Cave and Karst Science

The Transactions of the British Cave Research Association

BCRA

Volume 26 Number 2 August 1999

Early explorations in the Northern Pennines
Sediment in Joint Hole, Chapel-le-Dale
Limestone dissolution rates in Tibet
Tufa deposition in South Wales
Thermal waters in Bath
Forum

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:

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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. Manuscript papers should be of a high standard, and will be subject to peer review by two referees.

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

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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. Enquiries by E-mail are welcomed, to: D.Lowe@bgs.ac.uk or J.gunn@hud.ac.uk.

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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, preferably as a series of appendices.

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

If any problems are perceived regarding the nature, content or format of the material, please consult either of the Editors before submitting the manuscript.

Cave and Karst Science

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

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Cover photo:
Unroofed cave, White Mountains, Crete
Remnants of unroofed caves take many forms (see Report of the 7th International Karstological School in this Issue). This unusual example, in Jurassic limestone above the Nero Lango valley in the White Mountains (Levka Ori) of Crete, existed long before the incision of the valley. Beyond and just left of the obvious arch-like relic of a tubular cave passage is a pillar, representing the denuded remains of a second remnant arch. Despite many years of surface weathering, minute traces of a terra rossa-like cave fill lie on the "cave" floor. Looking along the assumed line of continuation of the former cave, patches of similar material, and a possible filled continuation, are just visible in the distant valley floor and side. (Photo: Dave Lowe)

Editors: Dr. D J Lowe — British Geological Survey, Keyworth, Nottingham, NG12 5GG.
Prof. J Gunn — Limestone Research Group, Department of Geographical & Environmental Sciences, The University of Huddersfield, Queensgate, Huddersfield, HD1 3DH.

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EDITORIAL

Dave Lowe and John Gunn

As commonly seems to be the case, production of the "summer" issue of *Cave and Karst Science* has been delayed. Happily the delay does not reflect a shortage of material available for publication. On the contrary, a healthy stock of potentially publishable material continues to arrive, and to begin wending its way through the review and editorial processes. The delay is actually a reflection of the time of year. Production of the journal is a "spare-time" occupation, and disruptions to work patterns caused by fieldwork, conferences of one sort or another and annual holidays affect all of those who are involved. Processes that can normally be dealt with relatively rapidly are stalled, as envelopes wait on desks, or electronic messages sit unread in e-mail directories. Even worse, the "laws" that govern these types of delay ensure that as one correspondent returns from absence, another departs. Not only the Editors are thus diverted and distracted, but also referees, the authors themselves and, not least in importance, the desktop publishing side of the operation.

Despite the annoyance caused by these summer delays, there can be coincidental benefits. The obvious one this year is that both Editors were among the many to enjoy, and thus able to comment upon, the excellent BCRA *"Hidden Earth"* conference in Leeds early in September. Most significantly from our point of view, we witnessed not only an upturn in the number of broadly science-related presentations at the conference, but also a larger audience than has often been the case in the past, despite a number of unavoidable clashes with other potentially interesting and entertaining material within the overall programme. The standard of the presentations was generally very good, in marked contrast to some of the other deliveries at the meeting, and each was followed by useful and informed discussion. That there are many cave explorers who have a healthy interest in cave science was re-emphasised by the number attending and, coincidentally, is also reflected by reports of other BCRA events among the Association News in Issue 85 of *Caves and Caving*. It is equally clear that many of these interested explorers, whether or not they have a scientific background or are currently associated with any University, have the potential to make valuable contributions to new or ongoing research.

We make no apology for returning to this topic, which we have discussed several times before, and return to the question of why many who could contribute, or indeed are already contributing, hold back from becoming involved or from disseminating their results and ideas. There is no simple answer, but various factors of varying importance influence different people. Many cavers simply want to get on with sporting caving, or digging, or surveying, with no time for what they see as abstract "science" – or no time for disseminating information. Yet, as we have commented before, many "sporting" cavers have provided, and continue to provide, vital support to a whole spectrum of research projects, some without even realising that their activities have potential scientific importance. It is also the case that a significant percentage of the caving population was first introduced to the sport while at University, and some have studied subjects of direct relevance to cave science. After graduation most may have no desire to undertake cave related research as such but for those who do, it is important to remember that the BCRA Research Fund exists to facilitate such studies.

Regardless of whether they have specific formal training or paper qualifications, many cavers carry out interesting and potentially valuable work that is broadly scientific, perhaps extending into related areas of speleo-history or technology. Whether such activities are intentional or coincidental, there commonly seems to be a lack of confidence, incentive or connections to take the results and ideas forward orally or in publications. At the other end of the scale, there are within the cave and karst fields a relatively few professional scientists involved in what would nowadays be called "alpha" research. Their problem is not <u>if</u> they should deliver or publish their results, but where and how they should do so to gain the optimum benefits, whether in terms of academic kudos, career advancement (or these days job security), ongoing funding, and so on.

As we have said in the past, the BCRA attempts to provide ways and means for all its members to find out about all aspects of cave and karst science, to become involved and to feed their ideas or results back into the system. Apart from the annual national conference, which hopefully will continue to cover science-related topics, locally appropriate facets of cave and karst science and technology are covered at Regional BCRA meetings and by various BCRA Special Interest Groups. Additionally, the full width of the subject is potentially covered by an annual Cave Science Symposium, the next of which will be held in Huddersfield on 25 March 2000. On the publications front, *Cave and Karst Science* offers new and inexperienced, as well as established, authors various ways to get their ideas and results into print. We cannot, for reasons that will hopefully be obvious, print work that is derivative, overly parochial or badly written, but we try to provide positive comments to all contributors, with suggestions as to how text might be improved. Another part of the cave science loop is provided through the pages of *Caves and Caving* where, from time to time, specialist authors attempt to synthesise potentially "heavy" topics into language that is readily understandable to the interested lay membership, and beyond. The policy of providing more easily digestible treatment of cave science and technology has also been pursued in various BCRA *Cave Studies* volumes.

The message that underlies all of this has been repeated so often that it is beginning to sound monotonous. Serious scientific work cannot hope to keep advancing without the continued support and input of cave explorers and cave surveyors, no matter how brilliant or dedicated the scientists at the leading edge. So, if so many cave explorers contribute to cave (and karst) science, isn't it time for us to find ways of encouraging a few more to appear at BCRA's scientific gatherings? Our editorials attempt to explain how welcome they, or their oral / written contributions, would be, but perhaps our current roles and background mean that we look at the problem from the wrong side? Acknowledging this, we ask you to at least try what's on offer. Then, if you still like the idea of science, but don't like the way that it's handled and presented by the BCRA, feed your ideas and suggestions for improvement back into the system, via the *Cave and Karst Science* "Forum", or by other means. Thus we might move on and boost the levels of appropriate activity and involvement simultaneously, though it's probably inevitable that any desirable changes will not be achieved overnight.

Moving away from proselytising, it is appropriate to reiterate an aspect of our Editorial policy that we have tried to stress in the past. New ideas are essential for any science to progress, and we are convinced that many are held back as their originators search for conclusive supporting evidence. In some situations such evidence may not be easy to find or obvious, leading to long delays in publication or no publication at all. However, potential evidence may already exist among results obtained in another area, another country or by researchers in a different discipline. Thus, we believe that there is justification for publishing papers or reports that are either "interim" or "speculative". The former implies that an idea is being pursued but "hard" data are still being assembled. In the latter case the idea may be based upon a hypothetical re-working of existing data or a lateral view of an earlier model in the light of a new approach, but might not be amenable to conclusive proof in the foreseeable future.

Some aspects of a paper by Waltham and Cooper in *Cave and Karst Science* 25/3 were described by its reviewers as "kite flying". The authors were happy to concede that the paper included speculation that lacked (and might continue to lack) concrete proof, though they stressed that it was based upon their best interpretation of the currently available evidence. A paper considering the origin of thermal waters at Bath in the current Issue is perhaps a more extreme example. It looks at a well-established and widely accepted (but actually unproven) concept, and attempts to offer an alternative explanation. The latter, based upon a lateral view of the data used to support the existing model, is acknowledged as currently unprovable "kite flying", yet it raises possibilities that were previously either unrecognised or dismissed in the light of accepted wisdom. The ideas presented are doubtlessly controversial and leave ample scope for debate or criticism. However, it remains vital to the health of the science that, as underlying ideas about processes and timescales of underground drainage and related phenomena evolve, existing models and explanations must be re-examined and questioned.

While discussing the above paper it is also appropriate to comment upon its history, parts of which provide object lessons and illustrations of the *Cave and Karst Science* editorial process. An early draft of an ancestral paper, written by the present lead author, was submitted to our predecessor, Trevor Ford, in 1993, and was sent out to three reviewers, including one of us [DJL]. The upshot of the refereeing process was that the paper was unsuitable for publication in its original form, but each of the reviewers, and the Editor, made suggestions about how it might be improved. A revised draft, the actual forerunner of the paper published in this Issue, eventually appeared. In producing it the author realised that his knowledge of geology in general and his familiarity with the concepts within the Inception Horizon Hypothesis were inadequate to provide the detail needed in the paper, and he asked one of us [DJL] to contribute as second author. There followed a series of re-writes, additions and revisions, interspersed by long delays, until the draft was finally re-submitted for final review earlier this year. If nothing else, the paper must hold the record for the longest gestation of any to achieve publication in *Cave and Karst Science* and, on a personal level, the second author cannot be accused of using his influence to jump the publication queue!

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A history of cave exploration in the Northern Pennines, United Kingdom, up to 1838

Stephen A. CRAVEN
7 Amhurst Avenue, Newlands 7700, South Africa

Abstract: Cave exploration in the northern Pennines, which goes back four centuries, is placed in its social, economic and logistical context. The early stimuli were mainly commercial i.e. the tourist trade; but there are a few reports by disinterested travellers with enquiring minds.

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INTRODUCTION

Any attempt to discuss early cave explorations must take into account the contemporary social and economic conditions, and infrastructure, in the north of England. The Romans are famous for having built a network of good roads throughout England, which were neglected after their departure in the fifth century AD. Thereafter England declined economically. The population was small, and largely settled and rural. Few people travelled; those who did travelled by necessity for military, business or administrative reasons. Very few travelled for pleasure, and probably even fewer took the trouble to record their experiences (Hyams, 1977).

By the Middle Ages the Roman roads had deteriorated for lack of maintenance to little more than muddy tracks. The responsibility for road maintenance devolved upon the parish through which it passed. Parishioners were reluctant to spend time and money on roads that linked the conurbations and therefore benefited only the city dwellers. This hopelessly inefficient system was changed in 1706 when the first Turnpike Trust was created. Private enterprise was permitted to design, build, maintain and operate roads, and to recover the expense by charging tolls. Although this relieved the parishioners of an intolerable burden, it proved unpopular with the road users, who took every opportunity to evade payment! Nevertheless, the new system was responsible for the improvement of the main roads, and made travelling a much less arduous, though still slow and expensive, occupation (Fletcher, 1918).

It was the Keighley - Kendal Turnpike, approved by Act of Parliament in 1753, that facilitated access to many of the caves in the north of England (Brigg, 1927). This turnpike mostly followed the familiar route of the modern A65 road through Skipton, Settle, Ingleton and Kirkby Lonsdale i.e. skirting the south-western periphery of the Carboniferous limestones of the northern Pennines.

It was not only poor communications that hindered cave exploration. Another important factor was fear of the unknown, by a largely uneducated and superstitious rural population. Caves were popularly believed to be dangerous and detestable places, and best avoided. This phobia is comparable to the fear of mountain dragons, a fear that inhibited exploration of the Alps for centuries (Clark, 1976).

EARLY CAVE EXPLORATIONS

Early cave records in the north of England pre-date the Keighley - Kendal Turnpike, and describe caves well away from the main road. The earliest known record of a visit to a cave in the north of England is that of J Durant of Newcastle, some time before June 1746. In a letter curiously dated "9 Feb. $167^3/_4$" to the Hon. Robert Boyle he describes:

"... some subterraneal Grottoes or Caverns in Weredale, about twenty Miles South-west of this place where, by a little hole creeping into the Side of a vast Mountain, is entered a spacious cavity, chambered with Walls and Pillars of decident lapidescent Waters; the Hollowness in some places being previous further than any yet has adventured to discover; the Darkness of these Caverns requiring the Help of Candles, which are often extinguished by the dropping water."

This unnamed cave may have been Fairy Hole, now unfortunately partly destroyed by quarrying.

The next visitor, despite the poor communications, went on a grand tour of the Yorkshire Dales. In 1751 Dr Richard Pococke, successively Bishop of Meath and of Ossery, travelled from Dublin to England (Cartwright, 1888). On 24 May he was passing south through Wharfedale. At Kettlewell he was,

"... informed there was a natural grotto in Shale Park, and about that place they find chrystals in the shape of two hexagonal pyramids with their bases joyned together."

This is Dove Cave; Pococke did not bother to explore it. On the same day he made a detour into Littondale. Passing through Arncliffe he came,

"... near to Old Cote, where I went in to see a grotto, which may be about twenty feet wide and two hundred yards long, a winding way and having several pools of water in it, and at last I came to deep water, which hindered me from going any farther, and I could not learn that any one had been at the end of it."

This description is compatible with Boreham Cave. The Bishop then went looking for Dowkabottom Cave; but since it was getting late in the day he changed his mind and proceeded to Grassington for the night.

The next day Pococke left for Bolton Abbey, Skipton, Broughton Hall, Gargrave, Malham Cove, Gordale Scar, Malham Tarn, Stainforth and Horton-in-Ribblesdale, arriving in Chapel-le-Dale on 28 May. There he visited and described Weathercote Cave, Hurtle Pot and Gingle Pot, which he grandiosely likened to Eldon Hole in Derbyshire. Going down the valley he noted the underground flow of the River Greta, and its rising at God's Bridge. He then crossed Twistleton Scar into Kingsdale, passing Braida Garth to Yordas Cave,

"... to which there is an entrance, something like that of the Peke of Derby, but not so large; it leads to a very grand high cave, the sides of which are smooth perpendicular rocks, about 30 feet high, except in two or three places, where there are some curious incrustations made by the water. There is a small passage to the left, but what is most extraordinary, we went into the passage to the left between the rocks, through streams of water, and came to a cavern, where two or three streams come tumbling down the rocks with a great noise for ten or fifteen feet, and in other parts there are cupolas so high that we could not see to the top."

He then left the cave, climbed to the top of the dry valley, and noted the water sinking into what we now know as Yordas Pot. Thereafter he went down Kingsdale, passing Thornton Force to Ingleton. On the way up Ingleborough he explored,

"Tatham Wife Hole, which is a small hole with a spring in it; it consists of a black stone; here many petrifactions have been found, as particularly scollop shells; but we could meet with none, but some curious corals, which are very sharp and hard."

Pococke then descended the south flank of Ingleborough to Clapham, and surprisingly does not mention the most conspicuous pothole on that side of the Hill - Gaping Gill. In spite of this and other omissions such as Meregill, the Bishop's diary is an important document, in that it gives the first description of many of the caves in the northern Pennines.

The next visitor to record his explorations was Adam Walker (1760) who described himself as a *"lecturer in natural and experimental philosophy"* of London. He had previously visited caves in Derbyshire. On 24 August 1760 he entered Dunald Mill Hole about 1½km ESE of Nether Kellet. He masochistically described the entrance as "pleasingly horrible", then walked and crawled as far as he could down the stream passage. He declined to estimate the length of the cave; but correctly reported that the water reappeared on the surface about 3km away near Carnforth.

In 1779 he wrote the following erroneous description of Chapel-le-Dale (Walker, 1779):

"In our road to Settle we met with the Ribble, which tumbles into a deep cavern, and is lost in the bowels of the mountain, for upwards of 3 miles, when it issues again into daylight, with a continued roar makes its way to Settle."

This error was repeated by R Gough (1789) in his edition of William Camden's Britannia.

COMMERCIAL CAVING

As mentioned above, the Keighley - Kendal and other turnpikes greatly facilitated travel for those who had the necessary time, money and stamina. It became fashionable for the southern gentry to travel up the Great North Road to Doncaster, thence northwest through Wakefield, Leeds, Keighley and Kendal to the Lake District. Ingleton, being on the turnpike where it is crossed by the main road between Lancaster and Wensleydale, became an important coaching centre with numerous inns, where the travellers rested themselves and their horses. The inhabitants took advantage of this tourist trade to the Lake District, by taking the travellers to the local places of scenic interest, including caves.

In 1761 there appeared a description of Ingleborough Hill, written by an anonymous clergyman with the pseudonym Pastor (Anon, 1761). Shaw (1971) has argued convincingly that the writer was John Hutton, even though at that time he was still an undergraduate at St John's College, Cambridge. He was not ordained until 1763.

Pastor was the first to appreciate the underground drainage of Ingleborough. He noted that streams sink as soon as they reach the limestone, and that they reappeared at the foot of the hill. He mentioned that Alum Pot has an oval orifice *"20 poles circumference"*, and that the depth is unknown. He continued with the first account of what is obviously Upper and Lower Long Churn Caves:

"Not far from this hole, nearly north, is another hole, which may be easily descended. In some places the roof is four or five yards high, and its width the same; in some places not above a yard; and was it not for the run of the water, it is not to be known how far you might walk by the help of a candle or other light. There is likewise another hole or chasm, a little west from the other two, which cannot be descended without difficulty: you are no sooner entered than you have a subterranean passage, sometimes wide and spacious, sometimes so narrow you are obliged to make use of both hands, as well as feet, to crawl a considerable way; and I was informed, some persons have gone several hundred yards, and might have gone much further, durst they have ventured."

Pastor also mentions "Gaper Gill" and "Long Kin" - obviously Gaping Gill and Long Kin West or Long Kin East. He describes "Johnson's Jacket Hole" as *"...resembling a funnel, but vastly deep"*. This description is compatible with Jockey Hole. Pastor's other caves, "Blackside Cove, Sir William's Cave and Atkinson's Chamber", have not been identified.

Pastor also confirms the commercial nature of caving at that time. He had visited Easegill Kirk, with its entrance like a *"pointed Gothic arch 60 feet high"* from whence several passages go under the hill, and warned the reader that *"lights and dues"* were required for their exploration.

The visitors who broke their journey at Ingleton prompted the Rev. John Hutton, who by then had been appointed to the living of Burton-in-Kendal, to have published in 1780 the first edition of his *"Tour to the Caves"*. Some idea of the size of the Ingleton tourist trade may be gained from the fact that it went out of print in less than twelve months, and that it was translated into German. The second edition of 1781 was reprinted nine times between 1784 and 1821 as an addendum to "West's Guide to the Lakes" (Hutton, 1781). Hutton describes what must have been the standard itinerary for visitors to Ingleton.

The tour began at the Thornton-Church-Stile inn (now the Marton Arms at Thornton-in-Lonsdale) where was hired a guide with candles, lantern and tinder box. The party proceeded up Kingsdale, past Thornton Force, Keld Head and Braida Garth to Yordas Cave - Hutton's first cave. Inside he noticed graffiti over 200 years old, and the Bishop's Throne and Chapter House - features still known by those names. He deplored the activities of vandals who had removed many of the formations.

Having inspected and described Hurtle Pot, Gingle Pot and Weathercote Cave in Chapel-le-Dale, they crossed the valley to Douk Cave on the north side of Ingleborough. Someone had conveniently provided a ladder to facilitate entry. Hutton described, but did not name, Little Douk Pot, beyond which he proceeded a hundred metres. Returning from the top of Ingleborough,

"... we visited the long, deep, and dreadful chasm of Meir-gill, on the west side of the sheep-fence wall, running north and south over the base of Ingleborough: it is about eighty yards long, but in most places so narrow that a person may stride over it, and is no-where above two or three yards wide; in one place there is a curious natural bridge over it. The depth is very different, in different places; at one end we found it a hundred feet, forty eight of which was in the water. One part will admit a bold and active adventurer down almost to the water by a gradual, but slippery descent: Here the shadow of the superincumbent rocks, like that in Hurtlepot, forms a very deceitful appearance in the water: The bottom seems not above two feet above the surface; but how fatal would be the attempt to wade this abyss in quest of farther discoveries?"

The next caves visited were Braithwaite Wife Hole and Hardrawkin:

"A little further to the east we came to another curiosity of nature, called Barfoot-wive's-hole: It is a large round pit in form of a funnel, the diameter at top being about fifty or sixty yards, and its depth twenty six. It is easily descended in most places, though on the south side there is an high rocky precipice, but is dry, the waters that are emptied into it, being swallowed up among the rocks and loose stones at the bottom. In our way back we also saw Hardrawkin, and some other subterranean passages of less note, which had been formed by the waters in their descent from the mountain adjoining to Ingleborough to the vale beneath. Indeed the whole limestone base of this monster of nature is perforated and excavated in all directions like a honeycomb."

They then went up the valley to Gatekirk Cave:

"The brook which runs through it forms a fine natural bason of transparent water at its egress, where we entered the cave, gradually increasing in depth till about five or six feet at most: Over the cave, where the water flows, is another subterranean passage, of about twenty four feet in length, and from three to ten in height: It enters the other obliquely, and looks like a natural orchestra. The roof is at least six yards high at the first entrance. From the roof were pendent large petrifactions in every grotesque shape; some like hams, others like neat's tongues, many like the heads and various parts of different animals. As we proceeded along we met with several bye streets or lanes, down some of which came tinkling little currents; but they seemed not to admit a passenger with ease to any great distance: As we went along we observed that the way divided for a considerable part of the whole length into two main streets, which united again, made by the current dividing above into two streams. After we had gone about seventy yards we met with an orifice, which easily admitted us above ground: We had no curiosity to explore any farther, as the roof was now become only some four feet high".

Just over 3km away, Greenside Cave was described more briefly:

"The mouth was wide and high, and the road rugged; but the roof gradually sunk, or the bottom arose, till it was troublesome getting along, soon as we were out of the sight of day. A small brook ran along the bottom, as in the other caves, but there was none of the curious petrifactions we saw in most of them to delight the eye."

Having taken refreshment at Gearstones Inn, the party explored Catknot Cave, which is described as being 400m long.

This accuracy was not repeated at Alum Pot, which was plumbed to a depth of 50m, of which 13 were in water. This 50m is more or less correct for the depth of the main shaft; but there is no 13m deep sump at the bottom of the shaft. He recorded that Alum Pot was surrounded by a low mound of earth, and perspicaciously commented that a stone wall would provide curious by-standers with materials to throw down for their own amusement. He mistakenly called Lower Long Churn Cave "Dicken-Pot" - an error that was perpetuated by several later writers. He explored it as far as St Pauls - the chamber near the top of the 12m shaft into Alum Pot, which connection he correctly predicted. At the same time he made a through circuit of Upper Long Churn Cave, and commented that a ladder would have facilitated the ascent from Dr. Bannister's Hand Basin.

Hutton realised that there are several other caves on the south flank of Ingleborough, but decided to postpone their exploration until another summer. At Horton-in-Ribblesdale he knew of the two main sinks of Hull Pot and Hunt Pot, and of the two main risings at Brants Gill and Douk Gill. Quoting evidence from water tracing experiments using muddy water and oat husks, he concluded that the Hull Pot water reappeared at Douk Gill, and that the Hunt Pot water rose at Brants Gill - crossing underground but not mixing. This statement was repeated by numerous subsequent writers, and found its way onto the 6-inch Ordnance Survey maps (Gemmell and Myers, 1952), remaining unchallenged until as late as 1949 (Simpson, 1949).

John Hutton was born about 1740. He was educated at Sedbergh School from 1755 to 1759 whence he proceeded to St John's College, Cambridge, graduating BA in 1763. He was ordained in 1763 and from the following year until his death in 1806 was Vicar of Burton-in-Kendal, in Westmorland (Wilson, 1909). He was therefore in a good position to know and to describe the topography of Ingleborough. As has been pointed out by Shaw (1971), Hutton is an important figure in the history of speleology because:

1. His are the first English language books dealing almost exclusively with caves.
2. He gives the earliest descriptions of some of the caves in Yorkshire.
3. He had much influence on later writers, many of whom copied his work with or without acknowledgement.
4. His are the first English books to treat caves as desirable places to visit, rather than as unpleasant places to be avoided.
5. He displays an early awareness of karst drainage, and in particular the concept of discrete drainage channels in limestone not necessarily governed by the water table.
6. He expounds a novel theory of speleogenesis.

Indeed, Hutton was a very well-read man. In particular, he gave an accurate description of the remote Table Mountain, long before the Cape had become a British colony (Craven, 1991).

One of the many visitors to the Ingleborough area was Francis Douce (1757 - March 1834) who, although he was Librarian at the British Museum, bequeathed his private library to the Bodleian at Oxford. He must have employed a better guide than did Hutton because he appreciated that the latter had confused Lower Long Churn Cave and Dicken Pot, and that it was Gayle Beck (and not the River Ribble) that flowed past Catknot Cave[1]. Unfortunately the date of his visit is not known.

As in the Lake District, the Ingleton scenery inspired the local poets, but not to the same extent. Thomas Dixon (1781) described the area in verse. In his poetry he mentions Yordas and Gingling caves, gives the first mention of Rowten Pot, and describes, but does not name, Austwick Beck Head, Gaping Gill and Clapham Beck Head.

The next original observer of the caves was Thomas Hurtley (1786), the Malham schoolmaster. He located Gingling (or Caleb's) Hole on the west flank of Fountains Fell where the stream disappeared into a man-sized hole and reappeared 1½km away at Neals Ing farm.

The eighteenth century tourists included the Hon. John Byng, who later became the 5th. Viscount Torrington (Andrews, 1936). He was travelling on horseback with Mr Blakey, a Manchester cotton businessman, who appears to have previously visited the caves. On Monday 18 June 1792 they hired a Chapel-le-Dale shoemaker called Jobson, described as a *"merry, hearty fellow"*. This is not surprising because he was newly married! He took his clients to Weathercote Cave, Gingle Pot and Yordas Cave, using ½kg of candles in the process.

