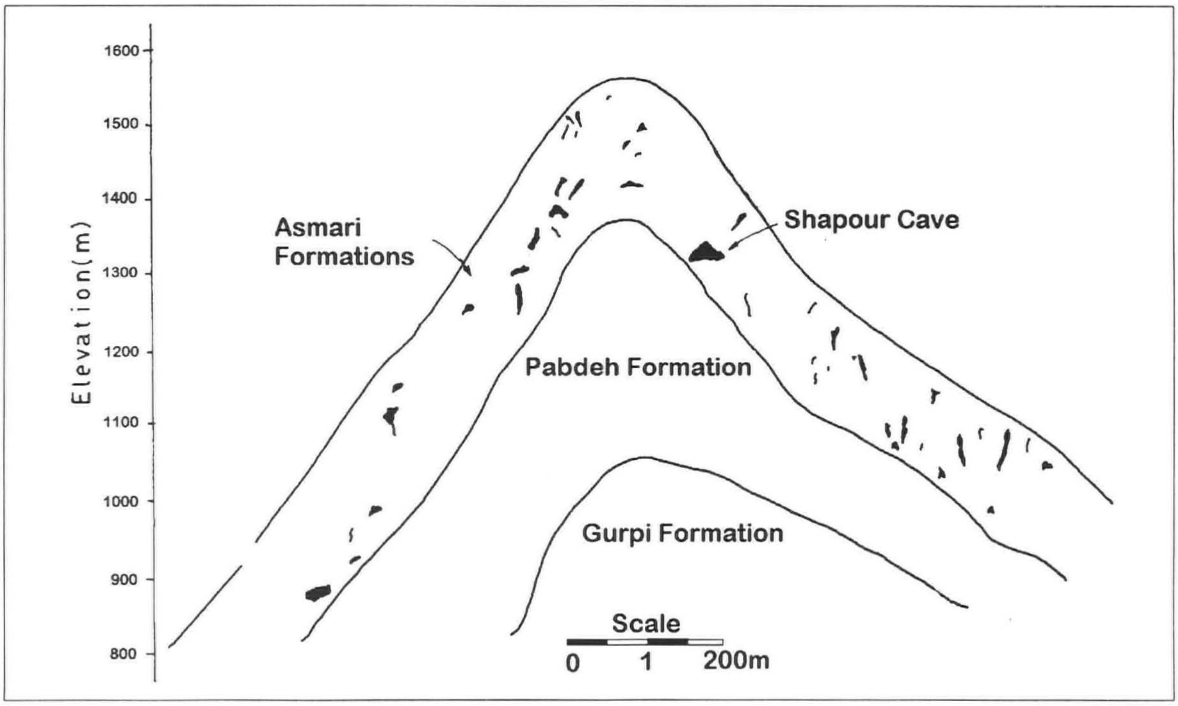


Figure 10. Distribution map of caves on the north-western cliff of the Chowgan Valley.

ACKNOWLEDGEMENTS

We sincerely thank Dr Wolfgang Dreybrodt for visiting the caves, reviewing an early draft of the paper, and offering valuable suggestions. We are also especially grateful to Dr John Mylroie, Dr Tony Waltham and Professor John Gunn for reviewing the paper and providing constructive comments. Thanks are also due to Mr M Afghah, for help with microfossil studies, and Dr Dave Lowe, who helped to improve the English in the paper. The authors thank the Research Council of Shiraz University for financial support.

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CAVE AND KARST SCIENCE Vol. 24, No.1, April 1997
Transactions of the British Cave Research Association

Kent's Cavern - whence and whither?

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Foreword: The following paper is reprinted, with permission, from the *Transactions and Proceedings of the Torquay Natural History Society*, Vol. XXI, 1995, 198-211. The content of the paper is reproduced essentially unchanged, but a number of minor editorial amendments and adjustments to the format have been made, to bring the text more closely into line with the *Cave and Karst Science* "house-style".

William Pengelly, lacking the apparent inhibitions of his predecessor John McEnery, revealed to a cautious and frequently sceptical Victorian world the immense geological and archaeological contribution of Kent's Cavern toward resolving the controversy concerning the antiquity of mankind. By devising a methodical system of excavation within the cave, keeping a meticulous record of details of sediments, fossils and artefacts, and making scrupulously conscientious and reliable reports to the British Association and therefore to the scientific community at large, he well repaid the investment of £1,900 made by the Association that made the 16-year excavation from 1865-1880 possible.

The information he assembled remains a highly valuable data-bank but his method is not without criticism. Against today's practice, which would take only a representative sample, far too much was dug out of the Cavern, perhaps to satisfy the Victorian fashion for acquiring personal and institutional collections of rock samples, fossils and artefacts, or simply destroyed. Three years after starting work, Pengelly stated that there was reason to hope that the Association would be willing to carry on this important excavation until the Cavern was completely emptied of its contents (1868, p.469). We must however be thankful that, although a captive of his time in this respect, Pengelly kept such superb records and in fact dug only a little more than a metre (4 feet) below the floors of stalagmite.

WHENCE CAME THE CAVERN?

The first question, *"When was the Cavern initiated?"*, is the most difficult to answer. Its formation is certainly linked with the development of the Ilsham valley, which, ignoring recent disruption by cliff recession in Anstey Cove, can be traced back to St. Marychurch. The valley is, however, associated with the remarkable Babbacombe-Walls Hill platform, which seemingly is cut across Devonian limestone and New Red Sandstone alike. Pengelly (1864) regarded this platform as a *"terrace of denudation"* produced by wave erosion during a former period of high sea-level. Jukes-Browne (1907) linked it with others around Torquay as *"parts of one inclined plane"* (p.107), possibly a *"remnant of the basal Eocene plane"* (p.114). More recently, Lloyd (1933, p.118) confessed uncertainty regarding age, but perceptively suggested that planation may have been initiated in Permian times.

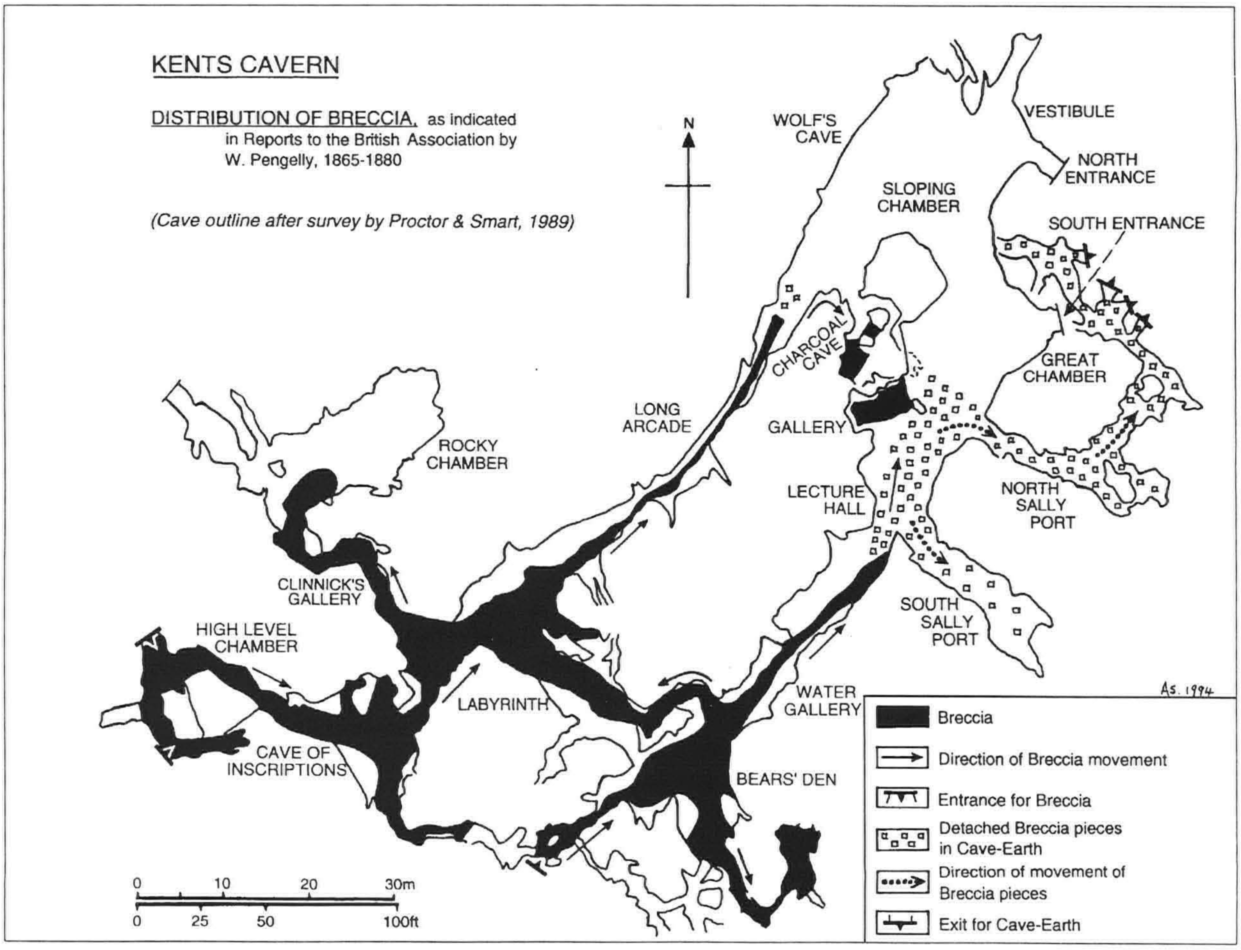


Figure 1. Distribution of the Breccia in Kent's Cavern.

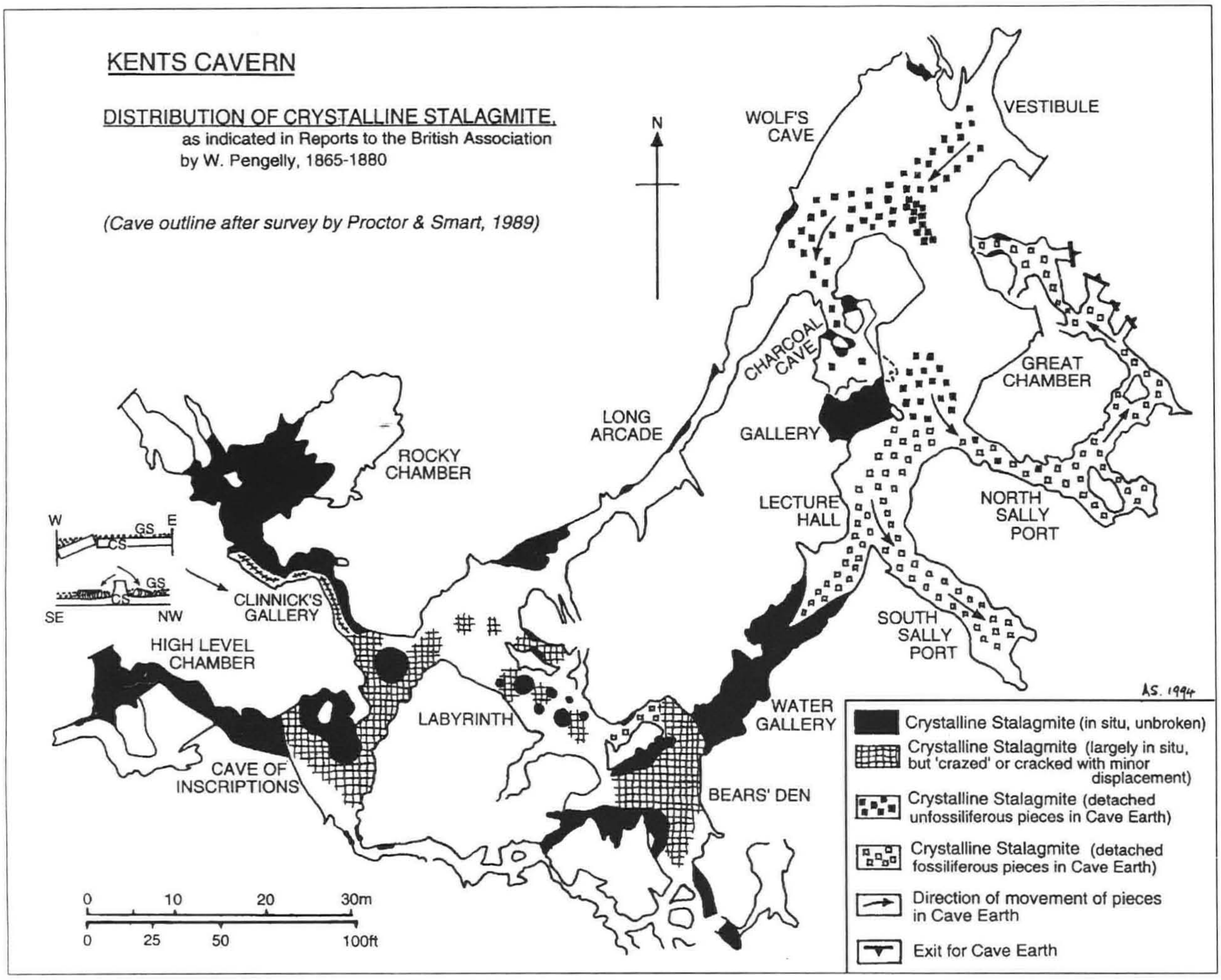


Figure 2. Distribution of the Crystalline Stalagmite in Kent's Cavern.

If the platform were produced by marine processes it could not, in the light of present knowledge, have been produced by either Cretaceous or Eocene transgressions over 45 million years ago, but, altitudinally, it does fall within the range of Pleistocene high sea-levels. There is evidence in South West England that a transgression over a long-eroded late Tertiary land surface reached a height of c.130m around the beginning of the Pleistocene Period, some 2 million years ago (Simpson, 1969; Straw, 1986). The Walls Hill platform might then have been eroded at a time when the descent of sea-level from 130m to its present height was reversed for a while, say about 1.5 million years ago, but it does not have the expectable seaward (easterly) gradient. Rather it slopes southwest toward the Ilsham valley, the alignment of which is in any case difficult to account for on such a hypothesis.

At St. Marychurch, the limestone gives way northward to a down-faulted mass of red Permian breccia and sandstone that originally stood higher than the limestone. There are numerous locations around Torbay where Permian rocks rest directly on eroded surfaces of limestone. These red rocks accumulated as debris fans and sandsheets wasted from adjacent hill and mountain slopes under a generally arid climate some 250 million years ago (Laming, 1982). In contemporary deserts such deposits commonly rest on abraded rock surfaces that may have been produced as pediments. Coarse Permian breccias, such as the Oddicombe Breccia, crowded with limestone and shale fragments, confirm much erosion of the rocks now forming the central hills of the Torquay promontory. Close to Kent's Cavern, breccia resting on limestone is exposed on the roadside next to the Palace Hotel gardens, and this may be a remnant of a former Permian cover of the Walls Hill platform, which could then be regarded as a portion of an exhumed Permian pediment. Lloyd (1933) and Richter (1966) have described fissures and galleries in limestones in the Torbay area that were produced by subterranean waters in Permian times even though the climate was hot and arid. Similar features may have developed in the Babbacombe-Kent's Cavern limestone outcrop beneath a Permian breccia cover, subsequently to pre-determine more extensive cave development such a vast time later in the early Pleistocene. Eastward retreat of the edge of a Permian cover from the rising shale slopes of Beacon and Warberry Hills would account neatly for the initiation and line of the Ilsham valley.

The south-draining alignment of this valley is important because it would influence the general southerly direction of groundwater movement within the limestone, confirmed by features in the Cavern. Such underground water would have had to come to the surface at the southern margin of the limestone outcrop because of the west-east fault that brings up the Lincombe Hill - Kilmorie Hill shales and grits, and this margin may well have been marked by a bluff created by the easier erosion of the shales and grits along the then Ilsham valley south of the fault.

The Cavern has developed through three overlapping phases. First, a *phreatic phase*, during which dissolution and abrasion by water and transported rock fragments occurred while the rock was still saturated. Second, a *vadose phase* when, with air in the higher passages, flowing water acted like a surface stream, and seepage induced speleothem deposition. These two phases probably spanned some 1 to 1.5 million years, and produced the macro-form of the Cavern we see today. Finally, a *sedimentation phase* of the order of 0.5 million years in which the introduction, accumulation and erosion of sediments occurred several times over. These sediments adorn and embellish the Cavern and have attracted intense human interest over the past 200 years or so.

The basic sequence, in descending order, is:

Granular Stalagmite
Cave Earth
Crystalline Stalagmite
Breccia

The oldest, the *Breccia*, accumulated as a series of debris flows under predominantly cold climatic conditions, and its distribution and composition confirm that it entered through passages at the rear of the Cavern (Fig. 1). The overlying *Crystalline Stalagmite* formed cumulatively within the cave as a speleothem deposit, probably over many periods of relatively warm climate, and once covered most of the floors of the galleries and chambers (Fig. 2). Recently-measured 'Uranium-Series' and 'Electron Spin Resonance' dates (Proctor, 1994) indicate that it aggraded between about 350,000 and 100,000 years ago. In places it lay directly on limestone (e.g. at the Bridge and in the front of the Cavern) but mostly it overspread the surface of the Breccia. Some time after 100,000 years ago *Cave Earth* accretion began in the front of the present Cavern, as extraneous material was introduced through the present entrances (Fig. 3). This too built up largely under cold climatic conditions, though warmer temperate phases are known to have occurred. It is overlain by the *Granular Stalagmite*, growth of which probably began after 11,000 B.P. (Jacobi et al, 1986). Rather than review previous accounts of these sediments, two problems will be addressed.

Soon after commencing digging Pengelly became intrigued by large disjunctive blocks of Crystalline Stalagmite that he found incorporated in the Cave Earth and Granular Stalagmite in the **Vestibule, Sloping Chamber, Great Chamber** and **Lecture Hall**. He quickly recognized their antiquity relative to the enclosing deposits and later discovered that the Crystalline Stalagmite originally had formed a Floor throughout the Cavern. But his attention was also caught by the appearance of this Stalagmite.

In the Lecture Hall (Pengelly, 1884, p.233):

> *".... masses of Crystalline Stalagmite were .... found everywhere in the Cave Earth, in the form of huge cuboidal masses with sharp edges. The Floor of which they are obviously remnants must have been fractured along planes at right and other high angles to its upper and lower surfaces."*

In the **Gallery, Charcoal Cave** and **Long Arcade**, the Crystalline Stalagmite survived as ledges or bridges adhering to the walls above the level of the Granular Stalagmite. In the Lake area, and again in the High Level Chamber it formed a continuous unbroken floor over the Breccia, but in **Clinnick's Gallery** (Pengelly, 1884, pp.371-2) it was curiously disposed:

> *"The state of the floor was a puzzling study. The Crystalline Stalagmite was broken in places near to, and parallel with, the left wall, and the fragments, occasionally considerable sheets, were raised some inches above their original level at their margin most remote from the wall, and depressed at that nearest to it, while everything remained intact at, and adjacent to, the opposite wall of the narrow gallery. The disturbance occurred obviously before the commencement of the formation of the Granular Stalagmite ..."*

John McEnery, who worked in the cave in the 1820s, had wondered also at the state of the Crystalline Stalagmite Floor in the **Bears' Den**, noting that the whole area was cracked/riven into large slabs, resembling flags in a pavement (Pengelly, 1869, p.307), and but for its division into insulated flags it would have been almost impossible to pierce through it (Pengelly, 1869, p.309). The **Cave of Inscriptions** was similar. Pengelly (1884, p.362-3) remarked that in its eastern part, although some portions were not dislodged, other masses had been removed by erosion, and in its western part (1884, p.378) the broken blocks were occasionally "faulted" to the extent of 2 or 3 inches. Both McEnery and Pengelly had considered possible causes of this disruption, including the fall of limestone blocks from the roof, undermining by animal burrows, subsidence of Breccia into lower passages, and streams of water coursing through voids between the Breccia and the overlying stalagmite after storms, the pressure of which burst the latter upwards. Vivian (1868) suggested, in addition, that the Breccia had undergone freezing, and that expansion had fractured the stalagmite, but Pengelly (1876, p.176) favoured a combination of block fall and water pressure under the stalagmite.