Another tourist who left a record was the Reverand William MacRitchie (1897), in 1795. On 29 June he stayed the night at Thornton-Church-Stile; the following day he explored Yordas Cave with a friend and with a shepherd as guide. Half an hour later he walked up Gragareth to "Pool-Pot-Hole" and still higher to Gingling Cave. From the position on Gragareth, and from the similarity of the name, "Pool-Pot-Hole" is most likely to be Bull Pot, of which this is the earliest mention. On the following day he examined Catknot Cave alone. Accompanied by Mr Elishaw, the curate of Chapel-le-Dale, he visited Weathercote Cave, Gingle Pot, Hurtle Pot and Gatekirk Cave. He continued that Mr Elishaw had explored Douk Cave for 800m, and had found no end.

The last recorded visitor in the eighteenth century may have been the Hon. Mrs S. Murray (1799). She called at Weathercote Cave, Hurtle Pot, Gingle Pot, Douk Cave and Yordas Cave, but had nothing original to add to her account.

THE NINETEENTH CENTURY

At the beginning of the century John Housman (1800) published his guide to the Lake District. Of caves in Cumberland he reported that Tutman Hole on Gildersdale Fell in Alston Moor had been explored for over a kilometre; while the solitary cave in Westmorland - on Dun Fell - had been explored for 3km by the Reverand William Richardson. Housman knew of no exploration of Dunald Mill Hole. His account of the Craven caves owes something to the Reverand John Hutton, whom

[1] Douce's annotated copy of Hutton's Tour to the Caves is in the Bodleian Library.

he erroneously describes as curate of Chapel-le-Dale; but there is no doubt that he toured the caves, because he made several original observations not recorded by Hutton.

In the 1800 edition of the book, the guide for the Ingleton caves is not named. In the 1802 second edition he is identified as William Wilson, an old soldier who added his military experiences to his descriptions of the natural features of the district. His tour took Housman via Thornton Force, Keld Head and Braida Garth to Yordas Cave. In addition to Hutton's "Bishop's Throne" and "Chapter House" he names "Yordas Bedchamber" and "Yordas Oven". Further up the hillside he passed Gingling Cave and other smaller potholes before crossing into Chapel-le-Dale.

Before visiting Weathercote Cave permission had to be obtained from the neighbouring farmer. Housman explored every corner of the cave before going downstream to Gingle and Hurtle pots. Across the road he penetrated 100m into Douk Cave for which a ladder was necessary to gain entry. On the way to the top of Ingleborough he passed and described Braithwaite Wife Hole, Meregill and Hardrawkin. Lower Long Churn Cave was explored as far as the large chamber called St Pauls; but the Dicken Pot misnomer is repeated. He advised his readers to visit the Alum Pot caves only in dry weather. In the Ribblehead area he described Greenside Cave, Gatekirk Cave and Catknot Cave.

In the Ribble valley Housman again reported the water tracing experiments at Hull and Hunt pots, and described but did not name Robin Hood's Mill. He gave the first description of Attermire Cave - about 70m long ending in a large chamber.

The following year William Seward (1801) of Burton-in-Lonsdale published a long, poetic and verbose account of Yordas Cave.

About this time there appeared an unsubstantiated report of the first attempt to descend a vertical pitch of more than trivial depth. In autumn 1803 Edward Dayes visited Hunt Pot on the western slopes of Penyghent (Brayley, 1825). He commented that, *"...a short time ago, a person was let down into this gulf by rope, to the depth of 100 yards, but his courage failing him, he roared out lustily, and his companions drew him up again."* This may, of course, merely be fiction invented to impress gullible tourists.

The next original and reliable recorder of the Craven caves is the Reverand Thomas Dunham Whitaker Ll.D., F.S.A. (1805), vicar of Whalley in Lancashire. In the 1805 first edition of his *"History ... of Craven"* he speculates on the source of the River Aire. He was not convinced that all the water in the river came from Malham Tarn, and he noted the two other risings below Malham. Still in this area he noted, *"In a cave near Malham were discovered, not many years ago, the skeletons of a herd of red deer."*

In Wharfedale Whitaker had descended Knave Knoll Hole (better known today as Elbolton Cave) *"several years ago"*, and found therein many sheep bones and a human skeleton. Further upstream he described Dove Cave as *"...the finest cavern in the district"*. In the 1812 second edition he briefly reported the finding of some well-decorated natural chambers in the Pikedaw Calamine Mines (Whitaker, 1812).

The famous landscape artist, J.M.W. Turner, made several tours to Yorkshire, sketching as he went. On 25 July 1816 he drew the entrance to, and interior of, Dove Cave near Kettlewell. His latest biographer, David Hill (1984), erroneously states that although "Dove Cave" appears in Turner's sketchbook, it was Dow Cave that was visited. However, the sketch is quite clearly of Dove Cave; and Dow Cave was not discovered until 1852 when the entrance collapsed (Harker, 1869). Turner took the opportunity to draw the better-known karst phenomena including Kilnsey Crag, Gordale Scar, Malham Cove, Yordas Cave, Weathercote Cave, Hurtle Pot and Gingle Pot.

By 1818 the Ingleton tourist trade had increased sufficiently for William Westall (1818) A.R.A., F.L.S. to publish the first illustrations of the caves. His twelve aquatints were of Dovecote Gill Cave near Sedbergh, Yordas Cave (three views), Weathercote Cave (four views), Gatekirk Cave, Malham Cove and Gordale Scar (two views). The entrance to Yordas Cave was much larger than it is today - there being no evidence of the stone arch that at some time had contained a gate. The cave guide is depicted with a light at the top of a 2m pole - compatible with descriptions given by earlier writers. The standard edition sold for one guinea (£1-05); the proof edition for 1½ guineas (£1-58). In September 1820 Westall married Ann Sedgwick, younger sister of Professor Adam Sedgwick of Dent and Cambridge. It is not clear whether Westall visited the caves before or after his association with the Sedgwick family (Clark and McKenny Hughes, 1890).

In July 1817 there was an enormous flood in Kingsdale that filled Yordas Cave with much debris, and caused the stream to vanish under the rubble. Subsequently the guide laboriously uncovered the stream. Whitaker (1823) must have visited Yordas after the flood, because he dismissed the place as *"...never a lofty or spacious cave"*.

In 1822 George Nicholson of Malton produced a lithograph of Hurtle Pot (North, 1951).

The caves at the northwestern end of the limestone area are well off the beaten track. It is therefore not surprising that Leck and Casterton fells received little attention from the topographers and guide book writers. This state of affairs persists today, when most of the visitors are potholers. The second man to describe Easegill also wrote under a pseudonym - "Valentine" - in 1820 (Anon, 1820). He and his friend explored the Witch Holes to a large chamber with a terminal sump, then passed Easegill Kirk on the way to Bull Pot of the Witches. They descended the chimney in the southern aspect of the entrance shaft for about 11m but were stopped when the pitch widened. They correctly postulated that there was a large cave beyond. Valentine also confirmed the great flood of 1817.

By 1822 the "Caves of Craven" were sufficiently popular to merit inclusion in Edward Baines' (1822) Gazetteer of the County of York. The compiler acknowledged John Hutton as the source of his information.

This history now moves to the eastern part of the limestone area. In 1825 John Phillips (1853) F.R.S. of York descended a lead mine shaft on Greenhow Hill, and entered a well-decorated chamber. Unfortunately it was soon robbed by *"...tasteless visitors and greedy miners"*, and by 1852 had become *"...one of the lost wonders of Yorkshire"*.

In the following decade T Allen (1832) made the first mention of Goyden Pot at the upper end of Nidderdale. He announced that Goyden could be safely penetrated with a lighted candle for two or three hundred metres. He made no claim to be the first man there; and the inference is that the place was already receiving visitors. Allen also gives the first description of Crackpot Cave in Swaledale:

> *"At the source of a brook that runs past it in its road to the river is a curious cavern called Crack Pot, the entrance of which is extremely narrow. A few yards from the entrance is a spacious cavern; proceeding a few paces further it descends rather abruptly; at the bottom is a deep water issuing out of the rock below, near which there is a curious pillar of solid stone. The narrow passages beyond it are not safe to traverse."*

Three years later the Reverand J L Armstrong (1835) described a visit to Dowkabottom Cave with a friend, and with a pick-axe to be used for carving their names on the wall. They dropped 9m into the cave, then changed their clothes and proceeded to explore. While inside they heard a loud explosion. There followed much argument over who should lead the way out with the pick-axe for defence. When they eventually emerged into daylight, they discovered that the explosion had been nothing more sinister than a thunderclap!

John Phillips (1836), in the course of his investigations into the geology of Yorkshire, was aware of caves in Barbondale and in Leck Beck, in addition to those previously described. Unfortunately he gave no detail.

In the winter of 1837 was discovered Lost John's Cave, Leck Fell, by the gardener to Mr Welch of Leck House. He has since been identified as J Mellray (Humphries, 1981); his first name may or may not have been John. The cave was visited shortly afterwards by Henry Harrison Davis, about whom little is known, except that was brought up in Kirkby Lonsdale, married Dinah Dawson, and died in about 1850. Davis commented that the stream, which was in places waist deep, and the drips from the roof, destroyed any pleasure that he may have derived from its exploration. Again illustrating the commercial nature of caving at that time, he continued that if some enterprising individual could divert the stream, he would be able to discover caverns of *"immense magnitude"* and open them to the public (Craven, 1974).

On 5 June 1838 Davis visited Yordas Cave with a guide who *"...lighted his candles, about 12 in number, fixed upon cross-pieces upon the top of a long stick"*. He appreciated that at one time the roof had been higher (though strictly speaking the floor had been lower), and offered this explanation:

"When it was first enclosed, a grating was put down in another place to prevent entrance: which, stopping the stones in their course, dammed the water in, which has left a deposit of gravel every flood since."

He makes no mention of the great flood of 1817, nor of the exact site of the grating. Davis later threw stones down Gingling Pot, and his account also mentioned Rowten Pot.

The following day Davis was taken on the standard tour of the Chapel-le-Dale caves by William Metcalfe, the son of the farmer at Weathercote. Metcalfe himself is of much interest, because he was one of the first explorers to attempt the descent of long pitches, and the techniques he used were clearly self-taught in the caves near his home.

All the cave explorers so far mentioned were content to examine only obvious cave entrances. They made no attempt to penetrate narrow passages, nor to dig with a view to enlarging or discovering caves. The first cave diggers operated in 1837 on the Ingleborough Estate, where Clapham Beck Head had been known for generations. The Estate had been owned by the Farrer family for some time, and the then Lord of the Manor was James Farrer of Ingleborough Hall.

There was a great flood on 16 September 1837. Water was gushing out of the Beck Head and overflowing 19m further up and out of Ingleborough Cave, which at that time was 52m long ending in a stalagmite barrier. Six days later James Farrer and one of his estate workers, Josiah Harrison, inspected the flood overflow sites. Two labourers were set to work removing stones from the higher overflow point, but they failed to force an entry. On the following day (23 September 1837) three labourers working under Josiah Harrison smashed the stalagmite barrier, thereby lowering the water level inside Ingleborough Cave. Two of the labourers penetrated 77m from the place where the iron gate was later installed. Later in the day Matthew T Farrer and Lord Encombe (second Earl of Eldon) reached the same place, which was then waist deep in water. Sometime during the next three days two labourers, Robert Bradley and John Grime, were the first people to enter Pillar Hall, which was subsequently visited on 26 September 1837 by Jaes Farrer, Matthew T Farrer, and Thomas Henry Farrer. On a second trip that day they were stopped after about 419m by "stalagmitic pebbles". On 29 September the Farrers penetrated 735m, and two labourers were sent into the deep water. On 11 October James Farrer, Matthew T Farrer, Lord Encombe and William Hind passed through the low waterfall and reached deep water 874m from the entrance. James Farrer tried unsuccessfully to proceed further by swimming with a lifeline tied to his waist (Mitchell, 1974).

Further exploration of Ingleborough Cave continued the following year. On 23 April 1838 James Farrer and some other men again unsuccessfully tried to extend the cave. On 5 October 1838 James Farrer and Professor Adam Sedgwick of Cambridge forced the cave to Lake Avernus. One man floated on some cork on the lake, with a candle in his mouth, but was unable to find a way through (Clark and Hughes, 1890).

The details of the exploration of Ingleborough Cave are difficult to follow. The Farrers recorded their exploits in the "Ingleborough Cave Book" - a manuscript volume bound in green velvet that has been lost since 1952. The details therefore have to be gleaned from abbreviated extracts and other secondary sources - a poor substitute for the original accounts.

The opening of Ingleborough Cave was trebly significant. Not only was it the first cave to be dug in the northern Pennines, it was the first northern cave to be surveyed. In 1837 the distances were measured using balls of string, but the following year an accurate survey was done by Thomas Hodgson, a Lancaster land surveyor. The survey, which was published 11 years later in 1849 (Farrer, 1849), showed the cave to be about 744m long. For many years the plan of Ingleborough Cave appeared on Ordnance Survey maps - the only cave survey to be so distinguished in Britain (Mitchell, 1978).

James Farrer was not content with merely owning a large cave. He was fascinated by the speleothems inside, and endeavoured to determine their age and rate of growth - the first attempt at cave research in the north of England. One of the speleothems is called the "Jockey Cap" onto which there was a steady drip of water falling from the roof of the cave. By measuring its dimensions in 1839 and again in 1845, Farrer found a 10% increase in height and a 5% increase in diameter. However, he did appreciate that it was not easy to take accurate measurements.

By 1838 Farrer had installed an iron gate and opened the cave to visitors. Josiah Harrison was appointed guide. He kept a visitors' book, which is also missing, in which each person had to record his name and address. The fiftieth visitor was Frederic Montagu of Lincoln's Inn (Montagu, 1838).

The Farrers also kept a red manuscript "Cave Book". This, too, has been lost; and all that remain are abbreviated abstracts (Mitchell, 1974). It is clear that the Farrers' interest in caves extended beyond Ingleborough Cave (or Clapdale Great Cave as it was sometimes called), and that in 1838 they explored caves elsewhere on and beyond Ingleborough. Some can be identified today; others have been lost. "Intake Cave" was explored on 27 August 1838, and noted to be about 205m long with occasional low passages ending in a muddy boulder choke. The next day they looked at "Banscar's Caves". One, in the direction of Batty Wife Hole, was said to be 186m long, and 273m in the opposite direction. They were not explored because they were too low. From the position, description and similarity of name they were probably Runscar Caves. "Arch Cave" on Blea Moor, a *"very lofty"* place was explored for about 366m in a northeast direction. The "Pothole Cave" of a similar nature was not explored for any great distance. Still in the Ribblehead area, Ivescar and Homeshaw caves were also explored.

On 1 October 1838 they pushed Douk Cave for 1,080m until it became too low. Nearby in Southerscales Allotment they explored "Dawson's Cave" for 283m in a northwesterly direction until progress was stopped by a 6m pitch. In the opposite direction they progressed 563m This place may have been Hardrawkin Cave and Pot. Across the valley they looked in Gatekirk Cave. On 9 November 1838 they were on the High Birkwith Estate north of Horton-in-Ribblesdale. At "Knott Gill Cave" they:

"...descended from the high entrance 275 yards and were stopped by a deep pool of water and heard a waterfall which we approached near to from the cave entrance after going about 60 yards. Could not get up the fall. The cave is in Fossil Limestone Rock."

On the same day they inspected "William's Waterfall Cave" with a low entrance soon rising to 22 or 25m and ending at a 9m waterfall that enters from Syke Pasture. Downstream there was a natural bridge across the beck. Assuming that the entrance has since collapsed, this cave could well have been Browgill Cave. To this list Phillips (1853) adds *"Gauber Hole, on the north side of Ingleborough, and another cavern ..."*.

Unfortunately these extracts give no indication of the identity of the cavers involved with the Farrers. It is believed that they included John Birkbeck II of Anley House near Settle, and William Metcalfe of Weathercote House (Dawkins, 1874), but there is no contemporaneous supporting evidence. There is no doubt that Birkbeck and Metcalfe were involved in the first potholing expeditions in the 1840s.

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Summary of first explorations and reports

Cave or other karst feature	Year	Explorer
Cave in Weardale ? Fairy Hole	1746	Durant
Dove Cave, Wharfedale	1751	Pococke
? Boreham Cave, Littondale	1751	Pococke
Dowkabottom Cave, Littondale	1751	Pococke
Weathercote, Hurtle Pot, Gingle Pot	1751	Pococke
Yordas Cave and Pot, Kingsdale	1751	Pococke
Tatham Wife Hole	1751	Pococke
Dunald Mill Hole	1760	Walker
Alum Pot	1761	Hutton
Upper and Lower Long Churn	1761	Hutton
Gaping Gill	1761	Hutton
Long Kin West or East	1761	Hutton
? Jockey Hole	1761	Hutton
Blackside Cove	1761	Hutton
Sir William's Cave	1761	Hutton
Atkinson's Chamber	1761	Hutton
Easegill Kirk	1761	Hutton
Great and Little Douk Cave	1780	Hutton
Meregill	1780	Hutton
Hardrawkin Pot, Chapel-le-Dale	1780	Hutton
Greenside Cave	1780	Hutton
Catnot Cave, Ribblehead	1780	Hutton
Hull Pot, Hunt Pot	1780	Hutton
Brants Gill, Douk Gill	1780	Hutton
Braithwaite Wife Hole	1781	Hutton
Gatekirk Cave, Ribblehead	1781	Hutton
Rowten Pot, Kingsdale	1781	Dixon
Austwick Beck Head, Clapham Beck Head	1781	Dixon
Gingling Hole, Fountains Fell	1786	Hurtley
? Bull Pot, Kingsdale	1795	MacRitchie
Tutman Hole, Gildersdale Fell	1800	Housman
Cave on Dun Fell	1800	Richardson
Jingling Cave, Kingsdale	1800	Housman
Robin Hood's Mill	1800	Housman
Attermire Cave, Settle	1800	Housman
?? descent of Hunt Pot	1803	Unknown
Source of the River Aire	1805	Whitaker
Cave near Malham	1805	Whitaker
Elbolton Cave, Wharfedale	1805	Whitaker
Pikedaw Calomine Mine	1812	Whitaker
Dove Cave, Kettlewell - sketch	1816	Turner
Dovecote Gill Cave, Sedbergh, Yordas,		
Weathercote, Gatekirk - aquatints	1818	Westall
Witch Holes, Easegill	1820	Unknown
Bull Pot of the Witches	1820	Unknown
Hurtle Pot - lithograph	1822	Nicholson
Lead mine, Greenhow Hill	1825	Phillips
Goyden Pot, Nidderdale	1832	Allen
Crackpot Cave, Swaledale	1832	Allen
Barbondale and Leck Beck	1836	Phillips
Lost John's Cave, Leck Fell	1837	Mellray
Clapham Beck Head	1837	Farrer et al
Ingleborough Cave	1837	Farrer et al
Ingleborough Cave - survey	1838	Hodgson
Runscar Cave, Ribblehead	1838	Farrer et al
Ivescar Cave, Ribblehead	1838	Farrer et al
Homeshaw Cave, Ribblehead	1838	Farrer et al
Arch Cave	1838	Farrer et al
Pothole Cave	1838	Farrer et al
Intake Cave	1838	Farrer et al
Dawson's Cave	1838	Farrer et al
Knott Gill Cave	1838	Farrer et al
William's Waterfall Cave	1838	Farrer et al
Gauber Hole	1838	Farrer et al

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Geomorphological controls on tufa deposition at Nash Brook, South Wales, United Kingdom

Heather VILES [1] and Allan PENTECOST [2]
[1] School of Geography, University of Oxford, Mansfield Road, Oxford, OX1 3TB, UK
(email: heather.viles@geography.ox.ac.uk)
[2] Division of Life Sciences, King's College London, Campden Hill Road, London, W8 7AH, UK

Abstract: Tufa deposition is an important short term influence on carbon cycling and an interesting, under-studied component of many karst landscapes. Nash Brook, in South Wales is a small, tufa-depositing stream located in a small valley choked with older tufa deposits. Tufa is currently being deposited along a suite of small barrages within the river channel. Studies have been made of the morphometry and arrangement of these barrages, and short-term (9-month) measurements of tufa deposition made across a sample of the barrages. The morphometric studies show a complex series of relationships between barrage height, spacing and slope gradient, and allow hypotheses about hydrological controls on barrage formation to be tested. Large woody debris appears to play an important role in the initiation of barrages, and various microflora (including the alga *Vaucheria geminata)* aid the small scale accumulation of tufa. The highest short-term rates of tufa deposition occur on barrage crests towards the headward end of the barrage system. Current tufa formation at Nash Brook appears to reflect the interaction of hydrological and biological controls. Although small in magnitude compared with the fossil deposits in the valley, tufa barrages continue to play an important role in this karst fluvial system.

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INTRODUCTION

Tufa barrages are an enigmatic component of many fluvial karst landscapes. They develop through calcium carbonate deposition along a river system forming a series of dams, and have often dramatic effects on the river's hydrology and ecology, sometimes producing chains of lakes. The term tufa is widely used to refer to freshwater calcium carbonate deposits formed either from ambient or thermal waters; travertine is an alternative term, commonly used synonymously with tufa, or sometimes restricted to describe hard and resistant deposits (Pentecost and Viles, 1994). The nature and world distribution of tufa deposits is reviewed by Ford and Pedley (1996). Notable barrage systems include those at Plitvice in Croatia, Band-e-Amir in Afghanistan and Sept Lacs in Madagascar (Ford, 1989). At Plitvice, for example, a sequence of 14 large lakes has been formed through the development of tufa dams up to 30m high along a 6.5km reach of the river Koruna as it flows through a gorge (Emeis *et al.*, 1987). Many smaller scale examples are found worldwide, ranging from the hydrothermally produced tufa barrages on Coal River Springs, SE Yukon, Canada (Guerts, *et al.*, 1992) to the cascade formed at Ban Khouang Si in Laos, on a tributary of the Mekong (Benoit, 1986), and the system of 0.5 to 2m-high barrages stretching about 1.5km along Louie Creek, in the seasonally wet tropics of NW Queensland, Australia (Drysdale and Gillieson, 1997).

Few examples are recorded from equatorial regions, although Humphreys *et al.* (1995) have studied a notable barrage system in the lowland rainforests of Madang Province, Papua New Guinea. Neal (1990) has carried out detailed investigations of a suite of small barrages in Cayo District, Belize. Within Europe, many tufa barrage systems of Holocene age, commonly small in size, are found. In France, for example, the river Argens in Var is influenced by four tufa barrages (Nicod, 1986). On a smaller scale, the Fleinsbrunnenbach in the Schwabische Alb, southern Germany (a tributary of the Erms), is crossed by many small barrages up to 30cm high over most of its 1km length (Pentecost and Viles, In Press). In Britain, the largest barrage is at Caerwys in North Wales (Pedley, 1987). Of early Holocene age and extending downslope through about 46m of relief, this barrage is no longer active. Actively-forming British examples are found at Slade Brook, Gloucestershire, Alport, Derbyshire, and several localities near Bath, W England (Pentecost, 1993; Pedley *et al.*, 1996, Baker and Simms, 1998).

Tufa deposition occurs where the equilibrium of waters containing dissolved calcium carbonate shifts, thus favouring the deposition of calcium carbonate, following the equation below:

$$Ca^{2+} + 2HCO_3^- \longrightarrow CaCO_3 + H_2O + CO_2$$

Several studies have shown that supersaturation of calcium carbonate needs to occur before such deposition can occur (Jacobson and Usdowski, 1975; Dandurand *et al.*, 1982). Degassing of carbon dioxide in turbulent waters may encourage calcium carbonate deposition, as may the biological uptake of carbon dioxide. Direct biological precipitation of calcium carbonate may be important in some cases, as may evaporation and cooling of water issuing from hot springs in other cases (Ford, 1989). Substrates, such as organisms and organic remains, upon which calcium carbonate can nucleate and precipitate, may also encourage tufa deposition.

THEORETICAL CONSIDERATIONS OF TUFA BARRAGE DEVELOPMENT

There has been much controversy over the origin and development of tufa barrage systems. Several authors have referred to tufa barrages as freshwater bioherms (Lang and Lucas, 1970) or phytoherms (Pedley, 1992) and drawn attention to the key role played by organisms in carbonate deposition and the production of barrage forms. Work from Plitvice and smaller barrage systems in Derbyshire and Spain (Emeis *et al.*, 1987; Pedley *et al.*, 1996) has shown the importance of micro-organic biofilms in calcite precipitation and deposition, and many studies have shown the importance of fallen trees and other large organic debris in initiating barrage development. However, hydrological controls are also probably important in the production of tufa barrages, and changes in bed slope may cause tufa deposition.

Studies have also been made of how barrages develop once initiated, given the variety in small-scale depositional environments. Liu *et al.* (1993, 1995), for example, studied deposition rates on the Huanglong tufa, Sichuan China. They found that the highest rates (just under 5mm per annum) occurred in places with fast water flow and thin boundary layers (such as on the rim of dams) and the slowest rates (around 0.4mm per annum) occurred in pools, where boundary layers were much thicker. Biological controls are also likely to be important, as different organisms tolerate different water flow conditions and impose their own signature on tufa deposition. Thus for example, the xanthophyte *Vaucheria geminata* grows preferentially in fast flowing water, and its frond-like form becomes encrusted with tufa producing a downslope-oriented streamlined mound of tufa.

Explaining the spacing, form and development of tufa barrage systems remains problematical as hydrological, biological and geomorphological factors all need to be considered. Pedley *et al.* (1996) made studies of Holocene barrage tufas in Britain and Spain and concluded that a climatological control significantly affected fluvial geomorphology, with semi-arid deposits possessing vertical, narrow rimmed arcuate structures and deep lakes, and cool temperate ones characterised by arcuate buttress development and shallow lakes. However, there has been little consideration of how and where the vertical barrages develop, or extension of this work to barrage systems in other climatic zones. Studies have been made of the occurrence of analogous features such as rimstone dams in caves that perhaps present a simpler situation with no organic controls. Hill and Forti (1997) suggest that rimstone dam height is positively related to cave passage gradient, and that as gradient decreases dams get lower and also more convoluted. Recent studies by Veni (1994) of rimstone dams in Honey Creek Cave, Texas confirm these findings, showing that the tallest and fastest growing dams occur along steeply sloping stream segments. Furthermore, Veni (1994) found that the number of dams also increases with gradient. However, contrasting findings have come from studies of similar rimstone dam features in surface environments. Ekmekci *et al.* (1995) studied the morphology of rimstone pools associated with hot springs at Pamukkale, western Turkey and found that here the size both of dams and pools becomes smaller as slope gradient increases. Thus, current studies indicate that within caves the biggest, most closely spaced barrages occur on the steepest slopes, whereas on hot spring terraces the steepest slopes contain the smallest, most closely spaced barrages.

This study aims to contribute to the understanding of the development of these enigmatic features through investigation of a small fluvial tufa barrage system, formed from waters at ambient temperature, in South Wales. Morphometric measurements have been taken, coupled with short term measurements of the nature and rate of deposition on various parts of this system to help answer the following questions:

1. Is the distribution of tufa barrages in Nash Brook random or non-random?
2. Is there a relationship between barrage development and stream gradient?
3. How are barrages initiated and how do they develop?

SITE DESCRIPTION

Nash Brook is a small coastal stream around 3km long, situated on Liassic limestone 6.5km west of Llantwit Major (Grid Reference SS/906702) in South Glamorgan, Wales (Fig.1). It rises in a series of fast flowing springs and runs across Jurassic limestones to the sea. Active tufa deposits are restricted to a 500m stretch at the coastal end of the stream as it passes through ash woodland, and associated with a clear break of slope (Fig.2). Along this stretch the stream course is cut into older tufa deposits, culminating in a spectacular coastal section some 5m thick. Evans (1977) and Evans *et al.* (1978) suggest that this coastal section contains three deposit types, i.e. basal screes, tufas with sporadic poorly developed soil layers, and overlying hillwash. On the basis of molluscan analysis, Evans claims that deposition of the tufa sequence began in the Pre-Boreal and continued through the Atlantic, finishing in the Iron Age, around 200 BC, possibly because of human activity clearing the forest. The sediments appear to be largely of marsh origin and may have collected behind a tufa barrage. The present area of actively forming tufa consists of a series of dams up to 1.4m in height extending over a distance of 250m. Several other coastal streams within the area exhibit valleys choked with older tufa and small active tufa deposits are forming within the Liassic cliffs along the coast, but currently there is very limited deposition within the other streams. Most of the surrounding countryside is agricultural land, given over to mixed farming with cattle, sheep and arable fields all common. The

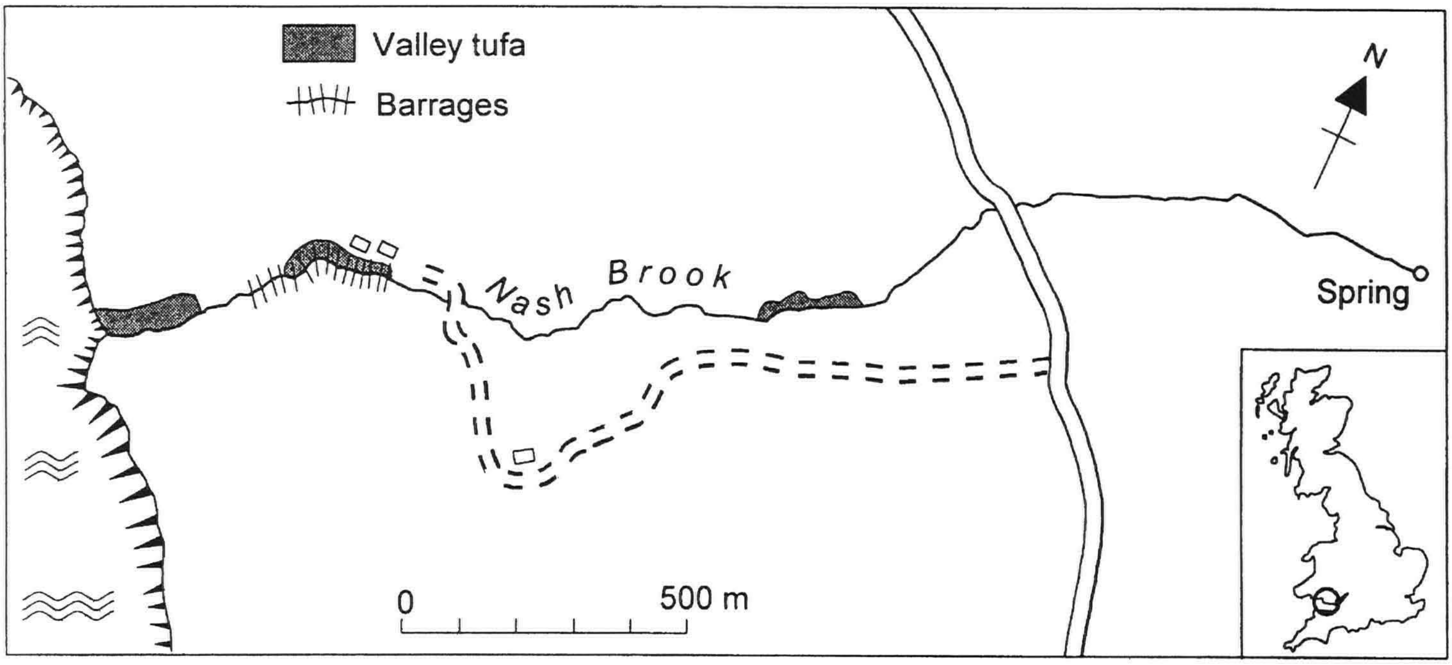


Figure 1. Location of Nash Brook, South Glamorgan.

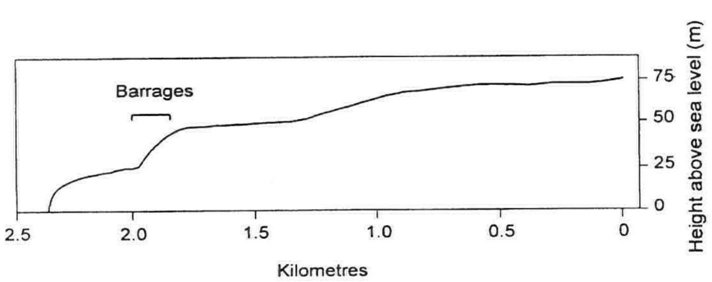


Figure 2. Location of the tufa barrages on Nash Brook.

lack of trees to provide shade and a source of large woody debris may be a factor preventing more widespread tufa deposition in this area.

EXPERIMENTAL DESIGN AND METHODS

Two types of study have been carried out in this investigation of the tufa barrages of Nash Brook. Firstly, morphometric studies have been made of the entire barrage system using close-range aerial photography and ground measurements. The aim of these studies was to provide accurate measurements of the distance between barrages, their height, crest length, behind-barrage pool area and volume. This information could then be used to test hypotheses concerning the distribution of barrages. A series of several hundred close-range aerial photographs (see Fig.3 for one example) covering the entire barrage system was obtained using a Nikon CF7 camera fitted with wide angle (24 mm) lens mounted on a 4.4m pole. The pole was placed in the centre of the stream at c. 5m intervals to achieve overlapping photographs. Conventional remote sensing was impracticable because of the dense tree cover. A composite image produced from these photographs was used to calculate individual barrage crest lengths and back-barrage pool aras for the whole suite of barrages. The photograph-derived figures were then checked by field survey. Barrage heights and pool depths and pool lengths of the upper 28 barrages in the sequence were also measured on the ground, and detailed morphometric measurements made of the top 15 barrages (shown in Fig.4).

The second part of the investigation involved placement of small (3.5cm x 0.5cm) cylindrical tablets of a Bath Stone (Stoke Ground Base Bed) within different microenvironments on several barrages to monitor spatial variability in short term deposition rates. The tablets had a groove cut around their circumference, allowing them to be attached securely with monofilament fishing line to the tufa deposit. 20 tablets were left on 4 barrages (5 tablets on each barrage) on 18/9/96 and collected on 5/7/97, providing 290 days of monitoring (the location of the tablets is shown in Fig.4).

After removal, the tablets were observed using light and electron microscopy, and identifications made of organisms growing on them. In the past many different techniques have been used to study short- and medium-term tufa growth rates. These include pegs, microscope slides, calcite seed crystals (Lorah and Herman, 1988), copper plates (Emeis *et al.*, 1987) and large sandstone blocks (Drysdale and Gillieson, 1997). Such methods provide a contrast with estimation from mass balance calculations (Lorah and Herman, 1988), and usually tend to produce smaller estimates of the amount deposited. Other approaches include measurement of the thickness of seasonal laminae in cyanobacterial tufa accumulations (e.g. Pentecost, 1988). In the present study, the amount of deposition was quantified by measuring the deposit thickness under the Scanning Electron Microscope (SEM) and dividing this by the length of the exposure period to derive a rate in mm/year.

RESULTS

Barrage morphometry

The 250m stretch of Nash Brook contains 69 complete barrages and a smaller number of subsidiary dams that only partly span the stream. The barrages occur along the steepest part of the stream channel, with gradients between 1:10 and 1:20. Many of the barrages are very complex in plan form, with sinuous crests and multiple small barrages making up a large complex (Fig.5). For the 28 measured barrages the distance between barrages (T_L) ranged from 0.6 to 7.1m, with a mean of 2.67m, and the barrage height (D) ranged from 0.03 to 1.32m (mean 0.25m). The variance to mean ratio for the distance between barrages gave a χ^2 value of 21.41, suggesting that the 28 barrages are randomly distributed (Diggle, 1983). A significant positive correlation ($r = 0.553$, $p < 0.01$) was obtained between the barrage height (D) and the distance to the next barrage downstream (T_L), suggesting that the higher the barrage the longer the pool below it. Assuming that D can also be used as a surrogate of slope, this correlation indicates that low gradients (i.e. small D values) are associated with shorter spacing between barrages, and for higher gradients the reverse applies.

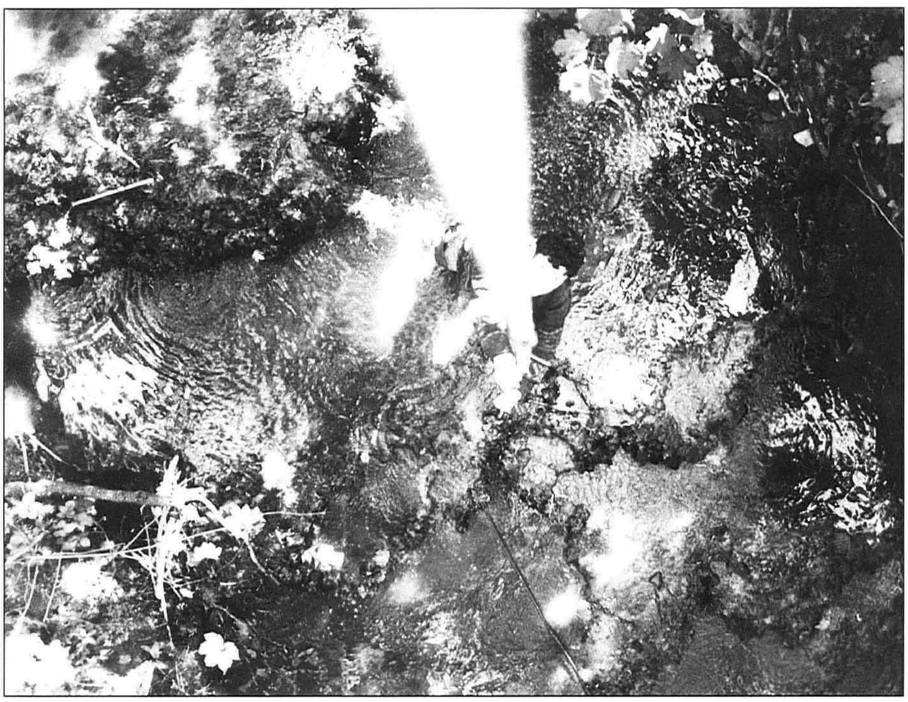


Figure 3. Part of the photomontage showing convoluted nature of the barrages. Note: part of the pole used to support the camera is visible in the upper central part of the photo.

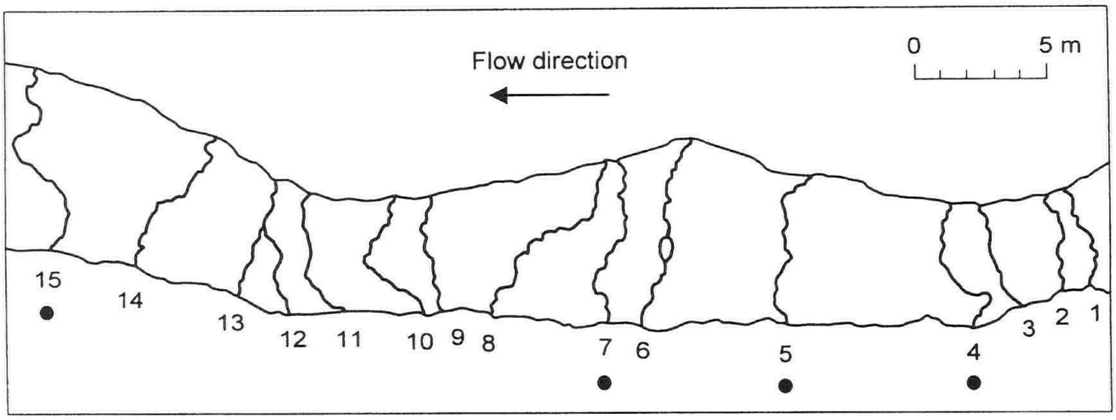


Figure 4. The upper suite of 15 intensively measured barrages. The solid circles denote barrages at each of which 5 rock tablets were left to monitor deposition rates.

Morphometric measurements for the subset of 15 uppermost barrages are shown in Table 1, and their plan views are shown in Figure 4. All the barrage crest lengths (L) considerably exceed the stream width at the point of their inception, with L on average being 122% of stream width. Many crests have a convex profile downstream, although a number show a wavy profile roughly perpendicular to the direction of flow. Figure 5 plots crest length against stream width and shows a strong, positive, linear relationship between the two ($R^2 = 0.88$). There was no significant correlation between L and D (height of barrage measured on the downstream side to still water depth). The pools averaged 0.2m in depth and had soft tufa mud on their floors. Oncoids were present within some of the pools, which tended to be deepest immediately downstream of the barrage, shallowing up to the next barrage downslope. Figure 6 shows pool depth plotted against dropwall height, showing a positive linear relationship ($R^2 = 0.59$). This is unsurprising, as the pools are erosional features, and higher dropwalls will provide greater energy for fluvial erosion.

Profiles measured from 4 barrages are shown in Figure 7. The crest width was quite variable, ranging from c. 10 to 60cm. The crest either sloped gently into the upstream pool (Fig.7a, c, d) or fell more abruptly (Fig.7b). On the downstream side there was usually an overhang, commonly as wide as 40cm (Fig.7d), with steep, irregular slopes beneath. The overhang is accentuated in many cases by dense tufts of the filamentous algae *Vaucheria geminata* and the less common *V. sessilis*, which provide a spiky microtopography. The overhang is usually the area where water flows freely over the crest. Below this, where the barrage face is submerged in quieter pool water, the tufa becomes nodular in form, and *Vaucheria* is replaced by the calcifying cyanobacterium *Lyngbya (Phormidium) incrustata.*

Short-term tufa deposition rates

A summary of the tablet data is presented in Table 2. Four tablets out of 20 were lost during the course of the experiment with the remainder recording deposition of organisms and tufa. As can be seen from Table 2, the calculated annual deposition rates (assuming a roughly constant deposition rate over the year) range from just over 0.2mm per year to nearly 1.27mm per year, with a mean of 0.56mm per year. Table 2 also indicates the flow regime within which each tablet was located. In Figure 8a it is clear that the fastest rates of deposition occur within the faster flow regimes - however, a Spearman's rank correlation between flow regime and deposition rate gave non-significant results. Figure 8b shows deposition rates plotted against barrage position with barrage 1 at the upstream end and barrage 4 downstream. The intra-barrage variation is high, and no clear trends emerge.

The deposition rates should be treated as very broad estimates, as they are taken from three measurements per tablet, on areas where notable deposition was present, and do not take into account areas of low or zero deposition. Looking at Table 2, it is clear that several tablets were only partially covered by clearly identifiable tufa deposits, although all were 100% covered by lime mud. The most commonly

Barrage No.	Crest length (m)	Stream width (m)	Dropwall height (m)	Pool depth (m)	Tailwater pool length (m)
1	4.75	3.9	0.14	0.12	0.81
2	4.32	3.8	0.09	0.18	2.04
3	4.66	4.2	0.28	0.11	1.2
4	6.43	4.65	1.32	0.32	6.73
5	6.24	5.4	0.41	0.27	5
6	8.54	7.3	0.18	0.15	2.05
7	8.16	6.1	0.13	0.17	2.4
8	9.1	7.3	0.6	0.41	4.38
9	5.26	4.5	0.03	0.16	1.2
10	7.04	4.6	0.3	0.19	3.25
11	5.35	4.6	0.11	0.15	1.5
12	5.03	4.8	0.42	0.15	3.67
13	3.43	3	0.2	0.22	-
14	6.73	5.55	0.58	0.3	4.54
15	7.48	6.5	0.08	0.14	7.05
MEANS	6.17	5.08	0.32	0.2	3.27

Table 1. Barrage morphometry.
N.B. See Figure 7 for explanation of terms used to describe the elements of barrage morphology.

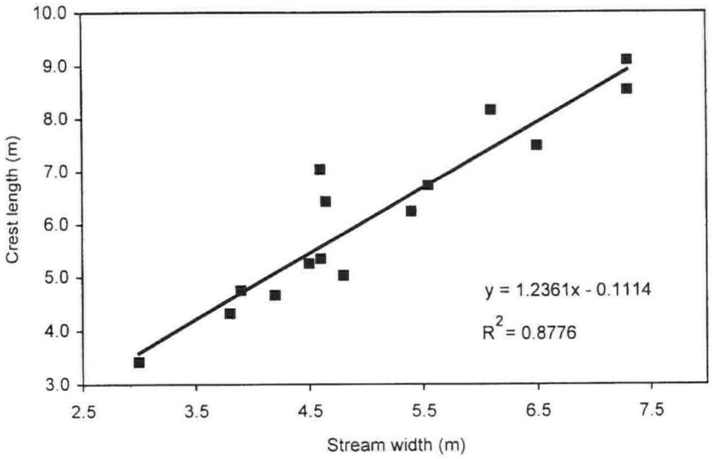


Figure 5. Crest length vs stream width.

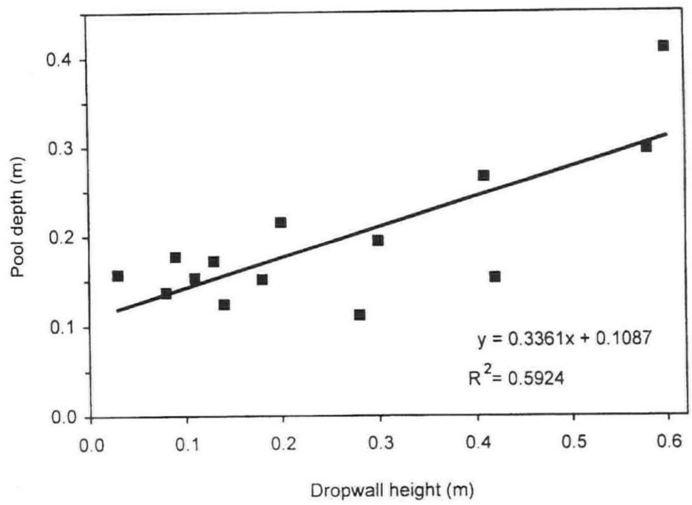


Figure 6. Pool depth vs dropwall height.

observed species forming clear organically-mediated deposits on the tablets were *Gongrosira incrustans*, a green algae, and *Lyngbya (Phormidium) incrustata*, a cyanobacterium - both of which are known to become encrusted with calcium carbonate (Pentecost, 1990). A host of pennate diatoms were also present, especially *Navicula cf tripunctata, Achnanthes spp., Fragilaria* and *Gyrosigma*. Oospores of *Vaucheria geminata* were also present in the lime mud, presumably ready for germination during the next season.

Using light and electron microscopy on cross sections through the tufa deposits on the tablets gives insight into their formation. Vast accumulations of diatoms with associated mucilage are found on and within most of the tufa deposits (Fig.9b). Where deposition is thick, clear seasonal layering is apparent (Fig.9a), with a thin diatom-rich basal layer (from autumn 1996), followed by a thick layer of sparite with relatively few organic remains (presumably from winter 1996/7) and a thicker layer of diatom-rich deposits near the surface. Calcite deposition can clearly be seen to be occurring around these diatom-rich biofilms, with both sparite and micrite occurring. A clear biofilm including algae and associated mucus can be seen on the surface of some samples (Fig.9c). In several cases (for example on tablet B4) encrustation of *Lyngbya* filaments is clearly observable (Fig.9d).

DISCUSSION

The apparently random spatial distribution of barrages along Nash Brook is in contrast to the observed regularity in distribution of analogous rimstone dams within caves. In caves, rimstone dams are thought to be largely formed through turbulent degassing of carbon dioxide favouring calcium carbonate precipitation, and to form self-perpetuating systems (Varnedoe, 1965; Shaw, 1979). Local turbulence below an initial dam increases deposition just below, leading to a further dam, then more turbulence and so on until the regular supply of calcite is exhausted. However, as already noted, freshwater tufa formation in streams is a more complex process, involving both turbulent degassing and organic initiation and encouragement of

Tablet No./ Barrage No.	Water flow type	% cover of tufa	Mean depth of tufa (mm)	Annual accumulation (mm p.a.)
A1/4	LOST			
A2/4	3	70% algal	0.33	0.41
A3/4	3	30% algal	0.31	0.39
A4/4	2	15% algal	0.21	0.26
A5/4	5	80% algal	0.17	0.21
B1/5	5	100% algal	1.33	1.67
B2/5	5	100% algal	1.02	1.29
B3/5	1	40% green	0.22	0.28
B4/5	2	100% algal	0.36	0.46
B5/5	LOST			
C1/7	5	20% algal	0.23	0.29
C2/7	2	100% algal	0.33	0.42
C3/7	LOST			
C4/7	4	25% algal	0.51	0.64
C5/7	4	100% algal	0.56	0.61
D1/15	LOST			
D2/15	2	100% algal	0.22	0.28
D3/15	2	50% algal	0.44	0.56
D4/15	1	100% green	0.29	0.37
D5/15	5	80% mud	0.55	0.69
		MEANS	0.44	0.56

Table 2. Short term tufa deposition.

Key for water flow type column:
1 = Mainly/ always dry
2 = Often/ seasonally dry
3 = Often wet with slow flow conditions
4 = Permanently wet with slow flow conditions
5 = Often/ usually wet with fast flowing conditions.

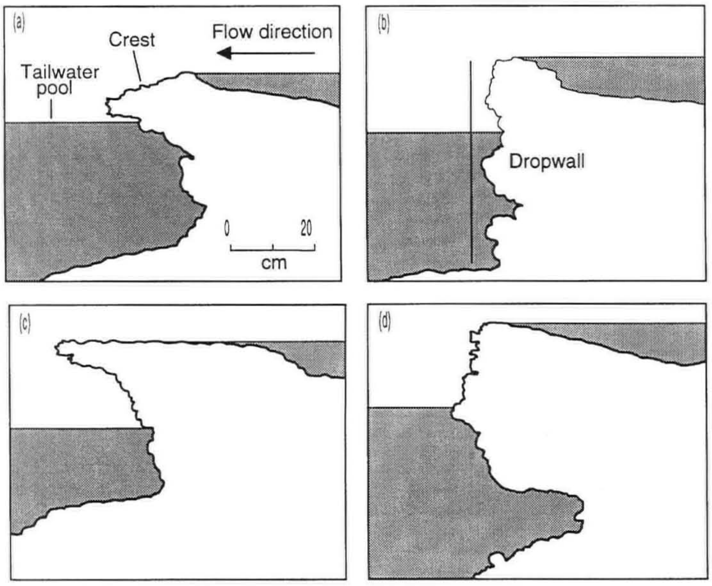


Figure 7. Sample barrage profiles.

calcium carbonate precipitation. Our findings echo those of Neal (1990), who surveyed 29 barrages on Little Barton Creek, Belize and found no regular spatial pattern of dams along the stream profile. He suggests that tree fall may contribute to the randomness of dam spacing (Neal, 1990, p.13), as fallen trees will increase turbulence and encourage tufa precipitation. Many of the barrages studied in Nash Brook have considerable amounts of large organic debris within them, ranging from entire tree trunks, through branches, down to individual leaves. It is highly likely that, as Neal proposes, trees falling across the stream provide initial obstructions favouring tufa barrage development.

Several geomorphological studies have been made of dams and other in-stream landforms produced by trees and other organic debris (e.g. Keller and Swanson, 1979; Keller and Tally, 1979; Marston, 1982; Robison and Beschta, 1990; Nakamura and Swanson, 1993; Gregory *et al.*, 1993). Such material, commonly called large woody debris (LWD), is usually defined as being over 10cm in diameter and consists of logs, branches, root wads, etc, which fall into channels in a range of ways. Most studies conclude that the inputs of LWD into stream channels are random in space and time. Studies of the impacts of LWD on stream hydrology and geomorphology indicate that they affect the dissipation of both potential and kinetic energy within streams, and play an often-important role in the development of pools, mid-channel bars and bank erosion. In several cases LWD residence times of >200 years have been reported (e.g. Keller and Tally, 1979), especially in low-order streams in high-relief areas, where 'flushing' of debris is limited. As far as we are aware, none of these geomorphological studies has been carried out in areas where tufa deposition may influence LWD build-ups within streams, but it is reasonable to suggest that where tufa formation occurs this can help to increase the permanence of such structures. Furthermore, where tree-fall occurs in tufa depositing areas, barrage initiation may be at least partly random as evidenced by this study.