All these are possible, but they would have been localized in effect and what is so impressive about the disturbance of the Crystalline Stalagmite is its manifestation in most parts of the Cavern as a cracking or crazing event. For such a phenomenon an external energy source would seem necessary - a force such that the brittle Crystalline Stalagmite lying passively over most of the Cavern floor after some quarter of a million years of growth was shattered like a stone-struck pane of pre-stressed glass. One possible cause is vibration or a shock-wave that might have been generated by the collapse of adjacent parts of a more extensive Ilsham valley cave system, but another, more likely because of the scale of the phenomenon, is an earth tremor of sufficient magnitude to shake the limestone mass and thereby dislocate the Crystalline Stalagmite, especially along and close to certain of the more important joints.

Pengelly (1875) considered but discounted the efficacy of earthquakes in loosening blocks from the roof of the Cavern and ignored it with regard to the disruption of the Stalagmite, which he believed had taken place cumulatively over a long period. He did concede (1884, p.372) that a tremor might have occurred to break a columnar stalagmite in Clinnick's Gallery into three pieces, which were subsequently enveloped in Granular Stalagmite.

The dates obtained by Proctor (1994) indicate that aggradation of the Crystalline Stalagmite probably continued in many parts of the Cavern until at least 100,000 years ago, before it was fractured. Pengelly noted the sharp fresh edges of Stalagmite blocks in the Cave Earth and, although these are in part a consequence of the crystal structure, the inference is that they were broken not long before Cave Earth accumulation began. The Middle Palaeolithic archaeological content of the Cave Earth, (Campbell and Sampson, 1971), the faunal assemblage, and a date of 53,000 years BP on speleothem above thin Cave Earth in the **High Level Chamber** point to Cave Earth deposition having commenced probably about 75,000 years BP.

It can be postulated therefore that a catastrophic event occurred between 100,000 and 75,000 years. BP, in the early part of the Devensian cold stage and that this event was a substantial earthquake. Not only was the Crystalline Stalagmite shattered but there might have been at least four other effects:

1. Soon after this time the present North and South entrances became open to allow the ingress of Cave Earth material (Fig. 3).

2. Numerous small fissures also opened or re-opened throughout the Cavern, which had been completely sealed to anything except water for some quarter of a million years, to allow entry of small amounts of surface materials to produce sporadic thin patches of Cave Earth in the inner parts of the Cavern (Fig. 3).

3. Lower passages reached by the **North Sally Port** and perhaps by the deep fissure of the Long Arcade and bottom of the Sloping Chamber became eased or unblocked to allow the descent in the front half of the Cavern of detached masses of Crystalline Stalagmite and Breccia as components of the intrusive Cave Earth (Figs. 1, 2).

4. The **Wolf's Cave** seems to contain only Cave Earth. Pengelly (1884, p. 310) recorded no traces of Breccia and, except in the south-eastern corner, none of the Crystalline Stalagmite floor (Figs. 1,2). Excavations in 1926-1940 in Wolf's Cave and the **Vestibule** by a joint committee of the Torquay Natural History Society and the British Association removed a further 3 to 4 feet (c.1m) of material below Pengelly's four-foot trench, entirely in undisturbed Cave Earth (Beynon et al, 1929). In the Vestibule the excavation reached a depth of 34 feet (10m) below the datum line (the base of the Granular Stalagmite), still in Cave Earth around its many contained boulders of limestone (Ogilvie and Tebbs, 1938). The absence of Breccia and Crystalline

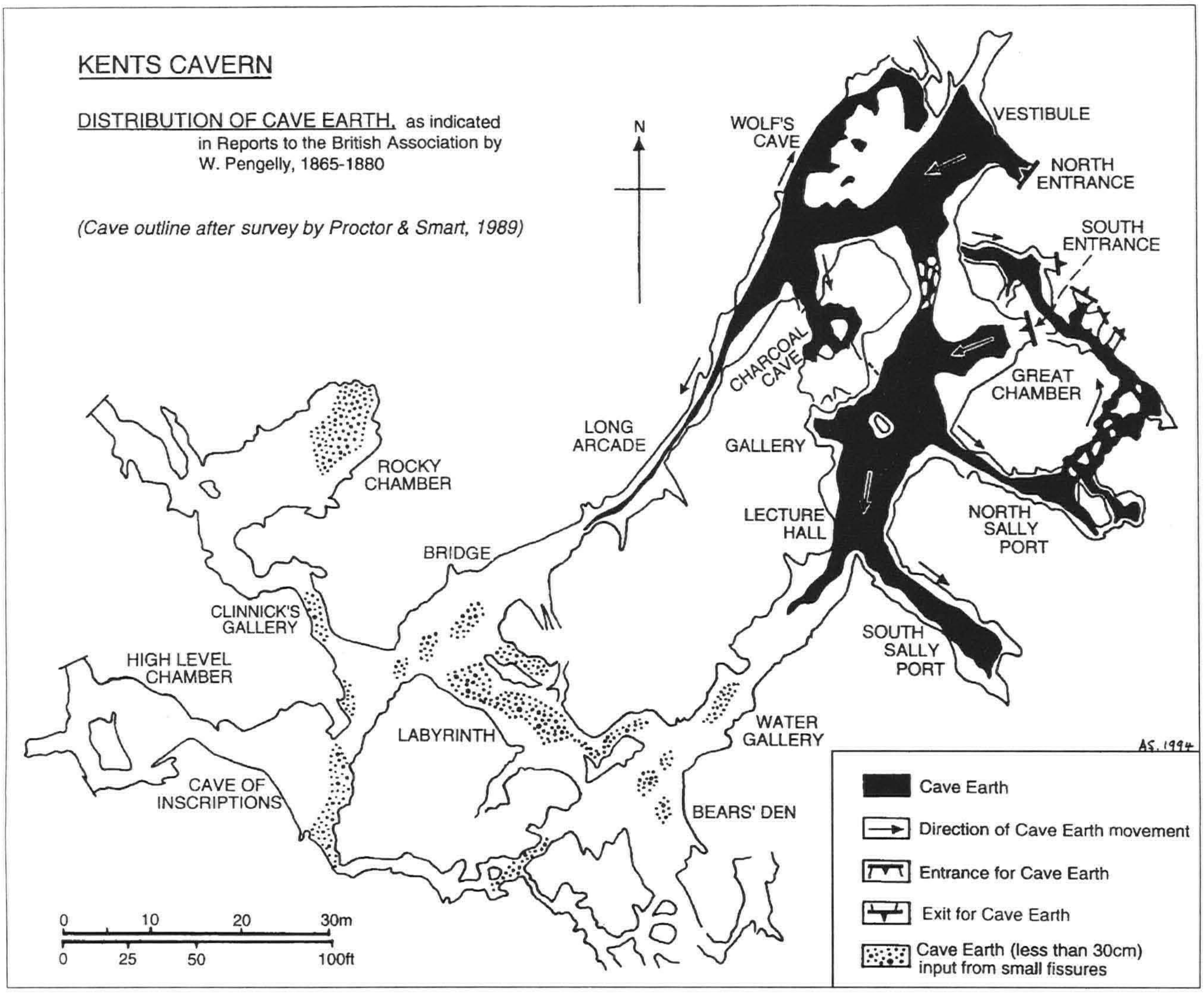


Figure 3. Distribution of the Cave Earth in Kent's Cavern.

Stalagmite becomes more significant when it is appreciated that these deposits formerly occurred at a somewhat higher level than the Cave Earth in the adjacent Long Arcade. It may well have been therefore that the floors of Wolf's Cave and the Vestibule were above the Crystalline Stalagmite level before Cave Earth time and that their lowering, perhaps by collapse into lower passages, was also a consequence of the earthquake.