Marston (1982) studied log dams (which he termed 'log steps') on streams in the central Oregon coast range, finding that over 163km of streams surveyed some 413 log steps occurred, with a mean height of 0.98m. Studies from the Lymington River basin, Hampshire, UK, revealed that over a length of more than 30km of streams surveyed between 0 and 12 dams per 500m stretch were present (Gregory *et al.*, 1993). Keller and Swanson (1979), in a study of 3rd order streams in Oregon, found that LWD-induced dams were spaced at an average interval of 1 to 2 channel widths, in comparison with the general trend for pool and riffle spacing to be some 5 to 7 times channel width. Our study shows a considerably higher density of dams over a short stretch of stream than these reports of LWD-induced dams. This might suggest that several of the barrages along Nash Brook were not related to LWD, or that the area was particularly prone to tree-fall.

Tufa barrages have also been found in catchments practically devoid of trees, indicating that LWD may not be a necessary component of barrage formation in karst river systems. At Nash Brook, the initiation of barrages is also clearly associated with a break of slope (Fig.2) from c. 1:60 to 1:20. Within this steep section of the stream, the association of more closely spaced barrages with lower gradients is interesting, and contrasts with the findings of Ekmekci *et al.* (1995) from the hot spring terraces at Pammukkale, and of Veni (1994) from Honey Creek Cave. In both cases barrage spacing was found to decrease with increasing gradient, and in neither case was there any tree growth. The role of tree-fall in creating such randomness needs further investigation.

In Nash Brook plants growing on barrage crests have a significant influence on barrage growth and morphology. This is in contrast with the barrages of Little Barton Creek, Belize where Neal (1990) found very little evidence of algal growth. At Nash Brook the filamentous alga *Vaucheria geminata* grows preferentially on dam crests. Its filaments become aligned in the direction of water flow, and are rapidly calcified and incorporated into the barrage fabric, especially in early summer. As a result, elongation of crests in a downflow direction occurs, and overhanging crests are produced. It may also partly explain

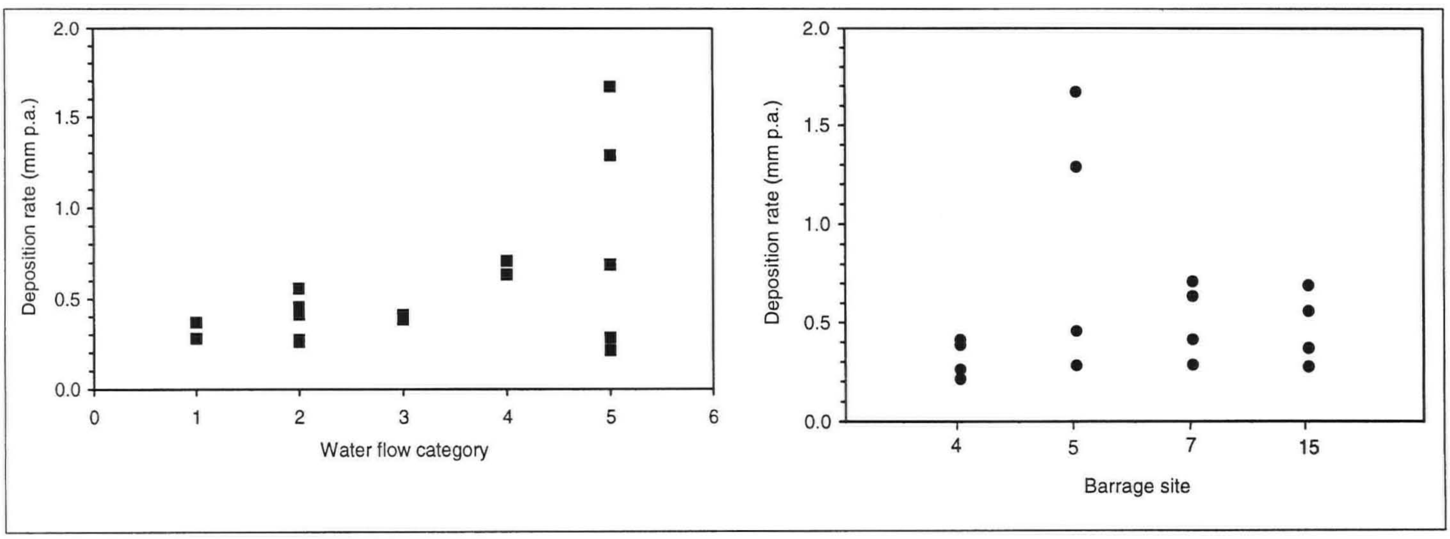
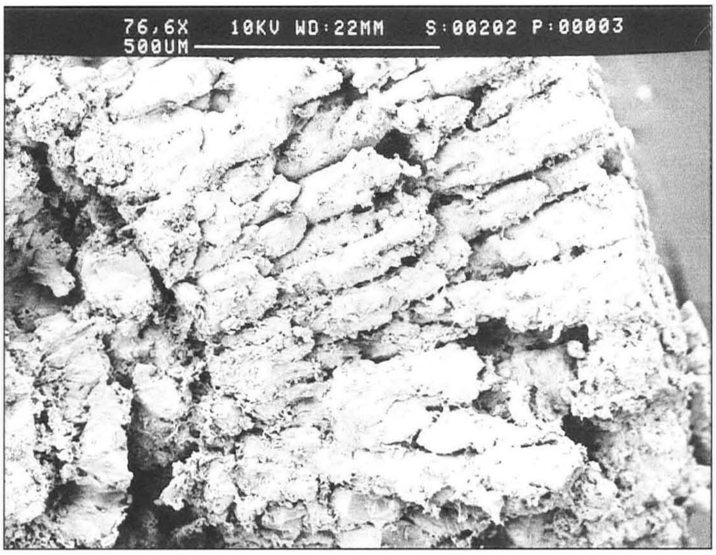
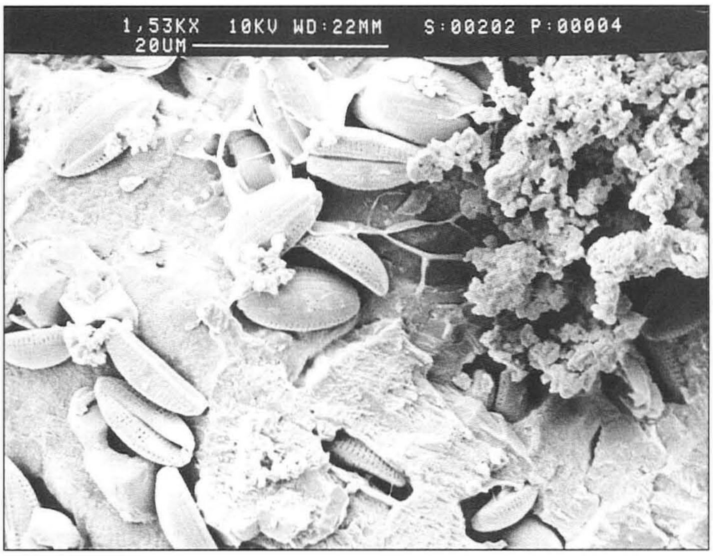


Figure 8. a) Deposition rate vs water flow category (see table 4 for key to water flow categories). b) Deposition rate vs barrage site.

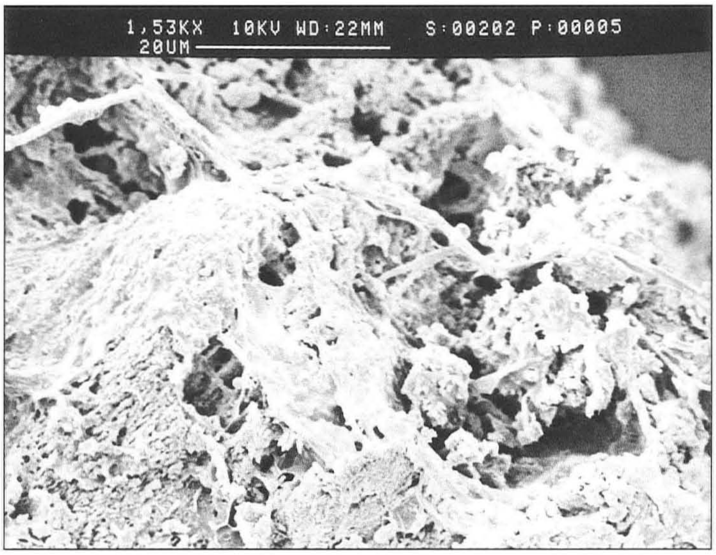
Figure 9.



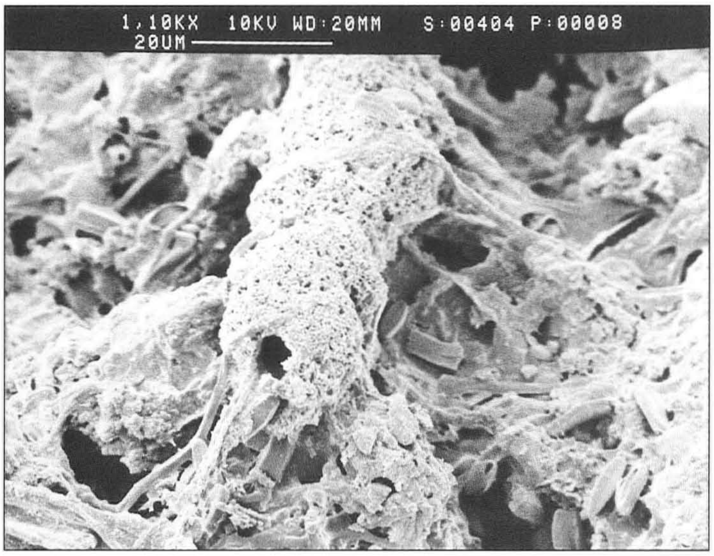
a) Low magnification view of layered deposit from tablet B2.



b) Diatom-rich layer at base of tufa deposited on tablet B2.



c) Biofilm of mucus and algae from the top of tufa deposit on tablet B2.



d) Encrustation of micrite around algal filament from the surface of tablet D4.

the convex plan-shape of many crests, as the water flow in the middle of the stream is the most turbulent, leading to more rapid deposition here. The high variability in deposition rates recorded by the experimental tablets indicates the importance of micro-environmental controls on travertine deposition.

This study has illustrated the potential of close-range aerial photography, in combination with conventional ground survey, in providing basic morphometric information on the size and spacing of tufa barrages. A hierarchy of controls on travertine development appears to be in operation at Nash Brook. At the largest scale, the hydrological characteristics of the river explain where tufa barrages can develop along the river profile. At the intermediate scale, geomorphological and biological factors determine the exact siting of barrages (through presence of LWD, etc). At the smaller scale, local water flow rates over the barrages determine how the profile and plan form shapes develop, once initiated. Finally, at the micro-scale, biological and geomorphological factors come into play once more, with algae (especially *Vaucheria geminata)*, mosses and other organisms determining the fine-scale nature of the deposit. There is still much to be learnt about these enigmatic features, especially over exactly how these geomorphological, hydrological and biological factors control their initiation and development under different environmental conditions.

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On the origin of the thermal waters at Bath, United Kingdom: A sub-Severn hypothesis

John WILCOCK [1] and David J LOWE [2]
[1] School of Computing, Staffordshire University, P.O. Box 334, Stafford, ST18 0DG, UK
[2] Limestone Research Group, University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, UK

Abstract: Possible sources of the Bath and Hotwells thermal spring waters are discussed speculatively in the light of some still-evolving modern views of cave development and groundwater movement, particularly the Inception Horizon Hypothesis of cave origin. A lateral viewpoint is adopted, that is not dominated by conventional ideas of underground drainage or by interpretations of "hard" data that provide partial support for a southerly water source, as preferred in the generally accepted "Mendip Model". On this basis, a tentative "sub-Severn model" for at least part of the drainage feeding the springs is considered, with possible water sources west of the Severn in South Wales and the Tidenham Chase and Forest of Dean Basin synclines in Gloucestershire. Several indications support the potential existence of underground flows from the west, but neither this source nor the seemingly more likely source in the Mendip Hills can yet be demonstrated conclusively as contributing to the flow of the Bath Springs.

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INTRODUCTION

Bath lies at the eastern margin of the concealed Bristol and Somerset Coalfield, where Jurassic and Triassic rocks dipping gently eastwards cover an eroded pre-Mesozoic surface. The deeper structure is more complex. Locally beneath Bath Carboniferous Limestone underlying the Mesozoic rocks passes beneath Coal Measures strata preserved in a number of deep synclinal basins (Fig.2). Hot water flowing from the Bath springs is generally assumed to rise from fissures that pass from the Carboniferous rocks and through the Mesozoic sequence to reach the surface (Kellaway, *in* Cunliffe and Davenport, 1985).

A healing cult may have been established at Bath before the Romans re-developed the site, providing bathing and religious buildings (Cunliffe and Davenport, 1985). The Poor Law Act of 1572 mentioned Bath as a place to which the sick resorted, and apparent medical benefits, probably deriving from water temperature rather than chemical content, assured its survival as a spa. In the 17th and 18th centuries Bath's popularity was enhanced by royal patronage, by the architecture of the Woods, Ralph Allen and John Carr, and by visits from socialites such as Richard (Beau) Nash (Granville, 1841). A bibliography on the Bath thermal waters was compiled by Whitaker (Richardson and Whitaker, 1928).

Three hot springs rise in central Bath. The King's Spring provides about 90% of the output, with a temperature that has varied between 45°C and 48.5°C over 200 years (Edmunds *et al.*, 1969). Water rises from a gravel-filled funnel in the floor of a polygonal Roman reservoir - upon which the King's Bath was superimposed in the 17th Century (Stanton, 1991) - before flowing into the Roman Bath and, via the Roman Drain, to the River Avon. About 100m west of the King's Spring, the Hetling (Hot Bath) Spring at 48°C and Cross Bath Spring (41° to 42°C) provide the remaining output. Chemical relationships between the waters are shown in trilinear diagrams for six ion species provided by Edmunds and Miles (1991).

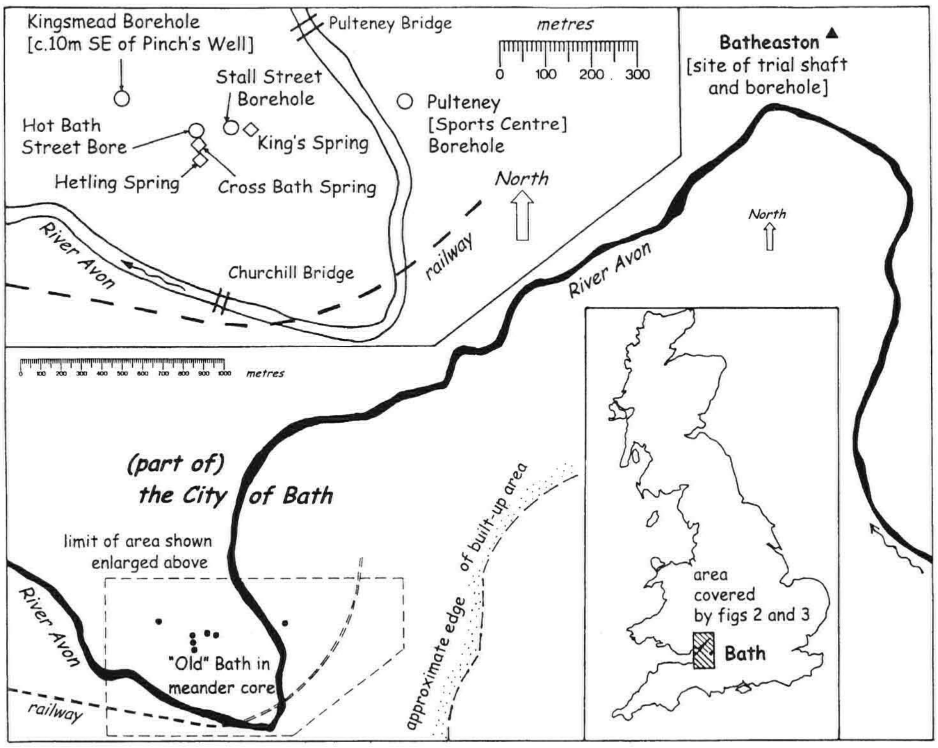

Figure 1. Sketch maps showing the location of the Bristol-Bath area within Britain, and the positions of the three Bath thermal springs, and various borehole sites mentioned in the text.

Armstrong (1838) reported that in November 1835 William Pinch, a brewer in Kingsmead Street (250m from the King's Bath and 200m from the Cross Bath), tapped a hot spring (37°C) at a depth of 51.5m, on the "Rhaetic" / "Keuper" boundary. Maximum flow was 8.6 ls^{-1} ($750m^3d^{-1}$), and it reduced the King's and Cross baths' output by about half. Flows were restored when the spring was stopped. In 1981-1982 the Wessex Water Authority proved Carboniferous Limestone in two boreholes beneath Bath. At Kingsmead Street, not far from the site of Pinch's well (Fig.1), the limestone was met about 50m beneath the surface (-30.7m OD), and hot artesian water (34° to 36°C) was met flowing from small fissures in conglomerate and red marl close to the base of the Triassic sequence. At the Pulteney No.1 (Sports Centre) Borehole (Fig.1) artesian water at 21°C issued from a 3m-high cavity in conglomerate, 71m below ground level (Stanton, 1991), and the Carboniferous limestone was met just a few metres lower.

The Bath spring water is of subaerial (meteoric) origin (Andrews *et al.*, 1982). Total output is about 18.5 ls^{-1} ($1{,}600m^3d^{-1}$), with a mean temperature of 46.5°C at the King's Spring, and a 10m piezometric head (i.e. to 40m OD). Flow is not affected by short-term rainfall variations. There are many dissolved gases in the water, and iron hydroxides precipitate on the conduits. Dominant dissolved ions are calcium and sulphate (Stanton, 1991). Geochemical evidence does not confirm a recharge area, but suggests the Carboniferous Limestone as the probable storage aquifer (Edmunds and Miles, 1991).

In 1978 pollution of the King's Spring caused the death of an 11 year-old girl by amoebic meningitis. Closure of the baths enabled excavation in 1979. Removal of the Victorian concrete floor of the King's Bath revealed the Roman reservoir, built on a revetted gravel bank, filling a washed-out funnel in "Lower Lias" marls (Dr G Kellaway, consultant to Bath City Council). An inclined borehole from Stall Street, west of the site (Fig.1), met a conduit transmitting unpolluted thermal water (45°C) after 84m (75m below the King's Bath). The water flowed from fractured strata believed to be part of the Upper Cromhall Sandstone, a deltaic facies of the Dinantian sequence, which overlies the Hotwells Limestone. This borehole now provides biologically clean water for bathing (Kellaway, 1991). Later, an inclined borehole was driven southwards from Hot Bath Street towards the Cross Bath (Fig.1). This hole encountered thermal water at several horizons, most notably at about 73m down the hole, in the Hotwells Limestone, where water at 41°C entered from a "fissure" (Kellaway, 1991).

Burgess *et al.* (1980) published detailed geochemical and isotopic data related to the Bath thermal water, aspects of which are reproduced below. They determined that when the solute load was dissolved the water temperature was between 64°C - 90°C. Considering the most likely geothermal gradient (20°C/km), the water circulation depth was probably between -2,700m and –4,000m, suggesting Dinantian (Lower Carboniferous) carbonates or Devonian sandstones as storage aquifers. However, isotopic evidence indicates marine carbonate equilibration/ evolution, suggesting that Dinantian beds are the main reservoir. Low tritium concentrations suggest no significant contribution of post-1953 recharge (i.e. water with high levels of tritium from atmospheric hydrogen bomb tests). Radiocarbon dating suggests a maximum age of about 19,200 years. Oxygen and hydrogen isotope values indicate a meteoric origin similar to that of modern local groundwaters. Water entering carbonates west of Bath was probably heated as it descended beneath the Bristol and Somerset Coalfield syncline (Edmunds *et al.*, 1969). Inert gas palaeo-temperature measurements indicate a recharge temperature of 8.7°C, resembling that of modern groundwaters. Glacial or periglacial recharge therefore seems unlikely. Considering all parameters, the most likely age for the Bath waters is 6,000 ± 2,000 years. However, anomalously high helium levels imply either a much longer residence time, or existence of an enriched radiogenic source. Uraniferous beds are known elsewhere at the base of the Namurian (Upper Carboniferous) Quartzitic Sandstone. A small amount of water could derive from the Old Red Sandstone and be up to 100,000 years old. Total dissolved solids of the spring water reach about 2,300mg/l.

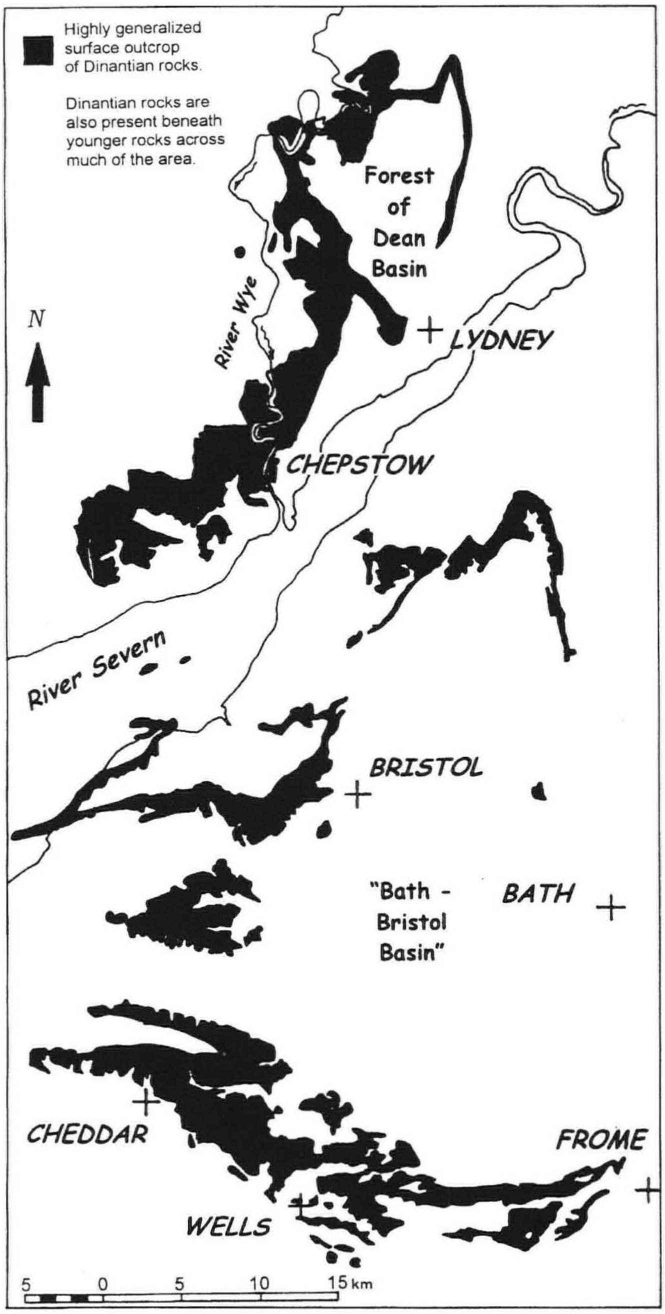

Figure 2. Sketch map showing the position of the Bristol-Bath area east of the River Severn, with the Mendip Hills to the south and the Forest of Dean to the north. The generalized outcrop of Dinantian (mainly carbonate) rocks is shown, but areas where the Dinantian rocks are succeeded by younger Carboniferous rocks and areas where they are succeeded by Mesozoic rocks are not differentiated.

Geochemical signatures suggest a water source in pre-Permian marine strata, and various potential flow routes may be envisaged. Some, considered within the "Mendip Model" (Burgess *et al.*, 1980), involve main flow from the south. In contrast, water could travel from north to south at depth, in fractured Palaeozoic rocks adjacent to the reactivated fractures of the Malvern Fault Zone (Kellaway, 1991b). Whatever the detail of the route(s), it appears that deeply buried Dinantian carbonates must contain a connected dissolutional void system, with a significant water storage capacity.