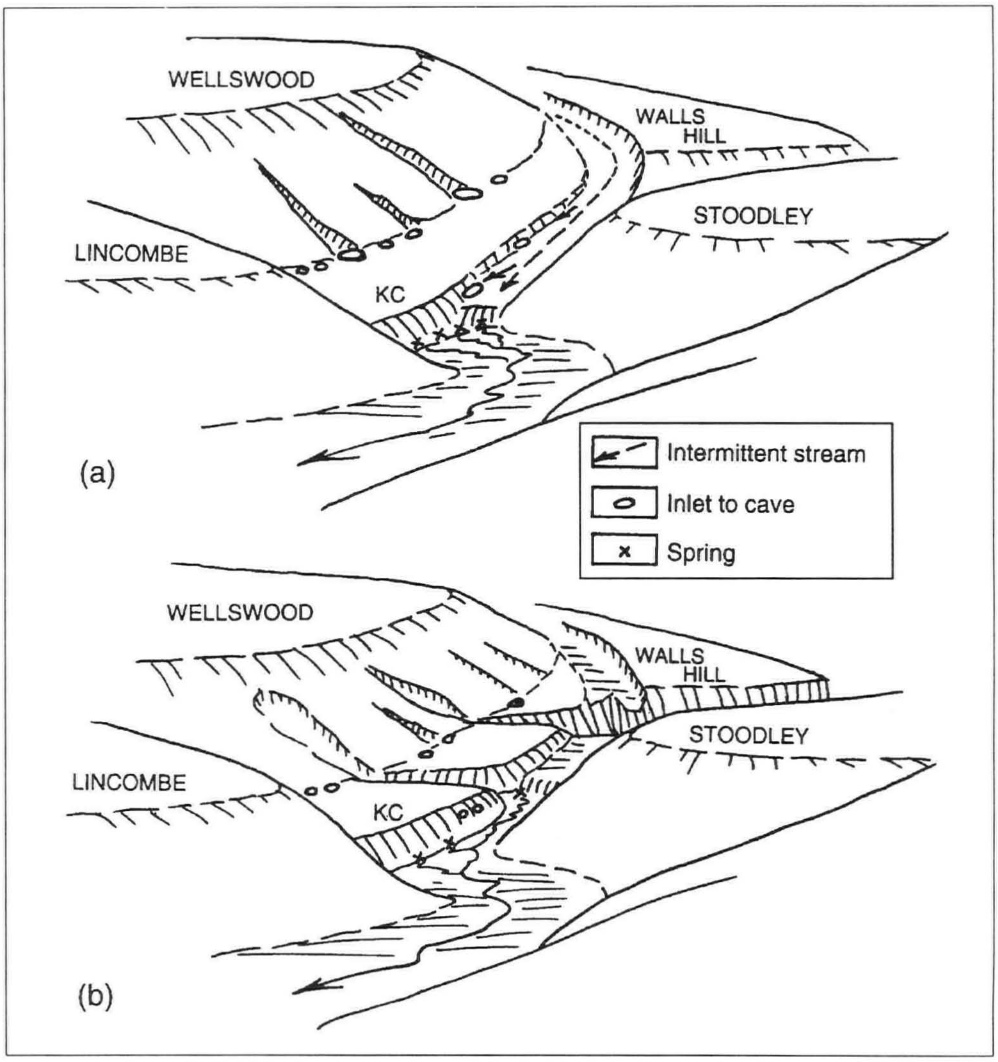
The second problem concerns the introduction of the Cave Earth through the present North and South entrances, over that period of time known in British Quaternary parlance as the Devensian. It contains a rich assemblage of mammal fossils including human remains and a wealth of artefacts referable to the Middle and Upper Palaeolithic as a consequence of the Cavern having served, alternatingly, as hyaena den and human shelter.

Pengelly (1880) maintained that although showing no signs of stratification the Cave Earth had accumulated by small instalments, washed in by flood waters and augmented by roof-fall blocks and fossil materials. Such a situation required the valley floor to be at the height of the entrances whereas it is now some 70 feet (22m) below them, and he admitted difficulty in accepting such valley erosion in hard limestone in the time available since the end of Cave Earth deposition. His speculative explanation was to regard the valley as deepened before Cave Earth formation, then filled with gravel up to the level of the entrances so that water could flow over the gravel surface into the Cavern. Finally, the unconsolidated gravel was rapidly removed. This smacks of special pleading, and an alternative suggestion can be made.

Today the Kent's Cavern limestone presents a steep slope, a bluff, to the Ilsham valley, and has a flattish upper surface that gives way abruptly on its northern side to the Ilsham Road gully (Fig. 4b). Previously the limestone surface would have been more expansive (Fig. 4a) with its bounding bluff standing further south-east and across the valley, closer to the west-east cross-valley fault that cuts off the limestone. Above the bluff the Ilsham valley would have been less deep than below it and through much of Devensian time its floor could have lain at about the level of the Cavern entrances. It is reasonable to suppose that surface streamflow was intermittent, with flood waters carrying successive increments of Cave Earth into the Cavern, while groundwater emerged as springs and seepage at the base of the bluff.

Cave Earth accumulation ceased fairly abruptly some 12,000 to 11,000 years ago, in part because the change then to more temperate climatic conditions would have reduced the supply of frost-worked material and snow-melt water, but more particularly perhaps because the valley floor was no longer at Cavern entrance height. For the last 9,000 to 10,000 years the Ilsham valley, breached by Anstey Cove and the Palace Hotel glen and without a stream, has geomorphologically been largely inactive. With so little time therefore available for so much valley deepening it seems inevitable that another catastrophic event took place. Noting the evidence for heavy roof-fall in the Wolf's Cave and Vestibule and the huge boulders blocking the north-west end of the Organ Chamber, it is proposed (though not proven) that the roof of a section of a 'master' system of underground passages along the axis of the Ilsham valley and a branch of it along what is now the Ilsham road finally gave way and collapsed to provide a 'new' valley floor at a lower level.

Figure 4. Sketch views of the Ilsham valley to NNW:
a) during Cave Earth accumulation;
b) after Cave Earth accumulation.



The Cavern as known today is not of course just a natural phenomenon. An object of human curiosity for at least 500 years, it gained its scientific reputation mainly through Pengelly who rendered substantial modifications to the appearance of the Cavern. In lowering the floors of most of the galleries and chambers by from 1 to 4m, he broke up and removed outside large numbers of limestone boulders up to 100 tons in weight that obstructed the passages, together with most of the sheets of Granular and Crystalline Stalagmite, including huge bosses of stalagmite in the Cave of Inscriptions, Labyrinth and Lecture Hall, and destroyed many stalactite and other dripstone features. He improved access to the Bears' Den through the Labyrinth, connected the Bears' Den and South West Chamber by burrowing under the Crystalline Stalagmite of the Lake, and provided an easier and lower route from the Arcade to the Cave of Inscriptions by removing congestion beneath the Bridge. He discovered Clinnick's Gallery, Organ and Rocky Chambers, High Level Chamber and Swallow Hole Gallery, and opened up the under-caves of the North Sally Port. He removed over 80,000 pieces of bone, artefacts and extraneous stones. As a consequence the Cavern became a larger, more extensive, cleaner, more accessible cave, but its original primeval, mysterious, challenging character was lost.

WHITHER GOES THE CAVERN?

What of the scientific future? A new survey of the Cavern by C. Proctor and P. Smart (1989) of the University of Bristol has allowed much better appreciation of the ramifications of the Cavern and its internal features, and samples of stalagmite taken for dating purposes have yielded age estimates that at last give a reliable framework of a chronology of events in the Cavern's history. More dates are needed, and further archaeological, geomorphological, geological, geochemical and palynological studies are desirable, in order to gain a thorough understanding, not only of cave history, but of the sequence and magnitude of climatic changes and their wider environmental consequences.

Whither the cave as a natural feature? It could of course be struck by a meteorite and obliterated, or by another earthquake and collapse like a 'house of cards', but by some 5,000 years ahead Britain could well be approaching the cold phase that will succeed our contemporary interglacial and a return to conditions that controlled accumulation of the Breccia and Cave Earth. What then?

1. With the Ilsham valley floor now well below the entrances, no Cave Earth-type material will enter.

2. The Ilsham Road valley will intercept and divert any water, rock waste or 'head' coming off the slopes of Wellswood Hill.

3. Breccia-type material might spread over the limestone surface from Lincombe Hill and descend, were passages are available, into the Cavern.

4. The entrances, if open to natural processes, will receive only scree, off the superjacent slopes, or wind-blown sediment.

5. Frost-action might affect the Cavern. The present Cavern temperature of 11°C reflects the annual mean air temperature of the Torquay area. During the last cold phase the latter was probably never lower than -5°C and it is very doubtful whether permanently-frozen ground existed, especially if annual snowfall was considerable. Permafrost is therefore unlikely in the future. Freeze/thaw oscillations within the Cavern would also be unlikely except close to any entrances where

frost-generated roof falls could take place. If freezing of the ground were only seasonal, groundwater could enter the Cavern, potentially to maintain speleothem formation. However lower biogenic CO_2 availability to this water would reduce the dissolved content of $CaCO_3$, and speleothem growth would be retarded, if not stopped.

The prognosis for the Cavern is therefore that when colder conditions approach, speleothem deposition will slow down and insoluble materials will enter only through small fissures and restricted entrances unless new openings have appeared. In the absence of humans it might again be encapsulated and slumber away for another quarter of a million years, awaiting the kiss of excavation by a future Pengelly. More likely, erosion will take its toll, and the Cavern's roof and the floors of its chambers will progressively thin, lose stability and collapse and, with that, eternal oblivion.

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CAVE AND KARST SCIENCE Vol. 24, No.1, April 1997
Transactions of the British Cave Research Association

An occurrence of mirabilite ($Na_2SO_4.10H_2O$) / thenardite (Na_2SO_4) in a cool temperate cave: Pollaraftra, County Fermanagh, Northern Ireland

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Abstract: Mirabilite (hydrated sodium sulphate) and thenardite (anhydrous sodium sulphate), whose occurrence in caves is normally restricted to tropical and semi-arid regions or caves where high temperatures are present, have been identified in Pollaraftra, a fault-guided cool temperate cave within the Dartry Limestone Formation of County Fermanagh, Northern Ireland. The minerals occur as fine, colourless to white, acicular crystals and as white powder on the matrix of a fault breccia, and are presumed to be derived from primary evaporite minerals within the Meenymore Formation, which overlies the cave-bearing Dartry Limestone.

INTRODUCTION

Pollaraftra is a 3.1km-long fault-guided cave developed within carbonate mudbank limestones, and their lateral equivalents, of the Dartry Limestone Formation in the Knockmore area, County Fermanagh, Northern Ireland (Figs 1 and 2). The Dartry Limestone is overlain by the Meenymore Formation, a mixed sequence of marine carbonates, shallow water sabkha style carbonates with evaporite minerals, and calcareous shales and mudstones. This in turn is overlain by the Glenade Sandstone Formation (Fig. 3). These formations are of Asbian (Viséan, Carboniferous) age. The Pollaraftra Fault appears to be a normal fault, with an approximate downthrow of 50 to 100m towards the south. On the surface, the Meenymore Formation is faulted against the Dartry Limestone, although within Pollaraftra, the Dartry Limestone forms both the foot wall and hanging wall of the fault (Fig. 3).