THE SOURCE OF THE BATH SPRINGS

The possibility that the Bath thermal waters derive from Mendip (Burgess *et al.*, 1980) was reiterated by Andrews *et al.* (1982), who stated in abstract that: *"Geochemical and hydrogeological evidence shows that the thermal springs at Bath originate from the Mendip*

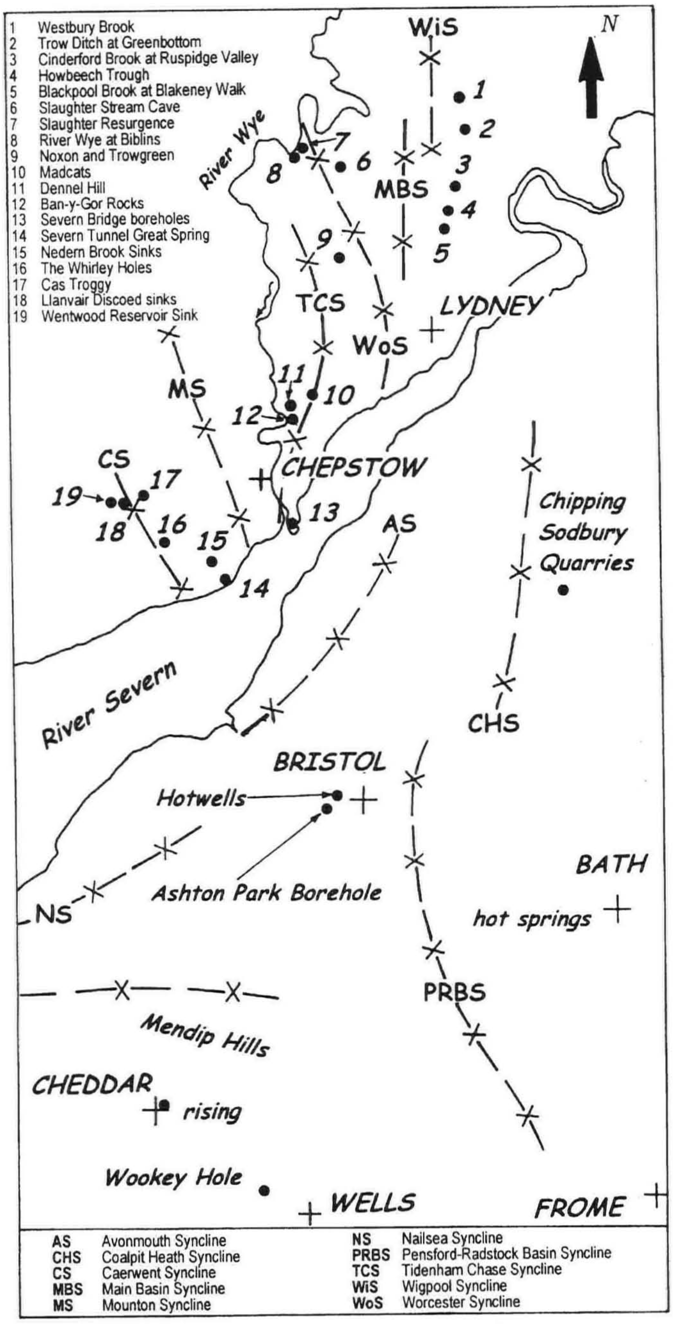

Figure 3. Sketch map at the same scale as Figure 2, showing locations mentioned in the text, and surface traces of major synclinal folds. The strutural information is highly generalized; to avoid confusion major faults/ thrusts and the anticlinal structures that lie between the synclines are omitted. More detailed structural and stratigraphical data are published elsewhere (British Geological Survey, 1961, 1982, 1988; Green, 1992).

Hills". However, the evidence is not unequivocal as, although Mendip has appropriate geology and sufficient elevation to provide a potential 10m piezometric head at the King's Spring, parts of the Gwent and Gloucestershire hills and the Forest of Dean (Figs. 2 and 3) provide similar but perhaps less obvious situations. Their possible involvement has not previously been described and the map provided by Andrews *et al.* (1982) shows no potential sources west of the Severn. In the same paper a diagram of local geological relationships is termed a *"conceptual model of the flow path of thermal water in the Bath-Bristol basin"*. Though conceptual, this was reproduced without comment by Edmunds (*in* Downing and Gray, 1986), by Stanton (1989), and by Burgess *et al.* (1991), perpetuating (perhaps unintentionally) a view that Mendip is the proven water source. Kellaway (1991b) questioned the hydrological continuity of the Carboniferous Limestone between Mendip and Bath, but lack of continuity is also unproven, and need not, in any case, be relevant to an artesian drainage model.

Burgess *et al.* (1991) state that hydraulic analysis is limited by paucity of data. Calculation of hydraulic gradient, estimated cross-sectional area of flow, permeability and porosity of the limestone led Andrews *et al.* (1982) to suggest a flow velocity of 0.01 to 0.1md^{-1}, and a flow-through time of 4,000 years from Mendip. This differs from a figure of 6,000 years $\pm 1\sigma = 2{,}000$ years suggested for water age on other grounds, although it is at the limit of one standard deviation quoted. If 6,000 years is accepted as the age, an actual distance of 1.5 times (6,000/4,000) the 15km distance to Mendip is suggested (22.5km), or twice (8,000/4,000) that distance (30km) if the other standard deviation bound is taken.

Stanton (1991) considered that any Mendip source would have to be on limestone outcrops north of the Old Red Sandstone periclines, probably between Green Ore and Stoke St Michael, with a maximum possible head of 170m. This area is a proven catchment for low-level springs at Gurney Slade, Ashwick Well and St Dunstan's Well on the north flank of the hills, as well as resurgences at Cheddar and Wookey Hole to the south (Fig.3). Confirmation of this relatively shallow flow does not rule out additional deep flow. Stanton considered flow from these catchments to be an early stage in the capture of local near-surface drainage by a much lower distant spring. He appeared unconvinced by the transmission calculations of Andrews *et al.* (1982) for flow from Mendip, and asked why the main flow was not to Hotwells. The main flow could, indeed, be elsewhere than to Bath. Stanton pointed out the reasonable assumption that if fissures are widened by dissolution, forming incipient caves, a few preferred routes would enlarge at the expense of the rest, creating conduit rather than diffuse flow. With only 15km between Mendip and Bath, it is difficult to envisage a conduit system alone providing sufficient storage capacity for the known flow, although cumulatively a network of pre-existing incipient cavities could provide significant storage. Andrews (1991) considered that the required storage would be available only if the entire Bristol-Bath basin was involved.

Hydrological work on the northern flank of Mendip, near the scarp edge, confirmed connections to resurgences at Rickford (e.g. from Lamb Leer, 58 hours; Wessex Water Authority, 1977), and Cheddar (e.g. from the slurry pit at Greendown Farm, Wessex Water Authority). Drew (1975) demonstrated the extent of the catchments of four major Mendip risings: Rodney Stoke, Wookey Hole, St. Andrew's Well and, particularly, Cheddar, with its huge catchment. All are on the southern flank and draw water from the north and east. The obvious south/north watershed thus lies close to the northern scarp (Drew, 1975). Unless significant underflow (*sensu* Worthington, 1991) occurs, little possible catchment area remains in Mendip to supply the Bath springs, but underflow taking several thousand years to resurge cannot be traced by standard methods. Nonetheless, deep flow northwards and shallower flow southwards from the hills must occur if Mendip water flows to Bath. In fact, Drew (1975, pp 202-3) pointed out the possibility of long residence flow derived from Mendip, which would be *"...removed from the hills as deep flow within the limestone beyond the point at which it dips beneath the outlying younger strata..."*. He noted that if this is the case the outlet point (or more than one point) is not apparent. Drew also suggested (1975, p.203) that water not flowing to known springs might actually permeate into overlying younger beds within a short distance of the Mendip scarp, but having said this went on to provide examples of evidence for deep flow, including boreholes near Frome (Figs. 2 and 3), east of the Mendip Hills, that draw considerable discharge from the Carboniferous Limestone.

The viability of the "Mendip Model" as the sole explanation of flow to Bath depends upon the assumption that Mendip provides the steepest potential hydraulic gradient in the Bath region. However, surface water is known to flow south, and hydraulic gradients of assumed deep flow route(s) are unknown. Underflow could follow old but relatively under-developed, low favourability, routes along regional hydraulic gradients, whilst high-level flow follows recently enlarged (newly advantageous) routes to closer risings related to modern landscape evolution. Realistically it is the effective "water-table" elevation beneath Mendip that is important, as this must limit the head available to drive postulated flow from Mendip, via the Radstock and

Pensford Basin, to Bath (and possibly Hotwells). Arguments for and against the "Mendip Model" and alternative models conflict. Some workers may have taken the "Mendip Model" too literally, disregarding wider possibilities of underground flow. Taking a larger area into account, at least some doubt about its sole viability is apparent.

Andrews *et al.* (1982) speculated that thermal water is stored in Dinantian carbonates along 15km of strike between Bath and Bristol. Besides the hot springs at Bath and Hotwells, historical records mention interception of tepid water in boreholes (Downing and Gray, 1986). For example, a flow of 3.0 ls^{-1} ($260m^3d^{-1}$) at a temperature of 16.7°C was met 86m down at Batheaston (Fig.1). Others have suggested that the Bath and Hotwells waters probably issue from Dinantian rocks, rising at the junction of fault fractures (Evans *et al.*, 1978; Benedek, 1984). Fractures in seeming continuation with the "Malvern Fault Zone" run northwest-southeast from the Forest of Dean area, traversing the Severn Estuary. Other major fractures run west-east through Hotwells, under Bristol, then southeast and east, approaching Bath from the southwest. It is noted here that interaction of these fractures with favourable horizons in the folded Dinantian rocks could provide routes for water emerging at Bath, though this seems relatively unlikely. Thus, Dinantian outcrops west of the Severn cannot be ignored as possible catchments.

Potentially, water following underground routes from Dinantian outcrops in Gwent, the Tidenham Chase area or the Forest of Dean would have a lower gradient than that from Mendip. Also, a proposed "Sub-Severn Model" must acknowledge leakage at the Severn Tunnel Great Spring and allow for water emerging at Hotwells. Underground drains from the west beneath the Severn would have to cross the Denny Island Fault zone, seen in the eastern end of the Severn Tunnel. Water certainly accumulates in Dinantian carbonates west of this fault, but carbonates may be locally thin or absent at the same level east of the fault, due to pre-Westphalian folding and erosion. Between Aust and Tites Point Dinantian rocks were removed by post-Variscan erosion. Thus, superficially at least, it seems that depositional continuity of Dinantian rocks now on opposite sides of the estuary, and any primitive drainage routes within them, could have been severed long ago.

There could be eastward groundwater movement beneath the Severn within Devonian sandstones, but chemical evidence suggests dominant contact with marine limestones (Edmunds and Miles, 1991). For water to enter the area directly from the main Forest of Dean basin would require flow within Devonian rocks or flow transfer via fractures, perhaps utilising the Malvern Fault Zone. Such a fracture link would be at, or north of, Tites Point. Kellaway (1991b) pointed out that the Lower Old Red Sandstone was removed by pre-Upper Old Red Sandstone erosion along part of the Malvern Fault Zone. There is thus a remote possibility that drainage in contact with insoluble Precambrian and Cambrian rocks along the fracture belt could also penetrate faulted Silurian, Upper Old Red Sandstone and Dinantian rocks in the northern part of the Bristol and Somerset Coalfield, and could dissolve carbonates from Llandovery, Wenlock and Dinantian marine formations. At face value such relationships seem highly improbable but not impossible.

Apparently, tapping of the Severn Tunnel Great Spring and subsequent pumping have had no significant effect upon water levels east of the Severn (at least none is noted in literature). However, if Hotwells and Bath are fed by water from deep beneath the Bristol and Somerset Coalfield, and the Forest of Dean provides an input, the impact of losses at the Great Spring may be relatively small. It is possible that the major component of Hotwells water travels south down the faulted margin of the coal basin, rather than eastwards through the folds between Milbury Heath and Kingsweston east of the Severn, where Dinantian beds are thrust over Coal Measures. However, the extent to which these beds are cavernous due to incipient flow routes imprinted before deformation is unknown. It is no less or no more likely that confined flow routes with sufficient head will cross folds or follow the strike around fold culminations at an appropriate level within a continuous carbonate aquifer, than for them to follow faults through otherwise impermeable rocks. Which option operates locally depends upon whether incipient conduits existed before deformation, whether any conduits survived subsequent folding and faulting, and which combination of structures and beds provides a more efficient hydraulic route towards a target output surface.

The Forest of Dean catchment, the eastern limestone outcrop near Wickwar, and the Chipping Sodbury quarries

Mining in the Forest of Dean was always hampered by excessive ground water (Richardson, 1930). The major axis of the synclinal basin runs north-south (Fig.3), and Coal Measures within the basin are ringed by Dinantian carbonates to the west, north and east (Lowe, 1989). In the southeast, carbonates present at depth are overstepped by the Coal Measures. The River Wye has incised the carbonates in the northwest, near the Slaughter and Biblins (Lowe, 1993). In the west the Dinantian outcrop is cut by small streams at Noxon and Trowgreen (Fig.3) (Bowen, 1992). In the east it is cut by several streams, including, from the north, Westbury Brook, Trow Ditch at Greenbottom, Cinderford Brook at Ruspidge Valley and Blackpool Brook at Howbeech and Blakeney Walk (Fig.3). Annual rainfall reaches 1,500mm, and water enters the basin by percolation through various strata, and by direct sinking into the carbonates and some overlying beds. Being aware of this, miners attempted to prevent water entering the mines, by building waterproof stream channels of packed stone, concrete or iron. These are long broken, and water sinks freely today.

Consideration of the geological structure suggests that water ponded in the basin must overflow southwards towards Lydney, where large volumes resurge close to the Severn, either from Devonian beds beneath the Dinantian carbonates, or from fractures that penetrate the Dinantian rocks and older beds. This is relatively easy to accept, but if so there is also a possibility that part of the basin's water continues southeastwards beyond the known springs, initially within the assumed Devonian aquifer beds along the basinal axis and then via fractures in the Malvern Fault Zone, to pass beneath the Severn. Such a drainage line would extend generally southwards, passing near Berkeley and Michaelwood, continuing within carbonate aquifers from Charfield, via Wickwar and Chipping Sodbury, where there are many flooded quarries (Fig.3), and via Wick to Saltford and Bath. In this area Dinantian carbonates fringe the northern part of the Bristol and Somerset Coalfield from Tortworth south by Wickwar and Chipping Sodbury (Kellaway and Welch, 1948). Farther south, Dinantian rocks are concealed, but reappear in inliers at Wick and Codrington. The postulated southward route from Lydney coincides with a major structural weakness, formerly termed the Bath Axis, seemingly related to the Malvern Fault Zone. Though the term "Bath Axis" is no longer geologically fashionable, the concept of the structural trend appears to remain valid.

Thus, although the connecting links are tenuous, including segments divorced from the main Dinantian aquifer, a remote possibility remains that the Forest of Dean could contribute water to the Bath springs by long residence, long-distance fracture flow. Of passing interest is the possibility that drainage that moves west towards the River Wye under normal conditions could provide some water at times of high flood. The Slaughter Resurgence beside the Wye probably represents limited upward leakage through the roof of the phreas (Lowe, 1993). Water budgets for the combined input via the Slaughter Stream Cave, many other allogenic sinks and autogenic capture, and output from the Slaughter Resurgence do not match; resurgent flow is normally much lower even than that in the cave. Remaining flow is deduced to continue beneath the river along the axis of the Worcester Syncline (Lowe, 1993). Conduit drainage along this high resistance route may back up under very wet conditions, perhaps causing water from upstream feeders to spill over into the main Forest of Dean Basin, as shown schematically in Fig.4. A flood mechanism such as this could explain a supposed but geologically unlikely water trace, from Hoarthorns Wood Swallet at Edge End to the workings of Cannop Colliery, mentioned by Richardson (1930). Other potential contributors to the main basin water body are the many streams on the

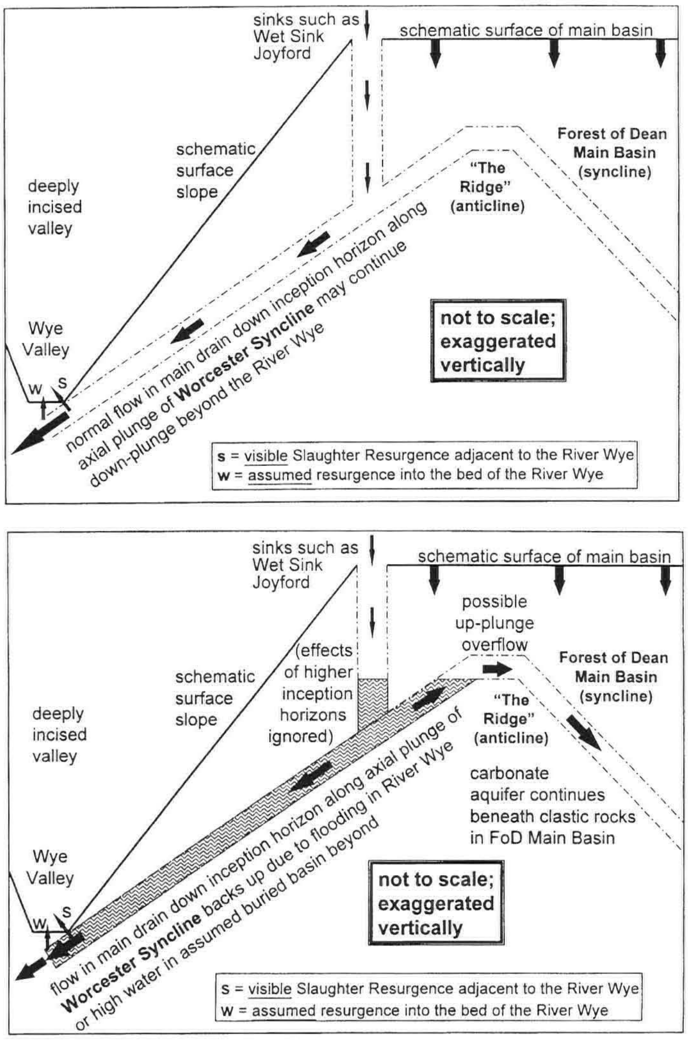

Figure 4. Simplified conceptual view of how drainage within the westward-draining Slaughter catchment might overflow eastwards into the Forest of Dean Main Basin. Note that the vertical scale is greatly exaggerated and the amount of back-up required to cause overflow may be small.

western and eastern Dinantian outcrops, and autogenic recharge, mainly by way of fractures, from extensive sandstone beds above the carbonates.

The main basin is potentially water-filled to whatever geologically guided "overflow" level can cope with climatically variable inputs. As pumping related to mining has now more or less ceased, the eventual destination of the inevitable overflow can only be guessed. As discussed above, a drainage route from the south of the basin, beneath the Severn and beyond is possible. However, as such a possibility relies upon the involvement of fractures and aquifer beds in the underlying Devonian sequence, its inclusion may be viewed as "special pleading". Whereas the Upper Devonian beds form an important aquifer in the north, particularly on the eastern side of the Forest of Dean Basin, they are apparently less productive beneath the Bristol and Somerset coalfields (Green, 1992), but the significance of this variation in the present context is uncertain. Another, arguably less tenuous, possibility is that ancient palaeokarstic voids within the Dinantian rocks, pre-dating imposition of the main structure, have been re-activated, carrying overflow drainage essentially westwards, southwestwards and then south, around the northerly culmination of the Dinantian beds in the Beachley-Clanna Pericline (a broadly anticlinal structure) somewhere near Bream, and into the same beds in the Tidenham Chase Syncline (considered separately below). A possibly analogous geological situation, with conduit development passing around anticlinal culminations, is illustrated and discussed by Ford and Williams (1989, Fig.2.12 and p.41). Detailed modelling of potential geological (underground) watershed levels around the Forest of Dean Basin, and of potential natural and artificial output points, is required, but subsurface data are lacking.

The Tidenham Chase Syncline, Dennel Hill and Ban-y-Gor

From the western side of the main Forest of Dean basin Dinantian rocks extend southwestwards towards Chepstow through the NNE to SSW-aligned Tidenham Chase Syncline (Kellaway and Welch, 1948; Welch and Trotter, 1961). The fold plunges towards the Bristol Channel, providing potential for underground drainage along its axis to continue in carbonate aquifers beneath the Severn. It is suggested here that at least one major drainage line follows the synclinal axis within the Lower Dolomite/Black Rock Dolomite, perhaps following an inception horizon, analogous to that guiding much of the Slaughter System at a similar stratigraphical level in the northwestern Forest of Dean (Lowe, 1993) and Otter Hole near Chepstow. Royal Forest of Dean Caving Club members have described a sink at Madcats (Fig.3) and other sites near Miss Graces Lane, in East Wood and in Woolaston Wood, which could contribute water to the postulated phreas. However, details of underground drainage in this area remain obscure. Likewise the catchment of a major rising at Ban-y-Gor Rocks (Fig.3) is unknown, but Ban-y-Gor Cave seems to be an up-dip flood overflow. Relict cave passages occur high in limestone quarry faces at Dennel Hill.

Broad meanders of the ancestral Wye were imprinted under floodplain conditions on younger rocks at relatively high level, long before the present valley was incised, cutting deeply into the Dinantian sequence. Caves above the modern river may relate to earlier meanders, when the Wye abutted the limestone at each locality in turn. Erosion occurred at different levels as the river profile re-graded rapidly (geological speaking) after Miocene uplift. However, the relict caves may be fragments of once-regional conduit systems, conceived long before the ancestral Wye existed. An obvious, more readily demonstrable, analogue exists in the Forest of Dean, where an extensive palaeo-cavity system was partially infilled with iron ore minerals during the Triassic Period, then dissected by river incision following uplift (Lowe, 1993).

At least part of the drainage beneath Tidenham Chase might utilise such ancient dissolutional conduits, following them southwards within Dinantian rocks in the synclinal axis, to pass beneath the Severn. Such drainage could be related to the deep flow intersected at the Severn Tunnel Great Spring and, regardless of leakage from this artificial short-circuit, the combined onward route would follow the stratigraphy, eastward beneath the Avonmouth Coalfield. Elements of such regional flow, which seems unlikely in the context of the modern landscape and complex geology, would have been imprinted long before these conditions evolved, then largely abandoned by shallow flow as more favourable local routes developed in response to tectonism and surface downcutting. If a deep "underflow" component persists, it could feed the Hotwells spring, and contribute to the Bath springs, if the overall head is sufficient to push water in the Dinantian aquifer over (or around) intervening folds. Exploratory boring for the first Severn Bridge (see below) proved freshwater-filled conduits beneath the Severn, but boreholes cannot prove cavity size or trend, nor illustrate the geological factors that guided conduit growth. Also, as the conduit proving was west of the Denny Island Fault system, a potential barrier to west-east drainage (see above), its full significance is uncertain.

Cas Troggy, the Nedern Brook, Sudbrook and the Severn Tunnel Great Spring

A cavity system emitting a strong flow of fresh water was intersected by the Severn Tunnel (Appendix 1). The idea of tunnelling occurred to Charles Richardson during construction of railway piers at the ferry in 1862. Jones (1882) described a section across the Severn based on borings and tunnel excavations. Shaft No.4, at Sudbrook Point (Fig.3, near site 14), is of chief interest. Below 4m of Triassic sandstone is

20m of Mercia Mudstone and 1m of Dolomitic Conglomerate lying unconformably on Carboniferous rocks. 22m of Upper Coal Measures sandstones and shales (?Downend Formation) lie unconformably on 4m of "Drybrook Limestone". The upper part of the latter, described as shale with large limestone lumps, may be of Namurian age (Green, 1992), and may represent a palaeokarstic surface with superimposed Namurian sediments enclosing Dinantian rock debris. Three springs, yielding 55,000 lh^{-1}, 120,000 lh^{-1} and 70,000 lh^{-1}, were tapped during the sinking. At Ifton, slightly farther west, the Drybrook Limestone included extraordinary palaeokarstic features (Dixon, 1921; Welch and Trotter, 1961; Lowe, 1993). Quarrying revealed doline-like features as well as ancient cave passages within the Drybrook Limestone, all filled with loosely consolidated material of "Millstone Grit" (Namurian) type. Remnants of similar Namurian strata were preserved above a clear unconformity marking a long period of non-deposition and erosion stretching from mid-Dinantian to Namurian times, and the Namurian remnants were in turn overlain unconformably by Triassic rocks. At least by implication, therefore, it is possible that "Drybrook Limestone" proved during tunnel investigation contains palaeocavities that were either open or infilled by relatively high permeability material, and that these palaeocavities existed long before imposition of the current tectonic structure and landscape.

Shaft No.3, about 400m inland (west) along the line of the railway, proved 4m of Triassic sandstone, 21m of Mercia Mudstone, 9m of Dolomitic Conglomerate and 7m of Upper Coal Measures sandstones and shales to the base of the borehole. A joint about 15cm wide with a large spring of fresh water was met in the Dolomitic Conglomerate, which consists of limestone clasts from 1cm to 60cm across, in a very hard reddish matrix.

Several workers (Standing and Standing, 1967; Drew *et al.*, 1970) investigated possible sinks and carried out spore and dye tests, and there is information from the pumping station that pumping rates must be increased about three weeks after local heavy rainfall. Despite recovery of only 2 spores, Drew *et al.* deduced that the Great Spring is fed from Cas Troggy (Fig.3, site 17), a large sink at the exit from a narrow valley (The Cwm). The spores took 10 days to travel the 6km to Sudbrook. Sinks at Llanvair Discoed and Wentwood Reservoir Sink (also known as Gray Hill Sinks) probably form part of the same system (Fig.3).

Between Cas Troggy and the Severn Tunnel is a marshy area crossed by the Nedern Brook, and farther west is the Roman town of VENTA SILVRVM (modern Caerwent). Well-preserved Roman walls remain, and in Roman times the Severn tide probably flowed to the base of the southern wall. Before work on the Severn Tunnel there were several major springs of bright, clear water (Walker, 1888). Historically the Nedern Brook lost all its water in dry conditions. Near Caerwent there was a resurgence called "Whirley Holes" (Fig.3, site 16). Today the stream dries up, but Whirley Holes never flows, and has not done so since pumping began at Sudbrook. These features thus appear to be part of the hydrological system intercepted by the Severn Tunnel.

The eventual destination(s) of the Great Spring water before it was intercepted by the Severn Tunnel must be considered. Drew (1975, p.205) implied a possibility that before its interception by the tunnel, water from *"...some twenty square kilometres of Mountain Limestone on the Welsh side of the River Severn"* could have fed into a *"Severn-oriented karst system"*, associated with freshwater springs near the islands of Steep Holm and Flat Holm, farther down the estuary. However, he admitted that no proof of such a relationship existed, and that limited evidence of deep flow in the Carboniferous Limestone could suggest an explanation of unbalanced water budgets on Mendip. If drainage from the west to mid-Severn is confirmed and if drainage from Mendip to mid-Severn appears as a possibility, it also seems that a possibility of a continuous, though perhaps intricate, system of deep drains crossing beneath the Severn must be admitted. It is suggested here that drainage intercepted by the tunnel could originally have continued eastwards down-dip under the Severn. It could have crossed the Denny Island Fault zone, remaining within the carbonate sequence that includes the Clifton Down Limestone, the Gully Oolite and the Black Rock Dolomite, the local equivalents of the Drybrook Limestone, Crease Limestone and Lower Dolomite of the Forest of Dean (British Geological Survey 1962, 1981, 1988; Kellaway and Welch, 1948). If so, it could contribute to the Hotwells water under the Avonmouth Basin. However, to reach Bath the water would have to cross, or pass around the culmination of another major fold between Bristol and Bath (see Figs. 2 and 3). Though extended, intricate and probably slow, such a route is a theoretical possibility.