LOCATION

The minerals occur predominantly on the matrix and, to a lesser degree, on the clasts of a fault breccia that forms part of the passage walls immediately downstream of Sump 1 (Fig. 2) in Pollaraftra. The breccia clasts are derived from the Dartry Limestone, while the matrix is composed of highly tectonised and weathered limestone.

DESCRIPTION

The Pollaraftra mineral deposits most commonly form a distinctive coating of translucent acicular (needle-shaped) crystals, approximately 5mm in length, with a bitter saline taste. The crystals, which occur as patches over an area of approximately $2m^2$, are sometimes replaced by a

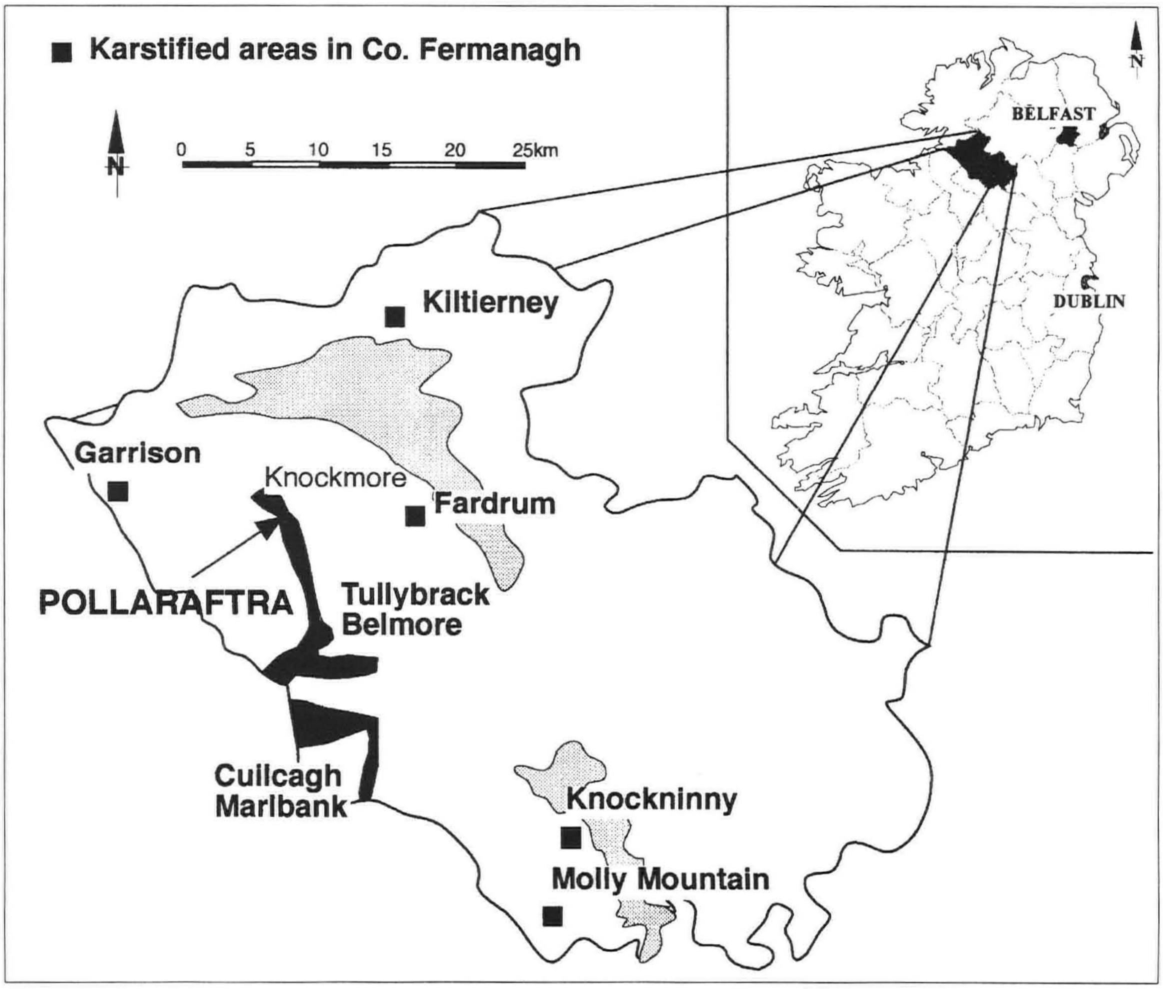


Figure 1. Maps of Ireland and Co. Fermanagh, showing main karst areas and location of Pollaraftra.

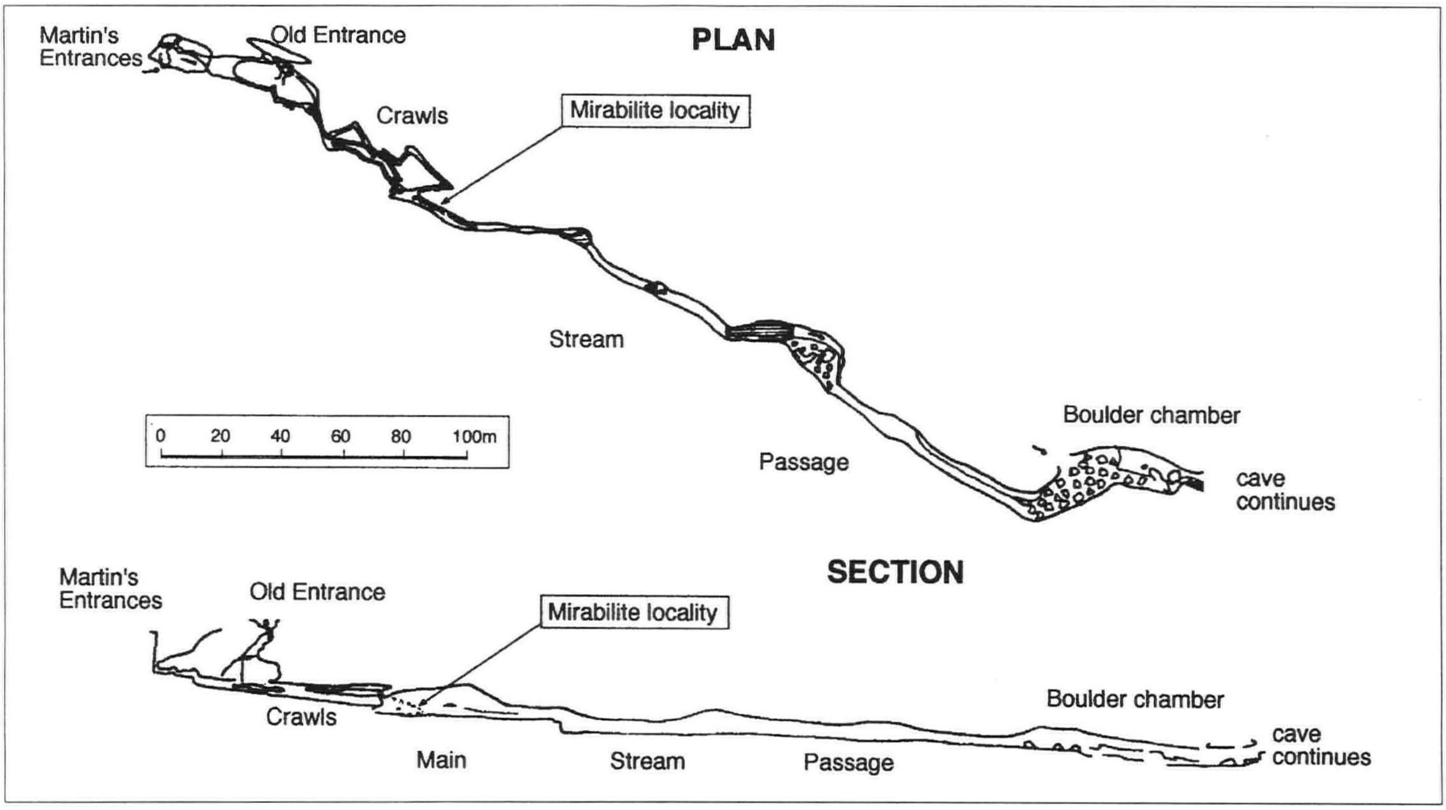


Figure 2. Survey of the entrance series of Pollaraftra, showing the mirabilite/thenardite locality. (Modified from a BCRA Grade 5c survey by R A Solari.)