Construction of the first Severn Bridge

The new (1996) Severn Bridge rests largely by dead weight on the English Stones (a low-lying island/reef, closer to the eastern bank of the Severn, east-southeast of site 14 on Fig.3), and little exploratory boring was necessary. However, earlier boreholes (Whittard, 1948) drilled before building the Severn and Wye bridges now used by the M4 provided useful data (Fig.3, site 13). Borehole 8, on the right bank of the Wye, tapped artesian fresh water 16m down, at the junction of Triassic and Carboniferous rocks. The piezometric head was 3m above sea level, and 7.6m above the river bed. Borehole 5, 120m west of the southeast end of Beachley jetty, detected a cavity with a flow of at least 1,600 lh^{-1} at the junction of the Triassic and Carboniferous rocks. This cavity could relate to void development in the core of the Tidenham Chase Syncline, postulated above. The lack of an above sea level piezometric head can be attributed to the Severn Railway Tunnel, where the head at the Great Spring is now about 50m below sea level. Borehole 13, on the rock of Great Ulverstone, tapped clear, artesian fresh water 4.5m down, with a small piezometric head.

Overall the boreholes confirmed Dinantian rocks extending beneath the Severn from Sudbrook to Aust (southeastwards from site 13, Fig.3), with an easterly dip. Beyond Aust the dip increases steeply, taking the Dinantian beds beneath the Avonmouth Coalfield. Provings of cavities and artesian fresh water in the boreholes suggest that conduits similar to that breached farther south by the Severn Tunnel exist locally. Though present piezometric heads are unimpressive, the potential for deep artesian flow beneath the Severn certainly existed before the Tunnel was dug. The water's origin is most likely up-dip, in the Dinantian rocks on the west bank of the Severn and, perhaps, in the Tidenham Chase Syncline. It is also feasible that ancient incipient conduits continue down-dip, deep beneath the Avonmouth Coalfield.

Hotwells

Hot fresh water discharges from Dinantian carbonates at Hotwells Spring (Fig.3), about 3m below high water, into river muds on the north bank of the Avon, southwest of Bristol. In his itinerary, William Wyrecestre described it as *"...like the water of Bath..."* (Richardson, 1930), saying that long before his time it was noted for its curative properties. The flow is about 2 ls^{-1} ($170m^3d^{-1}$) to a piezometric level 14m above sea level, at a temperature of 24.3°C. The water was at about 60°C when it dissolved its solute load (Burgess *et al.*, 1980). The site's history is described in Appendix 2. Other thermal springs occur nearby at the St Vincent's Spring, Sion Well, Jacob's Well, Mardyke Spring and the Rocks Railway borehole (Hawkins and Kellaway, 1991). Edmunds (*in* Downing and Gray, 1986) deduced that the Hotwells thermal water composition could reflect a 1:2.3 mixture of thermal water (from the reservoir feeding the Bath springs) with shallow limestone groundwater. Hotwells Spring may be a linear (fissure) discharge from a deep reservoir, and similar thermal discharge points might exist elsewhere along the Avon valley.

Ashton Park Borehole

The Ashton Park Borehole (Fig.3) (Kellaway, 1967), quite close to Hotwells, intercepted warm water. It also intersected a cavity, suggesting possible cavity development and/or palaeokarstic features at depth. (Appendix 3.)

DISCUSSION

In setting out his Inception Horizon Hypothesis (IHH), Lowe (1992) argued that speleogenesis can begin soon after rock formation, when directional or oscillatory fluid migration, driven by various mechanisms, leads to dissolution by processes other than the carbonic acid reaction. Very slow migration of relatively small fluid volumes across wide (potentially basinal) areas, begins during or soon after diagenesis, continuing through tens, if not hundreds, of millions of years. These processes, deep beneath the surface, were unrelated to modern landscapes. Thus, during inception, processes in buried rocks begin the transformation of effectively impermeable indurated carbonate material into a carbonate aquifer, and this more probably relates to input from and output to adjacent porous non-carbonate beds than to input from surface sinks or diffuse percolation through the carbonates themselves. Elements of underground flow and their host void systems related to modern landscapes are very recent (geologically speaking) and, again according to the IHH, they are simply local, better-developed, elements of an incipient three-dimensional void system that extends across all potential inception horizons in a succession and whatever fractures provide links between them. The IHH also predicts that:

- incipient void systems can be imprinted before tectonic deformation of the carbonate succession;
- elements of incipient void systems remain even after subsequent sedimentary infilling, and can survive tectonic deformation (including faulting and folding);
- after deformation and uplift but before creation of open system conditions, favoured routes for fluid transfer under confined conditions are inception horizons in the cores of plunging anticlines, but;
- when open system conditions establish after uplift, by interaction between the developing landscape and the incipient void system, the cores of plunging synclines become favoured. In both cases bedding dip and fold plunge may be so small as to be unresolved by eye;
- drainage can cross acute structures by following folded inception horizons or by using faults or joints as links between the same, or different, inception horizons (assuming that the drainage route lies along a regional hydraulic gradient). Some so-called strike-aligned passage segments may, in reality, represent "water-table" defined enlargements of inception horizons passing around the culminations of gentle plunging folds.

Early dissolutional and driving mechanisms that operate in buried and totally water-filled (traditional deep phreatic, but more accurately artesian) conditions eventually give way to, but are not totally replaced by, the effects of carbonic acid and broadly gravitational flow. Local hydraulic gradients are established when the imprinted inception system within the carbonate beds is cut by the lowering land surface. Combinations of the more favourable sections of the incipient system are first enlarged by flow concentration, in conditions traditionally referred to as shallow phreatic. Later they are drained and some are colonised by vadose underfit streams, as surface downcutting continues. These more efficient hydraulic routes tend towards being graded to currently visible resurgence points, but they may be left "hanging" if surface lowering outstrips underground erosion.

Another possibility is that artesian leakage can occur from "underflow" routes (*sensu* Worthington, 1991) in deeply-buried carbonates, penetrating upwards through tectonic fissures in otherwise relatively impermeable caprocks, such as occurs at Taff's Well in South Wales (Thomas *et al.*, 1983), might occur at the freshwater springs near Steep Holm and Flat Holm in the Severn estuary, referred to by Drew (1975, p.205), and could occur at Bath. Cases of natural or man-made artesian leakage are common, and seem to provide unequivocal evidence of deeply-buried, probably long-distance drainage, of the type predicted by the IHH. Possible examples include the North Crop/ Eastern Valley Phreas/Taff's Well (Thomas *et al.*, 1983), with possible southward extension to Schwyll and beyond (South Wales), the Derbyshire Peak District/Nottinghamshire (Downing and Howitt, 1969), and the Pennines/Harrogate (Yorkshire). Currently, contradictory geochemical evidence allows alternative explanations of these examples, particularly the latter, tentative example. However, if any are valid they add credibility to the concept of deeply buried flow, effectively unrelated to modern landscapes. Thus, Mendip need not be the only source for water that emerges at Bath, as the currently accepted model (perhaps unintentionally) suggests, and an alternative westerly source (or component) might have as much in its favour as the generally accepted southern origin.

Potential flow routes from the Forest of Dean, Tidenham Chase Syncline and assumed Severn Tunnel Great Spring system are shown diagrammatically in Figs. 5 and 6, the latter showing generalised relationships within the local geology.

The Dinantian sequence ranges in thickness from 550m in the north of the Bristol-Bath basin to 610m near Bristol. Effective permeability of the carbonates is calculated as $4md^{-1}$ (Burgess *et al.*, 1980). High levels of helium at the Bath springs could originate from uraniferous horizons, as commonly found in basal Namurian rocks in the UK, and proved in the Ashton Park Borehole. Or, they could suggest an upland origin (such as in the Forest of Dean or Gwent hills), with water penetrating Upper Carboniferous strata to enter the carbonates. If the Bath spring feeders include Cas Troggy or the Tidenham Chase Syncline, transmission could be continuously within Dinantian carbonates, or, as would be the case with a Forest of Dean source, could include fractures that provide locally advantageous routes linking pre-existing but structurally separated regional aquifer systems.

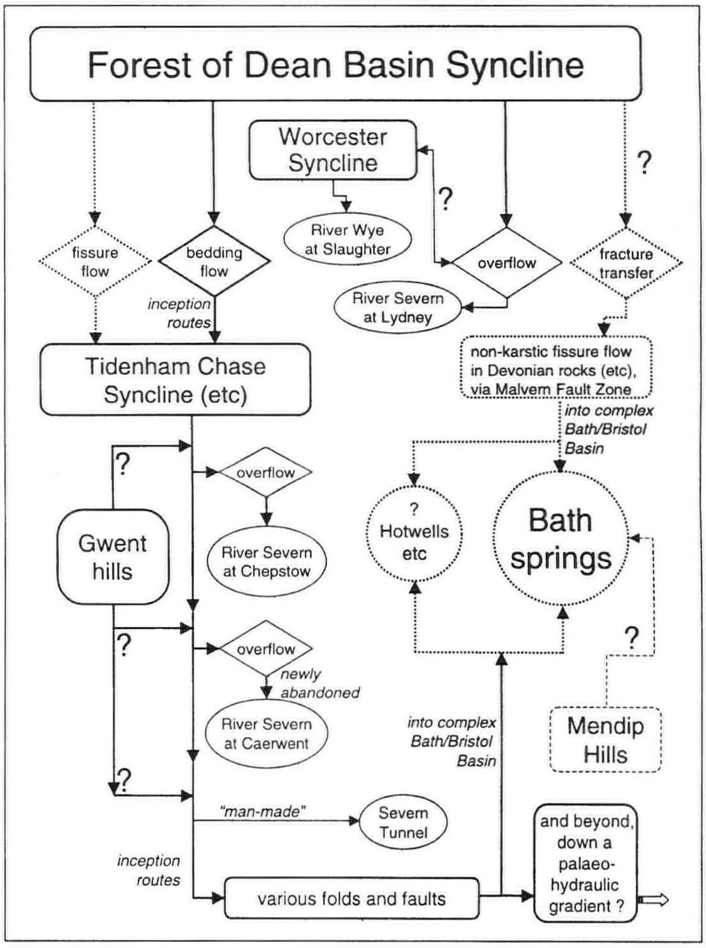

Figure 5. "Plumbing" diagram to illustrate conceptual hydraulic links from areas west of the Severn into the "Bath-Bristol" Basin and, potentially, beyond.

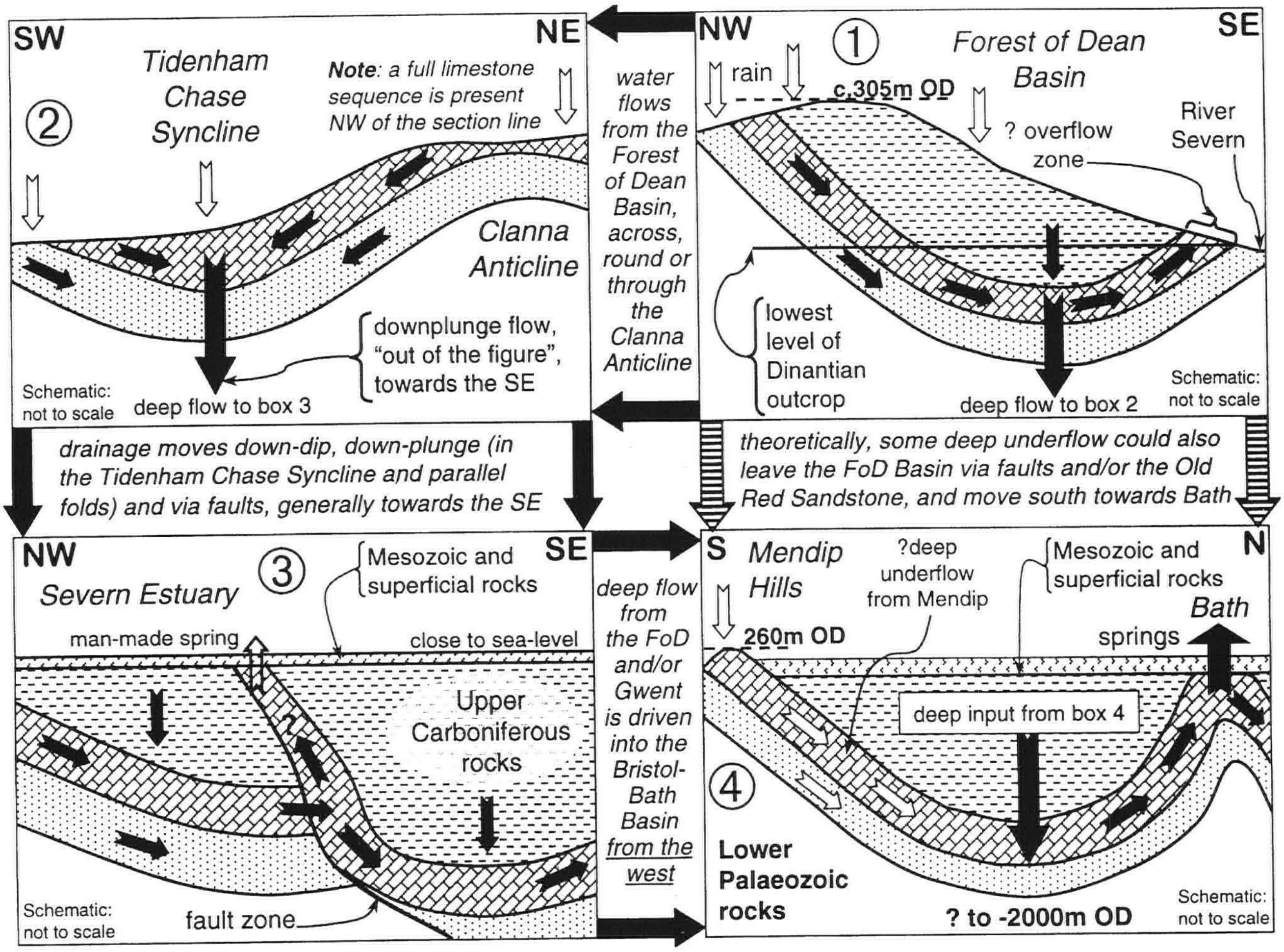

Figure 6. "Cartoon" cross-sections of generalized geological conditions at points between the Forest of Dean Basin and the "Bath-Bristol" Basin. The views are not to scale, either internally or one with another.

Regional karst drainage systems need not lie exclusively in carbonate beds, provided that a regional hydraulic head exists between input and output zones. However, confined aquifer conditions are necessary if, due to geological constraints, parts of the overall route are locally against the physical gradient. If the aquifer is not confined, perhaps in porous non-carbonates for part of its route, then water can readily take other, more efficient, routes to the surface. Dinantian rocks similar to those exposed to the northwest and southeast possibly underlie the Severn valley and the Bristol-Bath region, and strong west-east faulting could allow rapid rise of thermal waters at spring sites. Open joints trending NNW-SSE are recorded around the Hotwells Spring.

Circulation deeper than 2,000m is proposed by Burgess *et al.* (1980). Based on known parameters, calculations of the likely size of the potential system can be made. Taking the thickness of Dinantian rocks under Bristol as 600m, at depths greater than 2,000m, a flow-through time of 6,000 years, 50km sinks to risings distance, and an observed flow of 18.5 ls^{-1} at Bath:

50km in 6,000 years = 8.33 m/year [this is much smaller than the 4m/day calculated by Burgess]

$18.5\ ls^{-1} = 1{,}110\ l/minute = 66{,}600\ lh^{-1} = 1{,}598{,}400\ ld^{-1} = 583{,}416{,}000\ ly^{-1} = 583{,}416\ m^3y^{-1}$

giving an average cross-section of passages/fissures/phreatic tubes of $583{,}416 \div 8.33 = 70{,}038m^2$

If this existed as a single phreatic passage (not suggested as a serious possibility!), the calculated cross-sectional area could be supplied by:

- a 298m diameter circular cross-section, or
- a square cross-section 265m x 265m.

Passages approaching these dimensions do exist, for instance in the karsts of southeast Asia, but such a large conduit might not be expected to develop in isolation. More probably many small conduits, or sub-conduit bedding planes, faults, or palaeokarstic voids are involved, all contributing to the total cross-sectional area. Such sub-conduits could be less than 1cm in diameter if cylindrical, or 1mm high if bedding plane slots. For example, if 1% porosity is assumed across the whole 600m-thick Dinantian sequence, a transmission zone 11.7km wide is indicated. The figure of 6,000 years could be a gross underestimate, but the longer the flow-through time, the smaller the velocity, and the larger the total cross-sectional storage area must be.

Many examples of sink - rising distances greater than 40km are documented. For instance, in the system feeding the Fontaine de Vaucluse, where a depth of 315m below water surface (224m below sea level) was reached in 1985 (Jennings, 1971; Sweeting, 1972; Farr, 1991, pp. 22, 27-30, 171-174; Blavoux *et al.*, 1992), the longest recorded trace had a straight line distance 46km. The system lies on a series of faults, as supposed at Bath, and the resurgence reacts rapidly to rainfall. In long dry spells it shows an exponential hydrograph decline (characteristic of allogenic systems), which relates to a large allogenic water component from vadose conduits, originating from the Rivière Souterraine d'Albion and neighbouring potholes of the Plateau d'Albion. Chemical data support this view. Magnesium is inversely-correlated with discharge, while chloride values are 'peaky', corresponding with rainfall events. There is also a distinct seasonal variation. Resurgence static level is lowest in September-October (after the July-August dry season), with dramatic overflow in March-April.

Thus, much of the Vaucluse flow originates from several vadose caves, but visible output is confined to a single ascending conduit. If the Bath springs were part of a similar system, with source vadose caves in Mendip, and a confined ascending fault-guided outflow, a 'peaky' and seasonal output would be expected. This is not the case. At

Bath the flow is steady. Long-term groundwater residence is thus a pre-requisite of any proposed model. Available evidence does not disallow a possible "Mendip Model", but the springs would have to be fed by deep-seated *underflow* from Mendip. However, the head would be relatively small, as high level vadose input feeds resurgences to the south.

The "Sub-Severn Model" suggests that much of the Bath spring water could originate from Gwent, Tidenham Chase and, more tentatively, the Forest of Dean, being eventually confined within Dinantian carbonates that underlie the Bristol and Somerset Coalfield and mark its eastern flank. Leakage of as yet unheated water occurs at the Severn Tunnel Great Spring (only Gwent water) and warmer water appears at Hotwells (Gwent, Tidenham Chase and, possibly, Forest of Dean water, accumulated under the coalfield and ejected via a confined fault-guided route at its margin). Even so, it appears that sufficient pressure head exists for water to emerge via another confined, fault-guided, riser at Bath. Providing a pressure head is maintained, it is only necessary that the output is lower than the inputs in such regional artesian systems.

The authors suggest that attempts to relate cave development (other than recent modifications) to modern landscapes are misguided. More weight should be attached to the potential for relatively ancient cave origin under deeply buried and confined conditions, guided by inception horizons in Dinantian carbonates and adjacent porous sandstones. Such a model requires that the earliest (inception) drainage routes were imprinted deep underground within the Dinantian sequence many millions of years ago, almost certainly before the end of the Carboniferous Period. They would have been formed by the effects of "non-traditional" chemistry as fluids moved almost imperceptibly slowly along extended, basin-wide, routes. Such fluid motion would be driven first by the effects of differential pressure from overlying sediments and related mechanisms (Neuzil, 1986), and ionic diffusion related to the physical/chemical changes of rock formation (diagenesis). Later, earth-tides or tectonic stress (seismic pumping) might contribute to fluid motion. The earliest effects would be active before major tectonic structures mappable today were imposed on the Dinantian rocks, so that any geological gradients within them would have reflected depositional or syndepositional effects, such as lateral facies changes, vertical interfaces with material of higher (or lower) permeability, depositional dips and so on.

Subsequently an extensive basin of Dinantian rocks, originally continuous between southern Ireland, South Wales/Forest of Dean, the Bristol district, Mendip (George *et al.*, 1976), and possibly still farther eastwards (George, 1958), suffered major structural deformation on several occasions. Significant change began in the Dinantian, with local uplift (and complementary downwarping in adjacent areas), folding and fault movement. These effects produced the first structures that contributed to, for instance, the Forest of Dean Basin. Locally the element of uplift and erosion produced an unconformity of varying magnitude between Dinantian and later Carboniferous beds. More violent tectonism, sometimes termed the Variscan earth movements, occurred during latest Carboniferous to earliest Permian times (about 290Ma). Later tectonic events are less clearly known, but there was almost certainly significant reactivation of many existing structural weaknesses several times during the Mesozoic, altering relationships within the basement as well as propagating fractures and folds through the younger rocks. The most recent significant structural modifications occurred in Miocene times, when much of the area was uplifted along the northern fringe of the Alpine earth movements. It is interesting that the trend of acute and gentle Miocene folds affecting Mesozoic and younger rocks across southern England effectively parallels earlier, Variscan, structures deduced to exist in the pre-Mesozoic basement.

There is a general trend for coeval Dinantian rocks across the southern British Isles to become more deeply buried from west to east. In the context of underground drainage, it is tempting to speculate whether major eastward plunging fold elements extend at depth, superimposed upon the general eastward deepening of the Dinantian beds. Do major folds in these rocks continue beyond the exposed Dinantian sequences in Ireland and South Wales, beneath the Mesozoic cover of southern England and, more speculatively, into the anticlinal highs and synclinal basins of northwestern France and/or southern Belgium? Though seeming unlikely, such eastward-plunging structures, masked by more recent, parallel folds and offset locally by minor interference folds and major strike-slip faults, could continue to direct deep, perhaps infinitesimally slow, redistribution of underground water from exposed Upper Palaeozoic rocks (including Dinantian carbonates) in the west, down an easterly regional hydraulic gradient.

Initial continuity of Dinantian rocks between these widely separated areas has not been demonstrated conclusively, but some past authors (including George, 1958) have suggested that shallow-water carbonate deposition occurred along a belt stretching eastwards from what is now southern Ireland, through South Wales, on across the area south of modern Bristol and still farther eastwards, possibly into France and/or Belgium. Circumstantial confirmation is provided by provings beneath the Kent Coalfield of Dinantian limestone sequences that include a recognisable Lower Limestone Shales unit (also present in Ireland, South Wales, the Forest of Dean and Mendip) overlain by crystalline and oolitic beds similar to those at outcrop farther west.

Disregarding the structural complexity that must exist, consideration of known elevations allows a highly simplistic calculation of potential gradients. An example based on actual provings is provided by the vertical drop of about 1,700m between Dinantian outcrops in the Forest of Dean and borehole provings in western Kent, about 160km away, giving a gradient of about 1 in 90 or approximately 0.6°. Such a gradient is not insignificant in the context of rock development in basins far wider than the area under discussion (Neuzil, 1986), or in cave development. For example, Ford and Williams (1989, p.41) comment that water is believed to flow more that 1,000km within confined carbonate aquifers beneath the Canadian Prairies, with a residence time in excess of 30,000 years. The same authors (p.160) also provide a list of confirmed conduit systems more than 10km long, with gradients as low as 0.14°. Whereas the current geological situation beneath southern England is almost certainly more complex than that in the relatively stable centre of the North American continent, it is not unreasonable to deduce that prior to deformation of the former, conditions were analogous in both basins. Likewise the values for lateral extent of confined conduit drainage, hydraulic gradients and residence time seem to imply that figures deduced here for potential confined or partially confined deep flow in the southern UK area are by no means unreasonable.

CONCLUSIONS AND POSTSCRIPT

As yet there is no unequivocal proof that the Bath springs have a single origin in deep flow from Mendip (the "Mendip Model"), or from another source or sources. The hypothesis presented here tentatively proposes that water from catchments above the Forest of Dean and Tidenham Chase synclines, together with that collected around Cas Troggy, could feed the deep reservoir that supplies the hot springs. It appears at least feasible that water from these sources follows a long-established (now locally short-circuited) regional hydraulic gradient, which is also essentially down-dip, to pass beneath the Severn. The routes would be based upon an original inception horizon framework (not all of which need be in carbonates), upon which guidance by fold axes and faults has subsequently been superimposed. Such routes would converge beneath the Bristol-Bath region at depths greater than 2,000m (Burgess *et al.*, 1980, estimate 2,700 – 3,500m in Devonian or Dinantian beds). If this is accepted as a tentative working model, it allows deduction that modern hot springs (opened by erosional unroofing of their guiding fractures) are local leakages along a deep regional underground flow route that might continue eastwards, carrying underflow along tectonically modified fragments of the original regional/basinal fluid transfer gradient.

Some aspects of the proposed model are inevitably highly speculative, and likely to remain so, but several positive indications are discussed above. Arguably, some of the evidence for the widely accepted "Mendip Model" is equally circumstantial, with, as yet, few positive indications, even among the wealth of data that can be drawn upon for support. Indeed, hydrological studies along the northern Mendip scarp appear to give no support for the idea of a significant northerly flow component of the sinking water. Most allogenic input has been traced to major low-level springs south of the hills; a reasonable assumption is that most autogenic recharge will follow the same routes. However, IHH concepts and geological considerations allow that deep-flowing water required by the "Mendip Model" could derive from northward underflow, along elements of a relatively low-efficiency regional hydraulic gradient incorporating deep flow lines along inception horizons, fractures and palaeokarst. Flowthrough times for the water emerging at the hot springs is suggested to be at least 6,000 years (but perhaps far longer than 10,000 years), so there is no possibility of obtaining proof of the validity of either model (or a combination) by direct dye, chemical or radioactive tracing. The "Sub-Severn Model", an alternative but currently equally unprovable hypothesis, provides fuel for further discussion.

There is ample scope for ongoing speculation concerning both the development of the Bath springs themselves and the nature of their distant and local feeders. As with the points discussed above, there are indicative rather than confirmed similarities between features that have been observed, described and illustrated beneath Bath and those described in partially analogous but more recognisably karstic situations elsewhere. A good example is provided by semi-conjectural cross-sections of the detailed and general geological relationships beneath the Bath springs (Kellaway, 1991; Stanton, 1991), which lead to at least three further lines of speculation. Consideration of these sections reveals just how much useful information their authors have managed to extract and interpret, from a relatively limited set of "hard" data, and the picture they present of the output end of the thermal water system is convincing. However, it is impossible to avoid recognising:

(a) a strong (but possibly fortuitous) resemblance between the morphologies of the various "spring pipes" (fracture-guided transmission zones in the Mesozoic rocks) and those of "vertical through structures" (VTS), as described for instance by Klimchouk and Andrejchuk (1996) in the context of buried gypsum karst development.

(b) the nature of the erosion surface and unconformity beneath the Mesozoic rocks. Although fracture (or VTS-related) flow is undoubtedly instrumental in facilitating water movement upwards from the Carboniferous sequence, the cross-cutting nature of the unconformity is such that drainage within the limestones could be reaching the plane of unconformity via conduit flow along favourable bedding planes (inception horizons) that meet the erosion surface, rather than via sub-Mesozoic fractures.

(c) the dominant thermal water feeder zone for the Kingsmead and Pulteney boreholes is either at or close to the boundary between the Hotwells Limestone and the underlying Clifton Down Limestone. This corresponds to the boundary between the Asbian and Holkerian stages. It is well-known that commonly this boundary is marked by a very conspicuous palaeokarstic surface. There is also strong evidence that in some karst areas (the Yorkshire Dales, Derbyshire Peak District, South Wales, at least) the Asbian/Holkerian boundary is a major inception horizon.

VTS development related to strong conduit flow in the underlying Carboniferous limestones could offer a plausible explanation for the limited number of thermal water outlets and their restriction to a relatively small area, when otherwise outputs might be expected to occur extensively along a fracture-guided line or lines. Without doubt, much more investigation remains to be done before the full history and details of the Bath thermal drainage are unravelled and confirmed.

ACKNOWLEDGEMENTS

Putting aside its speculative elements, we acknowledge that this paper relies heavily upon a wealth of pre-published data by numerous authors. Updated versions of much of the earlier information are collected together and readily accessible in a compilation volume edited by Geoffrey Kellaway (1991). An early version of the manuscript that developed into the present paper was reviewed by Drs Tim Atkinson, Mike Edmunds and Dave Lowe, with additional comments from Dr Trevor Ford, all of whom are thanked for providing helpful and constructive comment. Subsequently the original text underwent significant revision, during which JDW remained essentially responsible for interpreting and reporting the previously published data on the Bath Springs in general and the "Mendip Model" in particular. DJL was invited to re-cast much of the geological content and contribute theoretical aspects related to the still evolving Inception Horizon Hypothesis and other recent ideas about cave development. Most of the earlier referees' comments were addressed during this major and extended overhaul. Professor John Gunn, to whom we also express our thanks, read the revised text. The biggest acknowledgement, however, is the acknowledgement that the model discussed in the paper remains unproved, if not unproveable, being based upon hypotheses that are as yet unconfirmed in this context.

APPENDIX 1

History of the construction of the Severn Tunnel

The authorisation Act for the tunnel was obtained on 27 June 1872 and construction began on 18 March 1873 (Body, 1986), controlled by Charles Richardson. Work progressed without difficulty until October 1879. From the start the tunnellers were preoccupied with potential dangers of flooding by river water. Several leaks did occur as the tunnel cut the Pennant and New Red Sandstone. Salinity levels indicated that the water originated from the Severn, and tunnelling was hardly interrupted. On 16 October 1879, the westward heading from Shaft No.4 at Sudbrook tapped fresh groundwater, about 130m west of the sea wall. Flow of about 90 Mld^{-1} under artesian pressure, was vastly greater than the pumps could master. Within 24 hours all the connected works were drowned (Walker, 1887). Pumps in adjoining headings could not cope with inundation from the flooded section, so work was halted before November 1879. The spring was at the junction of strata described as "coal shale" and "clay shale", 6m above a bed with limestone boulders, and 12m above the "Mountain Limestone". Presumably artesian pressure forced water from a stratigraphically lower karst system along incipient or open fractures towards the artificially produced low pressure area of the tunnel.

Sir John Hawkshaw then took over the enterprise, retaining Richardson as his assistant. Thomas Walker, the contractor to whom Tunnel construction work was let in December 1879, had helped build the North Staffordshire Railway, the Canadian Grand Trunk Railway, railways in Russia, Egypt and the Sudan, and the London Underground. Pumping recommenced in October 1880, when water level was lowered to about 10m above the flooded heading. An attempt by Alexander Lambert, a diver, to enter the heading with conventional air hoses on 3 November 1880 failed. A second attempt using the patent Fleuss portable compressed oxygen cylinder succeeded on 10 November 1880, when Lambert was able to close an iron door in the heading to the east. This minimised input from the flooded eastern heading and enabled the pumps to lower the level still further. However, Lambert also inadvertently opened rather than closed a sluice valve to the same eastern heading. Only when the level had dropped sufficiently for the foreman James Richars to reach and close the valve on 7 December 1880, did the pumps clear all the water. The inflow site was inspected on 13 and 14 December 1880. Walls were constructed to exclude water from the heading and facilitate pumping, and the operation was completed by the end of 1880.

After Hawkshaw took over as Chief Engineer, it was decided to deepen the tunnel on the Gwent side, to leave more rock between the tunnel and river bed at the Shoots and the Salmon Pool. This involved steepening the Gwent side gradient from 1 in 100 to 1 in 90. Work restarted in late 1881 and by 1883 the tunnel was complete, except for about 180m near the spring inflow, where the new tunnel was 5m below the existing heading. Unfortunately, another incursion from the spring (delivering 2.0m^{3}s^{-1}) entered the new heading on 10

October 1883. Several doors had been provided to block off the heading in the event of such eventualities. Lambert again closed the necessary door but, because of pump breakdowns and a severe tidal wave on 17 October 1883 (flooding workers' houses and pouring down shafts), the works were again inundated. Four large Cornish beam engines were needed to cope with the new inflow.

A new heading was dug north of the original line, and on 19 December 1884 this reached a large open joint. According to Walker (1888): *"...the fissure through which the Great Spring had passed was found to follow a most erratic course...in one place it passed directly across the tunnel from side to side...at another place it passed from side to side in an oblique direction...at another point the water boiled up from a hole 18 feet* [6m] *in depth with such force that stones the size of a man's fist dropped into the water would descend about 10 feet* [3m] *and then begin to flutter like a leaf in the wind, and then be thrown out again by the water".* Despite these difficulties the tunnel brickwork was completed by 18 April 1885, and water was finally shut out on 11 August 1885. Pressure from the spring continued to rise behind the brickwork. Eventually bricks were forced out, with sounds like pistol shots, and water again flowed in. The situation was clearly too dangerous, so a separate shaft was sunk, near the old Sudbrook main shaft, but outside the tunnel. The shaft, commenced on 8 February 1886 and completed on 7 April 1886, was designed to tap the spring via a short heading and a fissure. A large engine house containing six Cornish beam engines was provided, and pumping commenced on 1 July 1886. Finally, the first goods train used the tunnel on 1 September 1886 and, after official inspection on 22 November 1886, the line opened for passenger trains on 1 December 1886.

Pumping still continues, though the beam engines were replaced by electric pumps, and high quality fresh water has provided supplies for a steel works, a paper mill and a research establishment. When the spring was created during tunnelling, several local wells and springs, and the Nedern Brook, became dry for more than 8km from Sudbrook. The artificial short-circuit of the formerly constrained underground flow route had reduced the resistance of the system. More water could sink along the Nedern Brook, where it had previously backed-up behind limited capacity conduits along the regional hydraulic gradients, maintaining a surface flow. Hawkshaw believed that Nedern Brook was the chief water source, and decided to reduce water supply to the spring by constructing a 6km-long concrete invert in the brook's bed. Work begun in August 1884 was finished by 7 October 1884. Apparently little other investigation of water sources took place, although a borehole was sunk at the Nedern Brook in 1887.

APPENDIX 2

The history of use of the Hotwells Spring

In 1691 Sir John Knight, Mayor of Bristol, had stonework erected around the spring to prevent the tide from mixing with the thermal waters. However, impounding the waters caused them to find a new outlet, and the spring was in danger of being lost. In 1695 the Merchant Venturers granted a lease to Thomas Day *et al.*, who recovered the spring and built Hotwell House. In Victorian times Hotwells was operated as a spa, with a range of buildings. There was even a cliff lift, the Rocks Railway, dug as an inclined tunnel to Clifton above the Avon Gorge. The Assembly Room and Pump Room were pulled down in about 1870, to allow river widening at Hotwell Point.

APPENDIX 3

The Ashton Park Borehole

Planning of the Ashton Park Borehole (ST563715) on the Ashton Park Estate, about 1,750m SSW of Hotwells, began in 1951, and drilling commenced in July 1952 (Kellaway, 1967). Major influxes of tepid caustic water (16°C) were observed at depths of 366-377m and 396-399m, at the junction between the "Millstone Grit" and "Carboniferous Limestone", where Quartzitic Sandstone Group basal cherts are separated from the uppermost Hotwells Group by dark calcareous mudstone with limestone lenses. The water is cooler than that of Hotwells (which is 24.3°C). More than 1m of core was "lost", possibly indicating a cavity. Smaller influxes of water were also observed at 603m and 649m, in the Clifton Down Limestone. Fissures with haematite staining were observed at several horizons in the Coal Measures, Quartzitic Sandstone and Cromhall Sandstone, and a dolomitised fissure was seen at the junction of the Cromhall Sandstone and Hotwells Limestone (540m depth). The temperature at the bottom of the borehole (670m) was 23°C. There is thus some indication that water-bearing cavities exist at about 400m depth in the Ashton Park area.

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Field examination of limestone dissolution rates and the formation of active karren on the Tibetan Plateau

David Dian ZHANG
Department of Geography and Geology, University of Hong Kong, Pokfulam Road, Hong Kong

Abstract: Karst dissolution rates on the Tibetan Plateau were measured by using standard limestone tablets that lay in air, soil, sediment and on the limestone surface for more than 10 years. In most cases the tablets from the limestone surface and air show little sign of dissolutional processes, because of the prevailing highly arid conditions and low content of CO_2 in the air. Such low rates of dissolutional activity probably indicate that most types of karren found on the plateau are not active karst features. The samples in sedimentary detritus generally gained weight, indicating that deposition is taking place. This reflects both the overall aridity and the strong evaporation related to intense solar radiation input and the small amount of precipitation. Dissolution occurs only in the soil layer, which has a higher CO_2 content, indicating that biogenic karst processes are the major producer of currently active karst features in this cold and arid highland.

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KARST OF TIBET

Limestone dissolution is the major geomorphological process in karst areas, and karst and cave scientists have paid attention to the different dissolution rates in various natural environments. A joint research project using limestone tablets to examine dissolution rates at 60 stations around the world has been carried out by the Commission on Karst Denudation of the International Speleological Union (Gams, 1985). However, the Tibetan Plateau, with an area of about 2.5 million square kilometres and an average altitude of 4,000-5,000m above sea level (asl), was not included among the chosen stations. Short-term dissolution rates (15 months) on the Tibetan Plateau were examined by the author (Zhang, 1997), but little detail has been provided previously because of the short period of the field tests.

The Tibetan Plateau, the highest plateau in the world, has an average annual temperature that ranges from 0°C to 10°C and average annual precipitation of 50mm to 600mm. Precipitation falls in the form of rain, snow and hail. Intensity of solar radiation is very high, ranging from 140 to 210 kcal/cm^2, and it results in very strong evaporation. The average potential evaporation is 1,500 to 2,500mm/year and the average relative humidity is from 30-50% (Land Management Bureau of Tibetan Autonomous Region, 1994). Some warmer and wetter areas occur on the southern and eastern slope areas of the plateau, and these slope areas are not included in this study.

Many karst features have been recognised on the plateau and they are the highest karst landforms in the world. The major karst landforms found on limestone outcrops throughout Tibet are caves, karren and tufa deposits. Most of the caves are not active karst landforms, having stopped developing before the establishment of present day conditions (Waltham, 1993 and 1996; Zhang, 1995). Limestone pinnacles that were formerly considered to be remnants of tropical karst towers, are now recognised as the products of extremely strong physical weathering and not a karst landform (Zhang, 1996). Several varieties of karren have been found on limestone in Tibet, including rainpits,

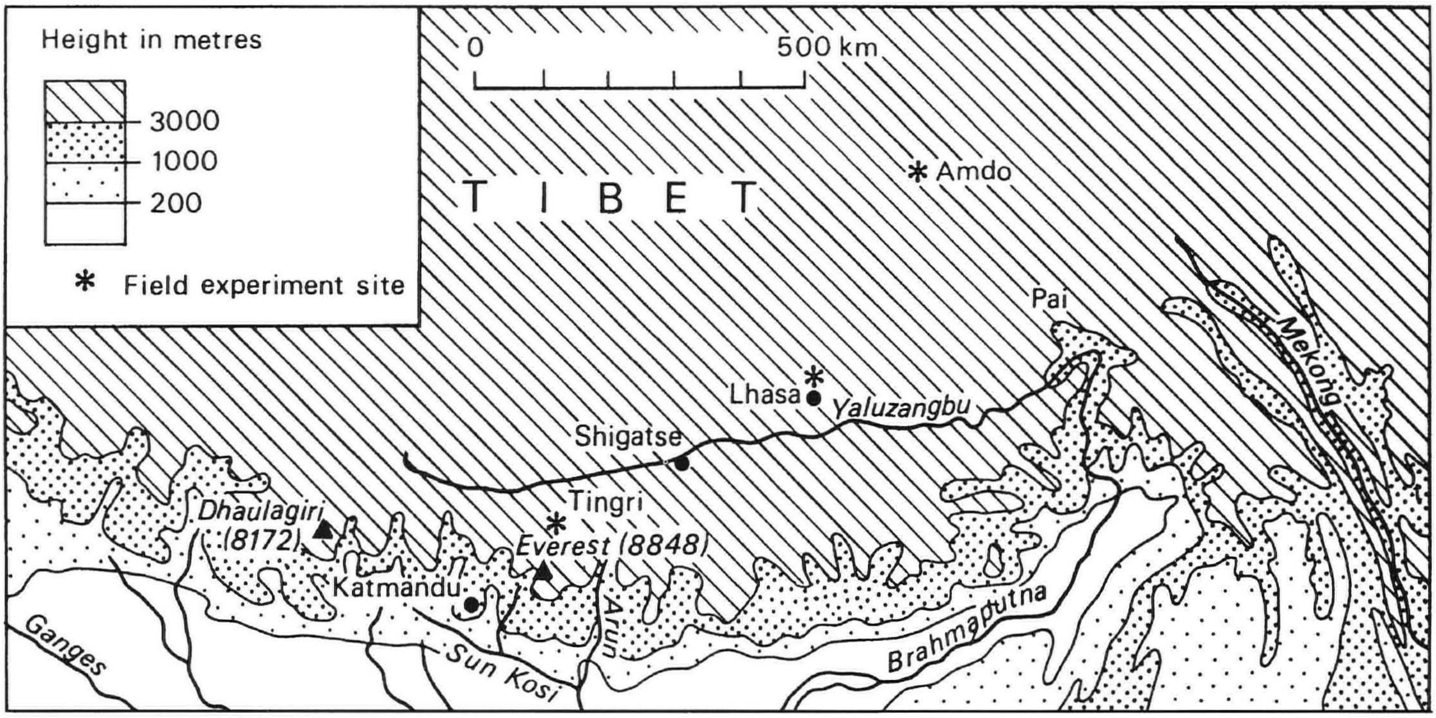

Figure 1. The locations of different experimental stations on the Tibetan Plateau.

Karren type	Location	Average size	Exposed or covered	Horizontal or inclined	Sharp or smoothed crests and edges
Rainpits	L, T(M)	5-10mm in diameter	Exposed	Horizontal	Sharp or blunt
Rillenkarren	L, T(M)	6-25mm wide, up to 500mm long, 3-10mm deep	Exposed	Inclined	Sharp or blunt
Solution pan	L, A, T(M)	20-1,000mm diameter, 10-200mm deep	Exposed or covered	Horizontal or inclined	Smoothed or sharp
Wall solution runnel	L, A	30-150mm wide, 30-100mm deep up to 10,000mm long	Exposed	Vertical	Blunt
Solution grike	A, L	5-100mm wide, up to 10,000mm long	Exposed or covered	Horizontal or inclined	Smoothed or blunt
Meandering solution runnel	T(M)	50mm-200mm wide, 30-100mm deep up to 20,000mm long	Exposed	Inclined	Sharp or blunt
Wall solution trough	L, A, T(M)	100-400mm wide 50-200mm deep	Covered	Horizontal or inclined	Smoothed

Table 1. Morphological characteristics of Tibetan karren. (L, Lhasa; A, Amdo; T(M), high mountain in Tingri.)

rillenkarren, solution pans, grikes, wall dissolution runnels and trough and meandering solution runnels (Table 1). From the smoothed or sharp edges and crests of karren, the author previously assumed that some surface dissolution processes were continuing, and that the karren could be considered as an indicator of contemporary karst processes (Zhang, 1995 and 1997). However, these conclusions lack support, because the field dissolution experiments were too short (15 months) and the visible evidence was only of the destruction of karren edges and crests by physical weathering.

In order to obtain more accurate dissolution rate data in this environment, and to explain the existence of karren on the plateau, field dissolution experiments have now been in progress for nearly 11 years, using limestone tablets.

DISSOLUTION MEASUREMENTS

Three karst regions were selected as field test sites, to represent major climatic zones on the plateau (Fig.1). Lhasa is in the heart of Tibet. Its average precipitation is about 500mm/year, with an annual average temperature of 6°C. The average potential evaporation is 2,200mm/year. The test site is in the garden of the Snow Lotus Hotel on the western side of Lhasa, and its altitude is 3,780m. Almost all types of karren found in Tibet are represented in the Lhasa area. The second test site is on the North Mountain of Amdo, located in the northern part of Tibet. The average annual precipitation and temperature are 400mm and -3°C respectively. The elevation of the site is on 4,820m and the potential evaporation is 1,760mm/year. The third site for field testing was established in November 1988, and is in Tingri County in southern Tibet. This is in the rain shadow of the Himalaya and its climate is very dry (less than 300mm/year) and cold (2.7°C). The site is in the Tingri valley at an elevation of 4,570m, and its potential evaporation is 2,550mm/year. On a nearby limestone mountain, meandering dissolution channels, rillenkarren and rainpits observed at an elevation of 5,200m were formed by the melting of snow, and reflect the higher precipitation on the high mountain.

Three pits for burying the limestone tablets were dug at the above locations. Tablets suspended in the air enable estimation of dissolution rates on bare limestone surfaces exposed to air.Those on the soil surface indicate the dissolution rates of limestone in close contact with the soil (Fig.2). In Tibet, a soil layer that contains much organic matter generally has a clear boundary with underlying detrital material consisting purely of clastic sediment. Thus, tablets at the interface of organic soil and detrital sediment layers were intended to examine limestone dissolution rates under a soil cover, whereas samples in the detrital sediments provide data on the dissolution of limestone under sediment cover.

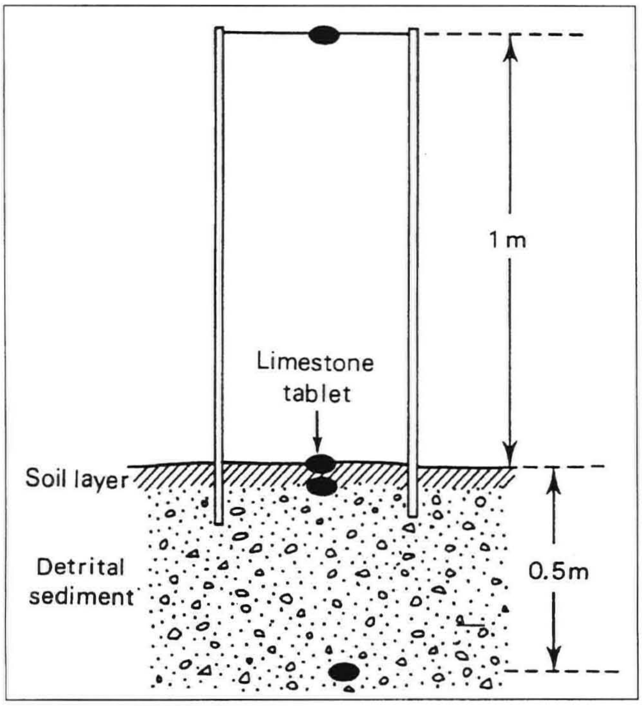

Figure 2. Sample locations in air, on the surface and in soil layers.

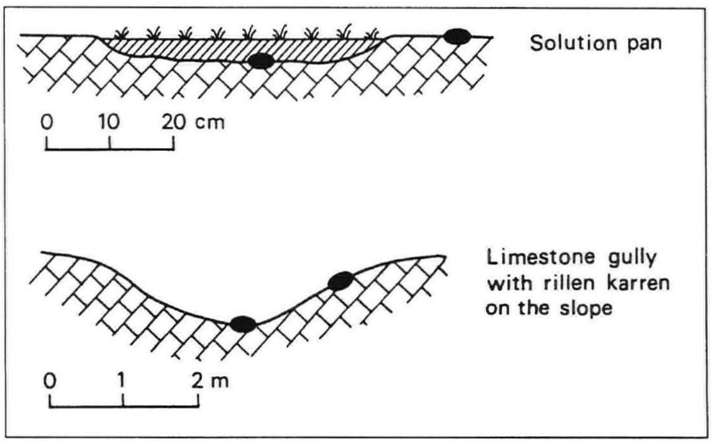

Figure 3. Sample locations on karst feature surfaces.

24 sample tablets were put on and in the three pits. Another 6 tablets were placed in various positions on landforms at the Lhasa and Amdo sites, in order to examine dissolution rates on different parts of the landforms. On the first landform feature, a soil-covered solution pan, which is common in the Lhasa area, one tablet was buried under soil and another was put on the limestone surface (Fig.3). Tablets were also placed in two limestone gullies in the Lhasa and Amdo areas. One tablet in the Lhasa gully was placed on a rillenkarren surface.

The test samples came from the International standard limestone tablets (Yugoslavian sample) and Chinese standard limestone tablets (Rongxian limestone). The tablets were cut into a circular shape with a diameter of 42mm and a thickness of 3mm. After a known period in the field, the tablets can be reweighed and the dissolution rate can be calculated from the weight loss of the tablets.

DISSOLUTION RATES

Dissolution rates were calculated according to the following function:

$$Sr = (W_2-W_1)/A \cdot t \cdot 2.7$$

where "Sr" is the dissolution rate (mm/year), "(W_2-W_1)" is the weight loss of the tablet during the test period "t" (years), "A" represents the surface area of the tablet (mm^2) and "2.7" is adopted as the average density of limestone.

After experiencing 11 years of natural weathering processes, the weights of the tablets changed according to their locations (Table 2). Dissolution rates have been calculated and their differences can be described in three respects:

Sample number	Sample origin	Test period (years)	Location	Site	Lost weight (W_2-W_1) mg	Dissolution rate mm/ka
S1	Y	10.9	Lhasa	Air, 1m above ground	46	1.13
S2	C	10.9	Lhasa	Air, 1m above ground	38	0.95
S3	C	10.9	Lhasa	Air, 1m above ground	54	1.32
S4	Y	10.9	Lhasa	Soil surface	215	5.27
S5	C	10.9	Lhasa	Soil surface	315	7.72
S6	C	10.9	Lhasa	Soil surface	197	4.83
S7	Y	10.9	Lhasa	Interface of soil and detrital sediment	38	0.93
S8	C	10.9.	Lhasa	Interface of soil and detrital sediment	151	3.7
S9	C	10.9	Lhasa	Interface of soil and detrital sediment	69	1.69
S10	Y	10.9	Lhasa	In detrital sediment, -0.5m	-110	-2.7
S11	C	10.9	Lhasa	In detrital sediment, -0.5m	-185	-4.54
S12	C	10.9	Lhasa	In detrital sediment, -0.5m	-39	-0.96
S23	C	9.7	Amdo	Air, 1 m above ground	75	2.07
S24	C	9.7	Amdo	Air, 1 m above ground	31	0.85
S17	C	10.9	Amdo	Polygon soil surface	62	1.52
S18	C	10.9	Amdo	Polygon soil surface	82	2.01
S19	Y	10.9	Amdo	Interface of soil and detrital sediment	30	0.74
S20	C	10.9	Amdo	Interface of soil and detrital sediment	-11	-0.27
S21	Y	10.9	Amdo	In detrital sediment, -0.5m	-29	-0.71
S22	C	10.9	Amdo	In detrital sediment, -0.5m	-201	-4.93
S27	C	9.7	Tingri	Air, 1 m above ground	28	0.77
S27	C	9.7	Tingri	Soil surface	31	0.85
S29	C	9.7	Tingri	Interface of soil and detrital sediment	-11	0.27
S30	C	9.7	Tingri	In detrital sediment, -0.5m	-302	-8.3
S13	C	10.9	Amdo	Gully bottom	25	0.61
S15	C	10.9	Amdo	Gully slope	29	0.71
S14	C	9.7	Lhasa	Gully slope with rillenkarren	59	1.63
S16	C	9.7	Lhasa	Gully bottom	31	1.02
S25	C	9.7	Lhasa	Solution pan under soil cover	301	8.29
S26	C	9.7	Lhasa	Solution pan surface	42	1.16

Table 2. Field dissolution rates of limestone tablets on the Tibetan Plateau.
Y. Yugoslavia sample (International standard limestone tablet), C. Chinese standard sample (the Rongxian Limestone)

Area	Air	Soil surface	Interface between soil and detrital sediment	In detrital sediment	Average
Lhasa	1.13	5.94	2.11	-2.73	1.61
Amdo	1.46	1.77	0.24	-2.82	0.16
Tingri	0.77	0.85	-0.27	-8.30	-1.74

Table 3. Average field dissolution rates (mm/ka) of limestone tablets in different areas and different locations in Tibet.