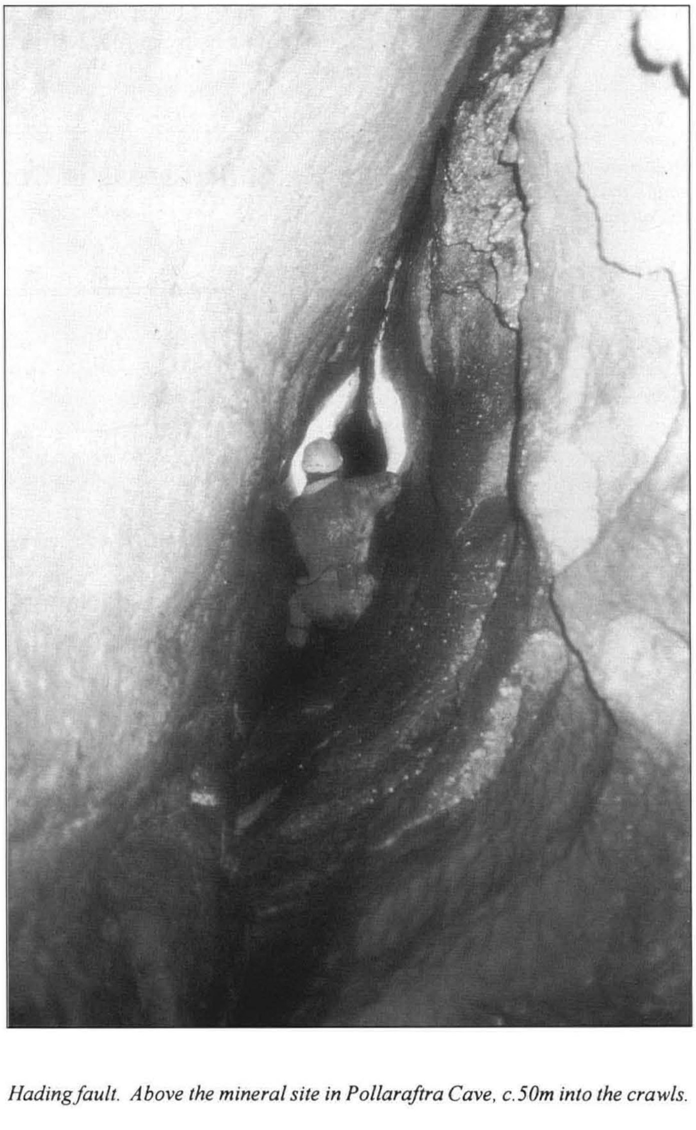
fine white powder. The cave passage floods regularly and neither crystals nor powder are always present. Flame tests give a strong yellow colour, distinctive of sodium, and this, the crystal habit and the distinctive taste confirm that the crystalline mineral is mirabilite ($Na_2SO_4.10H_2O$). The fine white powder, occasionally replacing the crystals at this locality, is thenardite (anhydrous sodium sulphate, Na_2SO_4).

SOURCE OF THE SODIUM AND SULPHATE

Mirabilite and/or thenardite are previously unrecorded within a temperate cave, and several unusual factors have combined to allow their formation in Pollaraftra. The sulphate within Pollaraftra is almost certainly derived from Carboniferous evaporite minerals (gypsum, $CaSO_4.2H_2O$; anhydrite, $CaSO_4$ and celestite, $SrSO_4$) in the overlying Meenymore Formation. Pseudomorphs after halite (NaCl) have also been recorded from the Meenymore Formation (Brandon, 1977), and halite, if present, could be the source of the sodium. In addition to the sulphates within the Meenymore Formation, the Dartry Limestone contains minor amounts of iron sulphides. Sulphides are also quite abundant within the Meenymore Formation, so there is a possibility that some or all of the sulphate is derived from their oxidation. Fluids carrying sodium and sulphate are presumed to enter the cave by one or both of two possible routes:

i) Water entering the cave via the fault plane carries salts in solution and sodium sulphate crystallises from this water above the locality. However, neither mirabilite nor thenardite has been observed in the roof of the passage above the locality.

ii) The sodium sulphate is derived from water introduced through the breccia matrix by capillary action and, presumably, crystallises due to evaporation of matrix water at the rock - air interface.



Hading fault. Above the mineral site in Pollaraftra Cave, c.50m into the crawls.

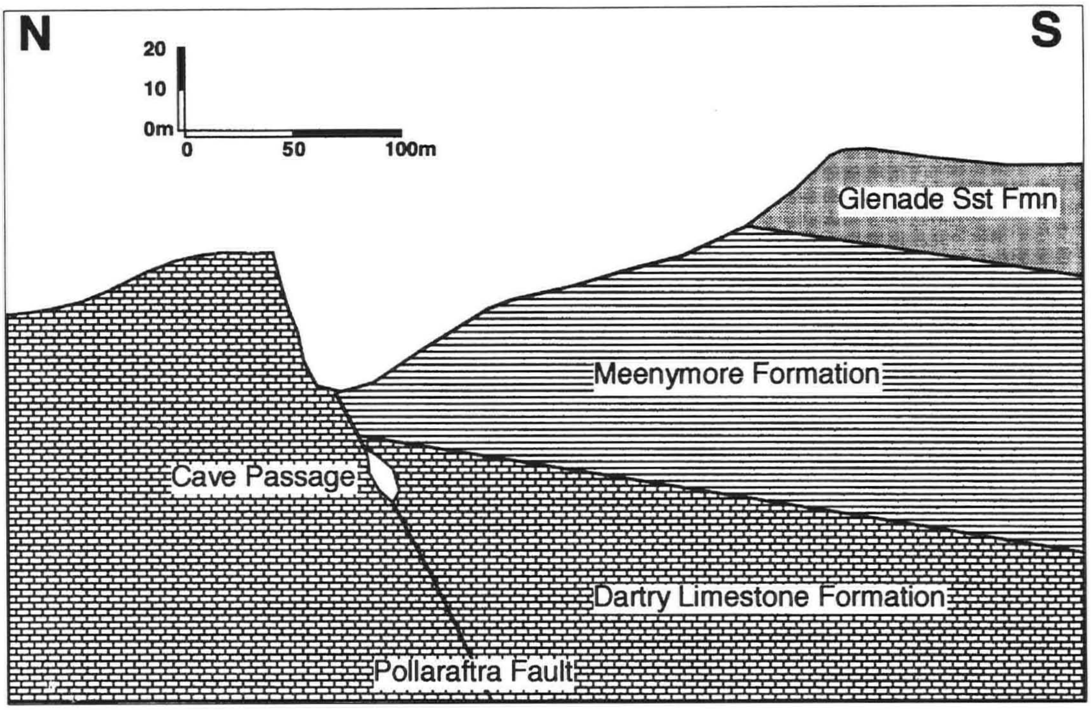


Figure 3. Cross section through the mirabilite/thenardite locality showing the relationship of the cave passage within Pollaraftra to the Pollaraftra Fault and the overlying Meenymore Formation.

DISCUSSION

Thenardite was first described from a cave environment by Bertolani (1958), who discovered mirabilite and thenardite together in an Italian cave. Here, mirabilite was observed to convert to thenardite at 21°C and 67% humidity (Fig. 4). Mirabilite has also been recorded from the Flint Ridge - Mammoth Cave System, USA (Davidson and Bishop, 1971), caves in the Guadalupe Mountains, USA (Hill, 1986) and Simpsons No. 1 Cave, New Zealand (Cody, 1978). Other examples of thenardite occurring in lava tubes have been recorded in California (Hill, 1980) and on Mount Etna in Italy (Hill and Forti, 1986). In the Guadalupe Mountain and New Zealand occurrences, the mirabilite has been recorded as being seasonal, being present only during seasons with higher humidities (Fig. 4). No seasonal variation has yet been observed in Pollaraftra.

In all the examples summarised by Hill and Forti (1986), the minerals are located in warm, dry caves, the cave temperature (except in Carlsbad Caverns) exceeding 20°C. Carlsbad Caverns also lie in an extensive desert area. The presence of mirabilite within Pollaraftra is therefore interesting, as the temperature within this cave probably varies within the range 5° to 10°C, as recorded in other caves within the Fermanagh karst. The presence (and absence) of both mirabilite and thenardite, at different times, in Pollaraftra, indicates that there is a significant variation in the temperature and/or humidity at this locality (Fig. 4). The sulphate minerals are present only sporadically, but this may be due more to the periodic flooding of this section of cave, than to deliquescence of the sulphate minerals.

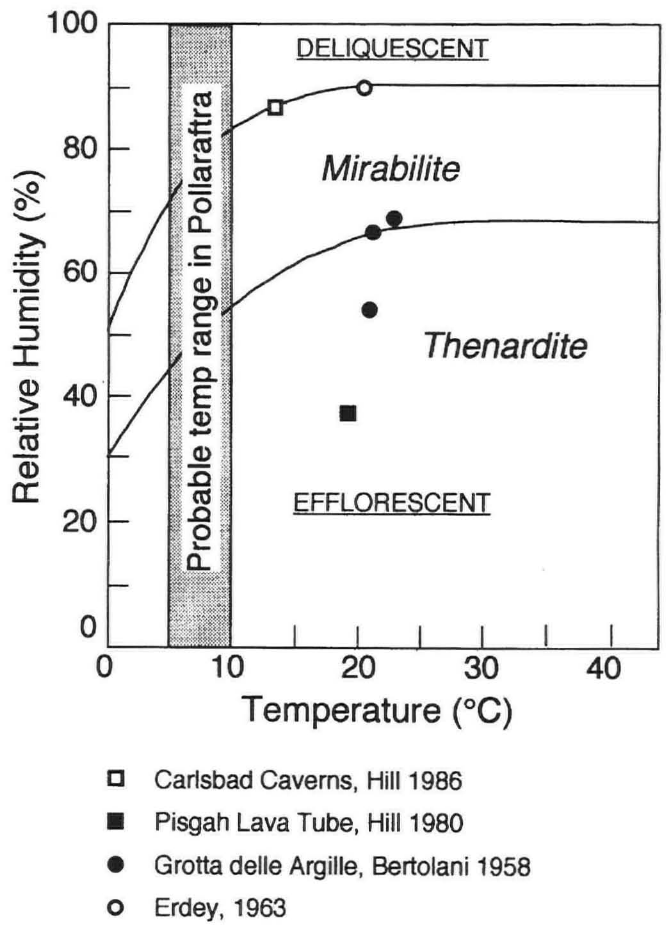


Figure 4. Stability of mirabilite and thenardite with temperature and humidity showing recorded examples and probable temperature range within Pollaraftra. (redrawn and modified from Hill and Forti, 1986).

ACKNOWLEDGEMENTS

This short paper is based on part of the Earth Science Conservation Review (Karst Geomorphology of Northern Ireland). Funding towards this publication was received from the Environment and Heritage Service, an Executive Agency within the Department of the Environment (Northern Ireland). Suggestions from Dr. Tony Waltham proved useful in initial identification of the mineral.

Pollaraftra Cave, about 200m downstream of the mineral site, showing the fault plane.

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CAVE AND KARST SCIENCE Vol. 24, No.1, April 1997
Transactions of the British Cave Research Association

Hydroporus ferrugineus (Dytiscidae): a subterranean water beetle recorded from Peak Cavern, Derbyshire, UK

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Abstract: Two new records of *Hydroporus ferrugineus* in Peak Cavern, Derbyshire, are reported at approximately 900m and 960m from the main cave entrance. Since the cave stream at this point is fed only by autogenic percolation water the records raise questions concerning the mode of colonisation, the ability of this species to complete its lifecycle in caves and the existence of a subterranean food web.

Hydroporus ferrugineus Stephens, a nationally notable diving beetle (Shirt, 1987), has been found at localities dominated by groundwater in Great Britain and most frequently at headwater spring sites (Atty, 1996; Carr and Philp, 1988; Merrit, 1995). Older records also exist from an intermittent headwater chalk stream in Dorset (Jackson, 1958) and several caves in the Peak District (Hazelton, 1977; Jefferson, 1976). *H. ferrugineus* has a western and central European distribution, ranging from the Balkans to Great Britain, but appears to be absent from Ireland, Fennoscandinavia and Denmark. Scotland appears to be the northerly limit to its distribution with records from localities as far north as the Isle of Skye and North Aberdeenshire (Foster, in prep).

During a visit to Peak Cavern, near Castleton, Derbyshire (30/10/96) (See Beck, 1991 for full survey details), three freshwater invertebrate samples were collected using the kick-sample technique (Furse et al, 1981). At two slow flowing backwater channel sites (<20cm deep), approximately 900m (NGR SK14488198) and 960m (NGR SK14518192) from the main cave entrance, *Hydroporus ferrugineus* was recorded.

The subterranean nature of *H. ferrugineus* has been known for over fifty years (Balfour-Brown, 1940). This has probably meant that it has been overlooked by entomologists and coleopterists. The adult beetles are relatively sluggish and inactive in water, compared to other Dytiscidae. As a result the beetle expends a minimum amount of energy and therefore requires less oxygen. The adults are typically found in shallow water where they can easily reach the surface to renew their air supply (Jackson, 1958). This feature of their ecology may be an adaptation to cave environments. The larvae are paler than those of any other species of the genus, perhaps reflecting their subterranean nature, although specimens have only been documented on two occasions in Great Britain. First, there is a record from Giants Hole (Derbyshire) (Hazelton and Glennie, 1962), and secondly, larvae have been reared under laboratory conditions (Jackson, 1958).

The biospeleology of Great Britain has been relatively poorly studied. This is primarily due to the low abundances and diversity of taxa historically recorded at most sites, and the lack of large exotic organisms (Chapman, 1993; Jefferson, 1976). Few troglobitic freshwater fauna exist in Great Britain, and most taxa recorded in caves are also associated with hyporheic water - found below the water/substratum interface of epigean systems (Hynes, 1983). The majority of aquatic cave fauna are therefore troglophilic by nature.

The new records of *H. ferrugineus* from Peak Cavern are important, as they add weight to the suggestion that caves comprise a significant habitat for this species of beetle in Great Britain. Colonisation probably occurred from hypogean sources, as the adults are thought to be flightless (Jackson, 1958) and as there are no surface stream inputs to the Peak Cavern streamway, the cave being fed by autogenic percolation water (Gunn, 1991). The importance of the subterranean hyporheic zone has been widely acknowledged within freshwater ecology (Jones and Holmes, 1996). It is known to provide a refuge for epigean species when surface

Hydroporus ferrugineus Stephens.
Body size is 3.5mm.

systems are subjected to disturbances such as floods and drought (Hynes, 1983). However, the importance of this zone for subterranean ecology and the potential routeways between the epigean and hypogean systems have been poorly studied (Ward and Palmer, 1994).

Given the limited knowledge concerning the ecology of *H. ferrugineus*, further research is required to establish: (i) colonisation mechanisms, (ii) the ability of adult beetles to reproduce successfully within caves, (iii) whether the larvae can develop fully in cave environments, and (iv) their sources of food. Both adults and larvae are carnivorous, and if the individuals recorded were part of a local population, this would suggest the existence of a subterranean aquatic food web. *H. ferrugineus* probably occupies the role of top predator or scavenger in this hypothesised system, although the other links in the food chain are unknown at present. At a time when water resources are at a premium and groundwater supplies are declining and vulnerable to pollution, other aspects of cave ecology need to be addressed before these remarkable communities are degraded.

ACKNOWLEDGEMENTS

Thanks to Dr. G. N. Foster for helpful discussion relating to this work and for supplying a list of source material, and to Prof. J. Gunn for the opportunity to carry out the work. Comments upon an early draft of this paper by David Lowe, Max Moseley and Maureen Agnew are gratefully acknowledged.

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Forum

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

All views expressed are those of the individual authors and do not necessarily represent the views of the Association unless this is expressly stated.

CORRIGENDUM

The editors apologise to readers and, particularly, to Dr. Steve Craven, for allowing two errors to appear in his paper on carbon dioxide variation in Cango Cave (*Cave and Karst Science*, Vol.23 (3), 89-92). The errors, not present in the original version, were introduced during digital file processing and were not noticed during final proof reading, which deals with the consistency and completeness of the copy rather than its scientific integrity. Table 2 of the paper (p.91) was corrupted; a corrected version is reproduced below. Text was also corrupted within, and omitted from, the first paragraph in the right hand column on page 92 of the paper. A revised paragraph is supplied below. We apologise again for any confusion that these errors have caused.

Revised paragraph to replace the top righthand paragraph, *Cave and Karst Science*, Vol. 23(3), p.92.

The original, natural, pCO_2 in Cango Cave before human visits cannot ever be known. It may be that the comparatively, low basal pCO_2 in Van Zyl's Hall has been caused by the cave winds dissipating the gas either to the outside and/or into the distal reaches of the cave. A possible additional or alternative cause may have been the removal of the guano which was present until 1948. It cannot be argued with certainty that the high pCO_2 in Cango III is natural because there may be free movement of air through an above-water passage which has not yet been explored. The lower pCO_2 at the sump, which is the lowest part of Cango II where could to expected to accumulate, deserves further comment. This lower than expected measurement suggests that the CO_2 may be removed by the stream either in solution and /or by convection current.

Revised Table 2: 'pCO_2 estimations in Cango Cave, April 1995', *Cave and Karst Science*, Vol. 23(2), p. 91.

Date	Time	Place	pCO_2	Corrected Vol. %
14	(1133 tourist tickets sold before 1700 hours)			
	1700	Van Zyl's Hall	0.4	0.43
	1730	Van Zyl's Hall	0.4	0.43
	1800	Van Zyl's Hall	0.4	0.43
	1830	Van Zyl's Hall	0.4	0.43
	1900	Van Zyl's Hall	0.45	0.48
	1930	Van Zyl's Hall	0.5	0.54
	2000	Van Zyl's Hall	0.5	0.54
	2030	Van Zyl's Hall	0.5	0.54
	2100	Van Zyl's Hall	0.5	0.54
	2130	Van Zyl's Hall	0.5	0.54
	2200	Van Zyl's Hall	0.55	0.59
	2230	Van Zyl's Hall	0.55	0.59
	2300	Van Zyl's Hall	0.55	0.59
	2330	Van Zyl's Hall	0.55	0.59
	2400	Van Zyl's Hall	0.55	0.59
15	0905	Van Zyl's Hall	0.2	0.22
	1020	Banqueting Hall	2.25	2.43
29	0855	Bushman display	0.1	0.11
	1005	Van Zyl's Hall	0.1	0.11
	1120	Registry - new calcite	0.1	0.11
	1215	Drum Room	0.4	0.43
	1305	Gen. Smyth's ladder	0.5	0.54
	1345	Japanese umbrella	1.5	1.61
	1405	King Solomon's Mines	1.75	1.88
	1515	Van Zyl's Hall	0.1	0.11
	(1009 tickets sold by 1515 hours)			
30	0845	Van Zyl's Hall	0.075	0.08
	1025	Ice Chamber	2.5	2.69
	1042	Devil's Workshop	2.5	2.69
	1104	Banqueting Hall	2.5	2.69
	1124	Banqueting Hall sm. chamber	2.5	2.69
	1155	Cango II (proximal)	2.5	2.69
	1310	Cango II (centre and high)	2.0	2.16
	1425	Cango II (distal)	2.5	2.69
	1442	Cango II (sump)	2.25	2.42
	1541	Cango II (proximal)	2.5	2.69
	1644	Van Zyl's Hall	0.1	0.11
	('about' 1000 tickets sold by 1600 hours)			

ABSTRACTS OF PAPERS PUBLISHED IN KARSTOLOGIA N°28 (2, 1996)

L. PERRITAZ
The "karst en vagues" of Aït Abdi plateau (central high Atlas, Morocco). *p. 1-12.*

The Aït Abdi plateau (2200-3000m, 160 km^2) is located in the calcareous High Atlas (32°N). It consists of massive Bajocian limestones which form a large brachysyncline and overlie the detritic Toarcian-Aalenian forming the regional aquiclude and the top of the half captive Middle Liassic aquifer. The rainfall comprises only 500 to 700 mm/yr and the effective evapotranspiration is about 400 mm/yr with a snow coefficient of 60 % and an infiltration rate of 40 %. This means that the recharge of the aquifer mainly occurs during snow melting. The morphology of this nival karst consists of a succession of sub-parallel and asymmetric dry valleys forming some "waves" ("karst en vagues"). The role of wind and snow in the genesis of these forms is predominant. An old speleological network with vertical shafts occluded lower down is proof of ancient more humid climatic conditions. U-Th dating methods on speleothems indicate ages between 3,200 and 220,000 yrs, or more than 400,000 yrs. The horizontal transfer is made by an interstrata network, ancient and dry in the upper part, or recent and phreatic at the base, near the regional aquiclude, attesting three karstification phases.

J.E.J. MARTINI and J.C.E. MARAIS
Hydrothermal caves in North-West Namibia. *p. 13-18.*

The authors investigated ten caves in Western Namibia, which is characterised by a semi- to hyper-arid climate. They seem to have formed in the past under hydrothermal conditions, which are evidenced by circular embayments, ceiling alveoles, avens, deposits of dog-tooth calcite and barite. The latter has been observed in one cave only. Fluid inclusions in calcite and barite indicate very low salinity and temperatures generally below + 70° C. It is proposed that the caves formed by mixing of hydrothermal solutions of deep origin with more surficial ground water in the vicinity of karst springs. Such ground water circulation patterns, close to the water-table, are suggested in several cases by the horizontal extension in caves, forming definite levels of passage networks cutting across the country rock stratigraphy. The alveolar avens developed upwards from these horizontal passages and seem to have formed subaerially by water evaporation from warm pools at the bottom, with condensation and corrosion above, against cooler rock. The suggested genetic processes are in agreement with models proposed by other authors. It is suggested that in arid climates, conditions are more favourable for development of this type of deep karst water circulation than under wetter conditions. It could possibly even be the predominant process of speleogenesis in very arid conditions. By extension, this concept - mixing of water of deep origin, not necessarily significantly hydrothermal, with surficial ground water - could explain the peculiar nature of most of the Namibian caves. The latter are typically characterised by the development of very large chambers and phreatic networks, but with restricted extension and not forming well integrated systems.

M. DZIKOWSKI, G. NICOUD, B. ARFIB, A. PAILLET and G. ROVERA
A gypsum aquifer in high mountain : physico-chemical measurements and tracer test in the Gebroulaz valley (Vanoise, France). *p. 19-24.*

During the high flow period of summer 1995, conductivity and temperature were periodically measured in two losses and five springs along a gypsum and anhydrite outcrop in the Gébroulaz valley. These experiments together with a water chemical analysis and an artificial tracer test have highlighted two kinds of flows through the evaporitic formations. The springs are characterised by a rapid flow directly influenced by the infiltration of melt water in a surficial karst. A slower flow shows a deeper circulation through a saturated and fissured milieu. So, in a high mountainous area, the gypsum layer shows a surficial karst over a fissured aquifer. This interpretation allows us to explain the stability of the physico-chemical parameters for the springs which are not influenced by karstic flow conditions.

D. FORD, J.-N. SALOMON and P. WILLIAMS
The stone forests of Lunan (Yunnan, China). *p. 25-40.*

"Stone forests" are well known in Southern China. We describe the type site in Lunan County on the Yunnan Plateau at about 1800m. "Stone forests" are a spectacular form of lapies, similar to the "tsingy" of Madagascar or pinnacles of Mulu. In Yunnan they are developed in massive Permian limestones and dolomites. The "stone forests" are high fluted towers, typically more ruinform in dolostones, that attain 20-30m in height, exceptionally 40m. They occur in patches of several square kilometres in extent in a rolling polygonal karst landscape with about 150m local relief. Three phases of evolution are recognized spanning 250 Ma from the Permian until the present : 1) Mid Permian karstification and burial by Upper Permian continental basalts; 2) Mesozoic erosion and re-karstification, then burial in the Eocene by thick continental deposits; 3) Late Tertiary and Quaternary exhumation and re-karstification. No other "stone forests" in the world show this complexity of evolution.

L. CUNHA
The Portuguese karsts, problems and perspectives. *p. 41-48.*

The Portuguese karsts owing to their geomorphological, speleological, hydrogeological and environmental problems, deserve to be better known and studied by the international scientific and speleological community. We present a brief synthesis of the Portuguese karsts in three parts: 1) the presentation of the main scientific works, mainly from the pioneer thesis written by Alfredo Fernandes Martins in 1949 on the Estremadura limestone massif, which was the starting point of karst geomorphological studies in Portugal; 2) a brief description of the main characteristics of the karst areas in the western Mesozoic border (Sicó and Estremadura), especially the pre-Cretaceous paleokarsts (recent and incomplete exhumation) and the importance of endokarst and exokarst (Estramadura); 3) some further research approaches are proposed, aiming at a deeper and more synthetical knowledge of the Portuguese karsts.

E. SANZ PEREZ
The karst of Lobos Canyon (Soria, Spain) and its hydrogeological functioning. *p. 49-56.*

The massif of River Lobos, NW of the Iberian Range, is characterized by an important karst crossed by a canyon 26km long. This canyon was dug into the Cretaceous limestones from a gradually eroded Neogene impervious cover by allogenous waters. The Cretaceous aquifer is drained by La Galiana spring. The general characteristics of the karstic relief and its hydrogeological functioning are described in this study. La Galiana spring is simulated by a mathematical model of precipitation-water flow. The results show a 4 to 5 day delay between precipitation and the spring flow.

RESEARCH FUNDS AND GRANTS

THE BCRA RESEARCH FUND

The British Cave Research Association has established the BCRA 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 must be the principal investigator, and must be a member of the BCRA in order to qualify. Grants may be made to individuals or groups (including BCRA Special Interest Groups), who need not be employed in universities or research establishments. Information about the Fund and application forms Research Awards are available from The BCRA Administrator (address at foot of page).

GHAR PARAU FOUNDATION EXPEDITION AWARDS

An award, or awards, with a minimum 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, Hurst Farm Barn, Cutler's Lane, Castlemorton Common, Malvern, Worcs., WR13 6LF. Closing date 1st February.

THE E.K.TRATMAN AWARD

An annual award, currently £50, made for the most stimulating contribution towards speleological literature published within the United Kingdom during the past 12 months. Suggestions are always welcome to members of the GPF Awards Committee, or its Secretary, David Judson, not later than 1st February each year.

BRITISH CAVE RESEARCH ASSOCIATION PUBLICATIONS

CAVE & KARST SCIENCE - published three times annually, a scientific journal comprising original research papers, reviews and discussion forum, on all aspects of speleological investigation, geology and geomorphology related to karst and caves, archaeology, biospeleology, exploration and expedition reports.
Editors: Dr. D.J. Lowe, c/o British Geological Survey, Keyworth, Notts., NG12 5GG and Professor J. Gunn, Limestone Research Group, Dept. of Geographical and Environmental Sciences, University of Huddersfield, Huddersfield HD1 3DH.

CAVES AND CAVING - quarterly news magazine of current events in caving, with brief reports or latest explorations and expeditions, news of new techniques and equipment, Association personalia etc.
Editor: Hugh St Lawrence, 5 Mayfield Rd., Bentham, Lancaster, LA2 7LP.

CAVE STUDIES SERIES - occasional series of booklets on various speleological or karst subjects.
No. 1 *Caves & Karst of the Yorkshire Dales;* by Tony Waltham and Martin Davies, 1987. Reprinted 1991.
No. 2 *An Introduction to Cave Surveying;* by Bryan Ellis, 1988. Reprinted 1993.
No. 3 *Caves & Karst of the Peak District*; by Trevor Ford and John Gunn, 1990. Reprinted with corrections 1992.
No. 4 *An Introduction to Cave Photography;* by Sheena Stoddard, 1994.
No. 5 *An Introduction to British Limestone Karst Environments;* edited by John Gunn, 1994.
No. 6 *A Dictionary of Karst and Caves*; compiled by Dave Lowe and Tony Waltham, 1995.

SPELEOHISTORY SERIES - an occasional series.
No. 1 The Ease Gill System-Forty Years of Exploration; by Jim Eyre, 1989.

CURRENT TITLES IN SPELEOLOGY - from 1994 this publication has been incorporated into the international journal Bulletin Bibliographique Speleologique/Speleological Abstracts; copies of which are available through BCRA.

BCRA SPECIAL INTEREST GROUPS

SPECIAL INTEREST GROUPS are organised groups within the BCRA that issue their own publications and hold symposia, field meetings etc.
Cave Radio and Electronics Group promotes the theoretical and practical study of cave radio and the uses of electronics in cave-related projects. The Group publishes a quarterly *technical journal* (c.32pp A4) and organises twice-yearly field meetings. Occasional publications include the *Bibliography of Underground Communications* (2nd edition, 36pp A4).

Explosives Users' Group provides information to cavers using explosives for cave exploration and rescue, and liaises with relevant authorities. The Group produces a regular newsletter and organises field meetings. Occasional publications include a *Bibliography* and *Guide to Regulations* etc.

Hydrology Group organises meetings around the country for the demonstration and discussion of water-tracing techniques, and organises programmes of tracer insertion, sampling, monitoring and so on. The group publishes an occasional newsletter.

Underground Photographer Magazine. This magazine was first published in December 1995, 48pp A4 with black and white photos. Subsequent editions have colour photos and articles on cave photography topics.

Speleohistory Group publishes an occasional newsletter on matters related to historical records of caves; documentary, photographic, biographical and so on.

Cave Surveying Group is a forum for discussion of matters relating to cave surveying, including methods of data recording, data processing, survey standards, instruments, archiving policy etc. The Group publishes a quarterly newsletter, Compass Points (c.16pp A4), and organises seminars and field meetings.

Copies of publications, information about Special Interest Groups, the BCRA Research Fund application forms, etc. are obtainable from the BCRA Administrator: B M Ellis, 20 Woodland Avenue, Westonzoyland, Bridgwater, Somerset, TA7 OLQ.