1. Regional differences of dissolution rates

In terms of average weight loss across all tablets, the weight loss in the Lhasa area was the highest (Table 3). The Amdo tablets had the second highest average weight loss, and the weight loss of air- and soil-related samples is close to that measured in the Lhasa area. However, disintegration of the air-suspended tablet's surface occurred in Amdo area, and its weight loss is the highest of all the air-related tablets.

2. Vertical changes of dissolution rates

All tablets buried in detrital sediment gained weight. Calcite crystals grew on the tablet surfaces. Comparatively, the air-suspended samples and those at soil/detrital sediment interfaces lost least weight, but the weight loss varies between individual samples. At the Tingri site, the interface sample gained weight. However, the highest average weight loss occurred at the soil surface.

3. Dissolution rates in different landform locations

The tablet under the soil of a solution pan lost a relatively large amount of weight, and the surface tablet nearby lost little weight compared with the soil-covered one. Dissolution rates of tablets placed on the gully walls were slightly lower than those of tablets fixed on the gully floors. Just like the air samples, the weight loss of all these tablets was small.

ENVIRONMENTAL INFERENCES OF DISSOLUTION

Measured regional differences of average dissolution rate basically reflect climatic conditions. The Lhasa area is the warmest and wettest of the three areas and its mean dissolution rate is the highest (Table 3). Among the climatic conditions, aridity may be the most important, because the average weight loss appears to depend directly upon the difference between precipitation and potential evaporation, rather than on precipitation alone. This finding agrees with those of investigations on the global limestone tablet dissolution rate (Gams, 1981).

Dissolution rate changes in different positions are complicated. Of the air-suspended samples, the greatest tablet weight loss was from those at Amdo. Examination of the tablet surfaces showed that all Amdo samples suffered some surface disintegration. This is not due solely to the temperature of -3°C. The area is not very dry, frost action is active, and most precipitation is in the form of hail and snow. Both frost weathering and the impact of hail may have an important role in surface disintegration.

The soil surface tablets suffered higher dissolution rates because of higher CO_2 content in the soil, as is normal in karst dissolution. However, it has been found that the pH value of soil is also related to the dissolution rate. Measured pH values in the soils that contained sample tablets indicated that dissolution rates decrease with the increase of soil pH values (Fig.4). This conforms to expectation on soil acid content: the higher the soil pH value, the less carbonic acid and organic acids are present in the soil.

All sample tablets in detrital sediments gained weight during the test period, because calcite crystallization occurs at the tablet surface. Tablet weight gain was highest at Tingri. In this area, the potential evaporation reaches 2,553mm/year and the solar radiation input (210 kcal/cm^2) is one of the highest in the world. Less precipitation and high solar radiation cause high aridity and strong evaporation. Under such climatic condition, the water in detrital sediments can evaporate quickly, and calcite is precipitated on the tablet surface. It is very common for concretionary tufa and laminar tufa to form in the sediments of this area.

The dissolution rates at the interface between soil and detrital sediment vary with climatic conditions. At Tingri, which is very arid, the tablets gained weight because of calcite precipitation. Tablets placed at the soil/detrital sediment interface were in a zone where pH passes from weakly acidic to alkaline. Evidence that distinct dissolutional and depositional processes occur on opposite sides of the limestone tablet is present, as calcite crystals have precipitated on the under-surfaces of most of the interface samples that lost weight. This test position was originally selected to test the limestone dissolution rate under a soil cover, which was believed to play a very active role in karst dissolution. However, as capillary water rising through the detrital sediments caused calcite deposition on the tablet under-surfaces, the limestone dissolution rate under soil cover cannot safely be deduced from this experiment.

The tablet buried under soil in the solution pan had the highest dissolution rate among all the samples studied. This indicates the relatively strong dissolution processes that occur in solution pans. The reasons for such locally high rates of dissolution are that there is higher soil acid, and water is retained in the pan for extended periods because the underlying limestone surface is impermeable. With sufficient time available, all of the acid in the water can be used to dissolve limestone and to support organic activity, which can produce more CO_2 and more acid. The dissolution rate recorded for the nearby limestone surface sample is much less than that of the soil-covered sample. Such local differences of dissolution rate can create a solution pan in a period of several hundreds years.

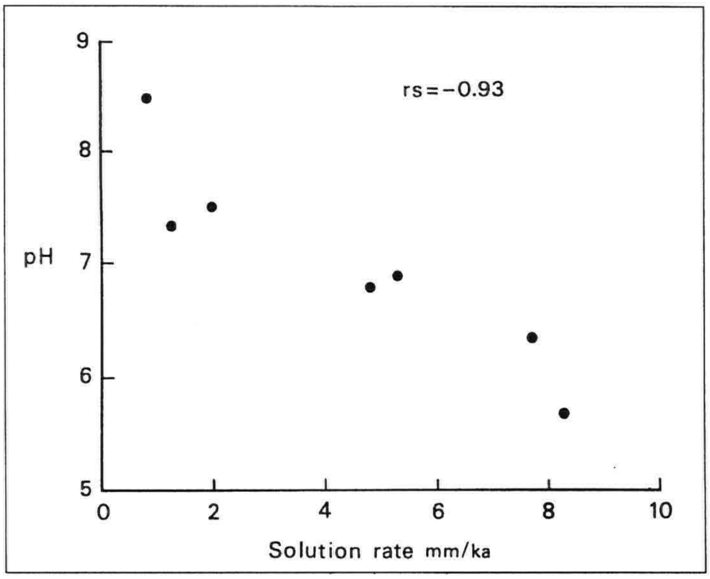

Figure 4. Soil pH values and the dissolution rates of limestone tablets on the soil surface and under soil cover on the Tibetan Plateau.

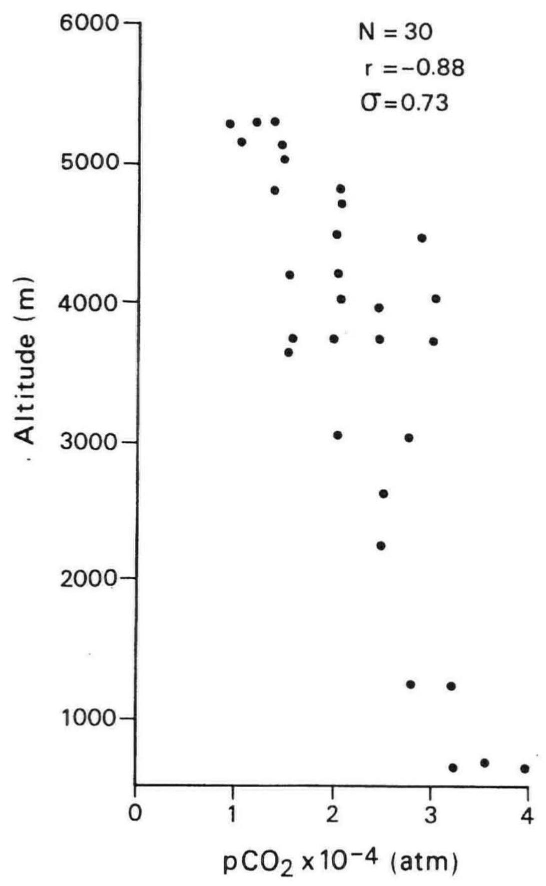

Figure 5. Atmospheric CO_2 contents and altitudes in Tibet.

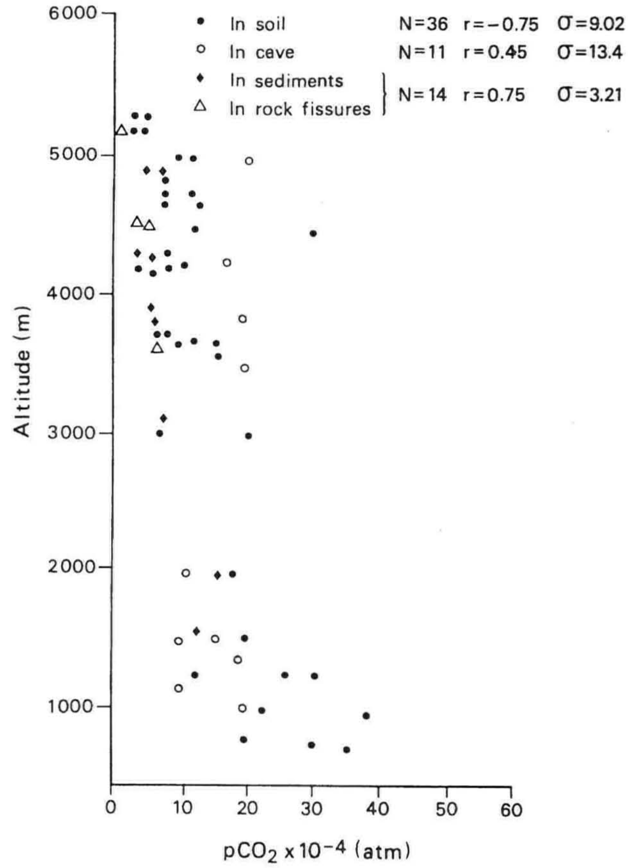

Figure 6. CO_2 contents in cave, soil, sediment and rock fissures of the Tibetan Plateau.

Sample tablets in limestone gullies revealed only a small difference between dissolution rates in the gully bottom and gully slope. This indicates that positions where water accumulates (gully bottom) do not suffer much more dissolution than other locations (gully slope). This result may provide important supporting evidence related to the formation of rillenkarren and other small features. Rillenkarren formation is due to the difference in dissolution between rill ridges and rill floors, with the latter getting more water and hence suffering greater dissolution. Thus, the length of the formational period of rillenkarren can be estimated by calculating the dissolution rate difference between the channel flow (gully floor) and sheet flow (gully slope). According to calculations based on the largest measured difference in the tests of the two gullies, the formation period for the smallest karren form, rillenkarren, is about 10,000 years. Therefore, according to the dissolution rate difference between channel flow and sheet flow, rillenkarren and rainpits on the Tibetan plateau, which were once considered to be active karst features, cannot have formed under the present climatic conditions. Possibly, the rillenkarren and rainpits on the plateau were formed during the last warm and wet period in the Holocene, and the limited available weathering time since then has allowed them to avoid destruction and to retain sharp ridges or crests.

KARST PROCESSES

Mean dissolution rates for the Tibetan tablet samples are very low compared to those from samples studied in other regions around the world (Bögli, 1961; Sweeting, 1966; Atkinson and Smith, 1976; Peterson, 1982, Kirk, 1977, Trudgill, 1985; Jennings, 1985; Zhang *et al.*, 1995). In addition to the reasons of dry and cold climates, two specific environmental characteristics account for such low dissolution rates.

Firstly, the high altitude of the plateau leads to a low atmospheric CO_2 pressure (Fig.5). Such low CO_2 content leads to precipitation being less aggressive, so that the dissolution process is very feeble. When such weakly aggressive meteoric water enters the soil, which also has low CO_2 (Fig.6) and low organic acid contents (because of the dry and high environments), water aggressiveness increases only slightly.

Secondly, the high solar radiation is important. Tibet has the highest level of solar radiation in the world. This leads to a high atmospheric aridity, and to strong evaporation. When rain falls on the ground, water evaporates quickly and the available reaction time for dissolutional processes is very short. In such circumstances, the water can dissolve only a limited amount of limestone, and the dissolved limestone can re-precipitate as calcite on the limestone surface after the water has totally evaporated. Precipitation of calcite on the limestone surface has caused widespread development of tufa films on limestone surfaces around Tibet.

Destruction of the air-suspended tablet surfaces in Amdo, with its colder climate and frequent hail storms, indicates that weight loss of limestone tablets is caused not only by dissolution but also by frost weathering and hail impact. The dissolution rates at the soil surface and under soil cover in a solution pan are higher, indicating that organic CO_2 and organic acids are very important in karst development in Tibet today. Because of the arid environment and high solar radiation input, strong evaporation has led to calcite precipitation in the detrital sediments. All the sample tablets in detrital sediments gained weight.

The factors leading to differences in karst dissolution are environmental, including climate and geomorpholgical aspects. Very low dissolution rates in Tibet indicate that karst dissolution in this cold and arid region is hardly active when compared with that in other karst regions. Among all types of karren, only solution pans and solution troughs can be considered to be active karst features on the plateau. Though rainpits and rillenkarren with sharp edges and crests have been found, their formation would need a period of over 10,000 years under present climatic conditions, so it is doubtful that they are active features. Meandering runnels develop only in Tibet's high mountains, with runoff from melting snow, and they are not an indicator of currently active karst dissolution on the plateau as a whole. From the above, it can be concluded that the effects of contemporary karst dissolution in Tibet are very insubstantial.

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Sediment studies in Joint Hole, Chapel-le-Dale, North Yorkshire, United Kingdom

Phillip J MURPHY
School of Earth Sciences, The University of Leeds, Leeds, LS2 9JT, UK

Abstract: Observation and analysis of the sediment covering an area of the floor in the main passage of Joint Hole, a flooded cave system in the Yorkshire Dales, has revealed a two-fold division of the deposits. The lower division of pale-coloured, clay grade, material consists of calcite and quartz. The upper division consists of sand, gravel and coarser grade material with clasts, both covered with and cemented by dark friable iron rich material. An origin as glacial rock flour associated with active glacier ice and washed into the cave is proposed for the clay grade material, whereas the overlying coarser material has been emplaced in the cave during a time of increased water flow, possibly associated with deglaciation.

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INTRODUCTION

The mainly flooded cave system behind Gods Bridge risings in Chapel-le-Dale has over four kilometres of explored passage and is the second most extensive phreatic conduit system so far explored in the United Kingdom (Fig.1). Although the literature covering the diving exploration of the system is extensive, very little has been written regarding its origins and development.

A description of each section of the system, intended for the use of divers and summarising the many entries in the Cave Diving Group Newsletter, is given by Monico (1995). It includes a summary of the system's complex and not yet fully understood hydrology. The geomorphology of the system was reviewed by Waltham *et al.* (1997), and its place in the landscape evolution was considered by Waltham (1990).

CAVE SYSTEM MORPHOLOGY

The system consists of two main trunk passages. The more northerly trunk passage has been explored upstream to a boulder choke at the end of The Deep. From the boulder choke it runs southeastwards before turning towards the south, where the waters from upstream Chapel Beck enter via a series of bedding-guided passages passing through Weathercote Cave and beneath the open shaft of Jingle Pot. The passage then essentially follows the bedding, which rises gently towards the south, though northwest-southeast orientated faults (not joints as stated by Waltham *et al.* (1997)) guide the passage into at least three phreatic loops (Fig.2). Hurtle Pot provides a window at the apex of one such loop, and presumably it formed due to collapse as a result of the loss of buoyant support to the roof as the valley was deepened. Up-dip the large passage rises gently towards Midge Hole, where it is truncated at the surface. The active flow cuts eastwards across the

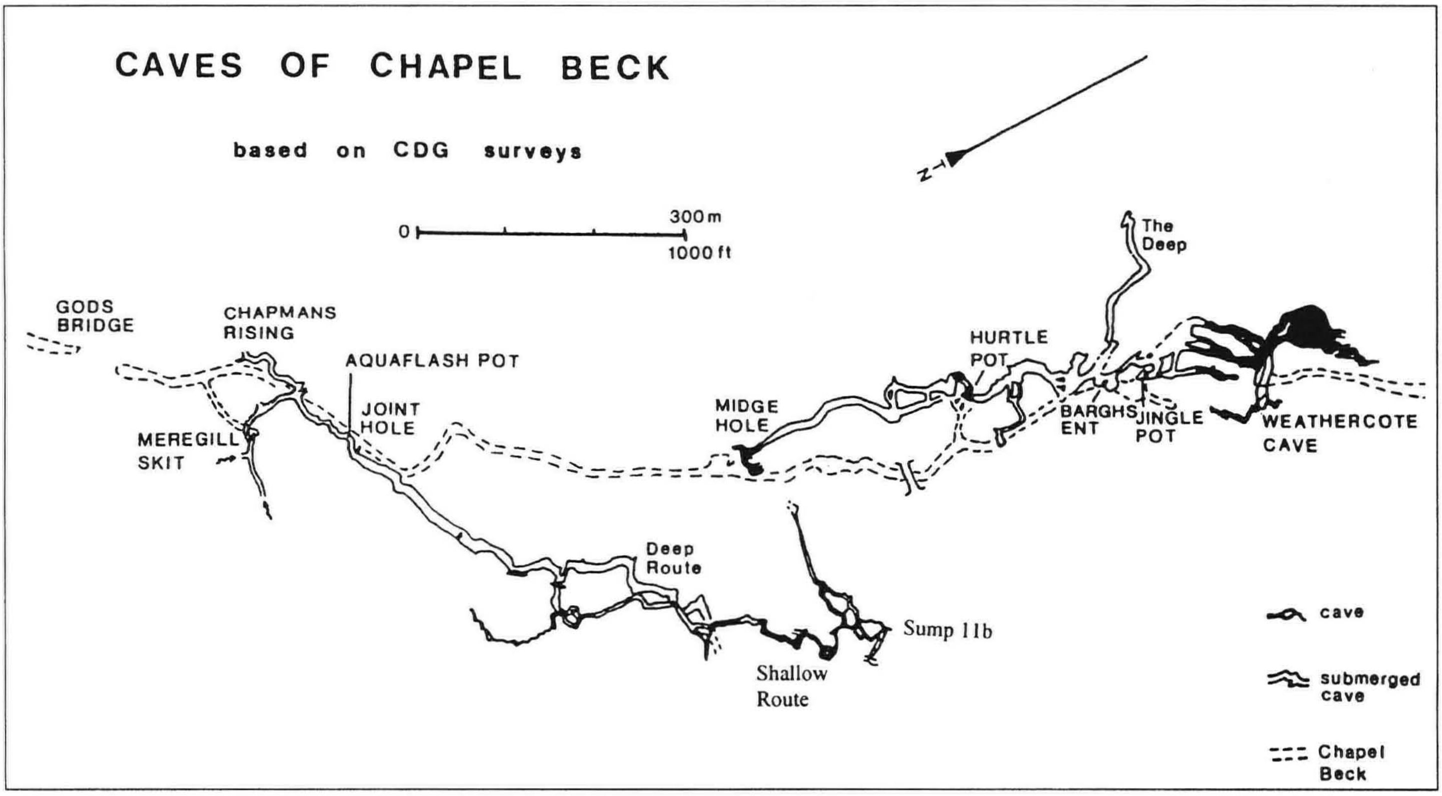

Figure 1. Plan of the caves of Chapel Beck. Reproduced from Brook et al (1996) with permission.

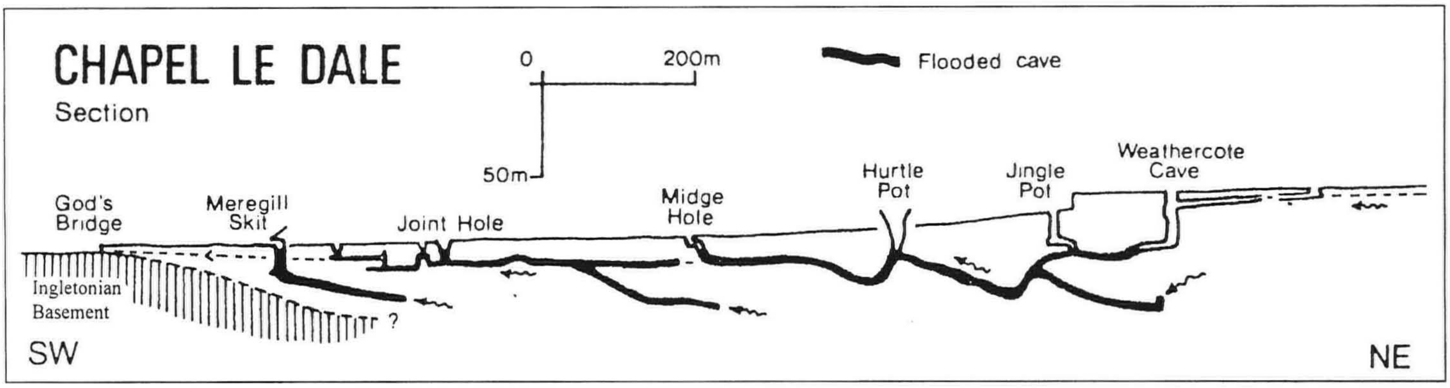

Figure 2. Section of the caves of Chapel Beck. Reproduced from Waltham and Davies (1987) with permission.

valley in a series of immature bedding-guided passages, before the flow is lost into sump 11b of Joint Hole. This flow is believed to enter the other main trunk passage via a series of immature bedding-guided passages called the Deep Route. The second main trunk passage runs southwestwards from the junction of the Deep Route and the Shallow Route. It passes the artificially widened window of Joint Hole to reach a point where the main passage is lost in a confusing area of low bedding-guided passages between Meregill Skit and Chapman's Rising. The water is next seen in the immature caves associated with the Gods Bridge risings.

The size of the two main trunk passages, commonly 5 to 8m wide by 3 to 5m high (and much larger in areas of cross joints), indicates clearly that the passages are of considerable age. They have been protected from draining and subsequent erosion because they lie behind an inlier of Lower Palaeozoic Ingleton Group metasediments that forms the valley floor to the southeast (Fig.2). Waltham (1990) proposed the existence of a pre-Anglian cave system that probably extended just below or beside the contemporary floor of Chapel-le-Dale, and he speculated that remnants of this system may survive within the multi-level flooded passages of Joint Hole.

SAMPLING PROCEDURE

The sediments described in this paper cover an area of passage floor 14m upstream of the Joint Hole entrance. Samples were collected by the author, using standard UK cave diving techniques as detailed in Balcombe *et al.* (1990). This sampling area was chosen for ease of access and for showing sediment features typical of those seen throughout the main passage of Joint Hole. Four core samples were cut and recovered by pushing lengths of 5cm-diameter plastic pipe into the sediment. Push fit caps were placed over both ends of the pipe once it had been withdrawn. This simple procedure gave excellent sample recovery, and resulted in minimum impact of sampling on the cave environment. Once preliminary descriptions of the samples had been completed at the cave entrance the samples were air dried. Sample point locations shown on Fig. 3 were obtained using the special underwater cave surveying method outlined by Cordingley (1997).

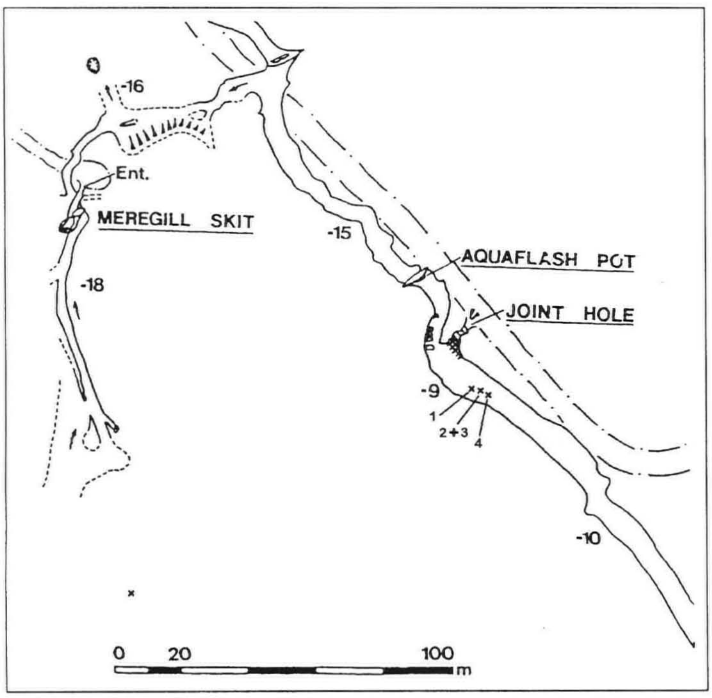

Figure 3. Location of the sampling sites in Joint Hole. Reproduced from Monico (1995).

SEDIMENT DESCRIPTIONS

The upper layer of sediment consists of angular and sub-rounded gravel size clasts (reaching cobble size in other areas) cemented by and covered with a brownish black (Munsell colour 5 YR 2/1) flaky crust (Fig.4). X-ray diffraction analysis revealed this material to be hydrated iron oxide (goethite) (Fig.5). The coating makes any attempt to quantify the differing clast lithologies very difficult. The black material also forms a cement between the clasts. This has minimised post depositional reworking of the gravel and has protected the underlying deposits. The occurrence of black iron- and manganese-rich coatings on stream clasts is fairly common in cave environments (Onac *et al.*, 1997), but not usually to the extent of cementing a deposit. The gravel consists dominantly of sandstone clasts, of both coarse and medium grain size. Other lithologies present in the gravel include metaquartzite pebbles, platy clasts of black shale and small (granule size) clasts of non-calcareous pale yellow clay and silt. Clast shape appears to be controlled by rock type, with the sandstone clasts having a moderate to high sphericity and the shale clasts having a tabular form. Fragments of wood are also found within the gravel. The clasts are generally rounded to sub-angular granule and pebble grade material. The scarcity of limestone clasts indicate a very small input of breakdown material. The rounded nature of the clasts indicates a significant transport distance. The crust can be from 50 to 150mm thick.

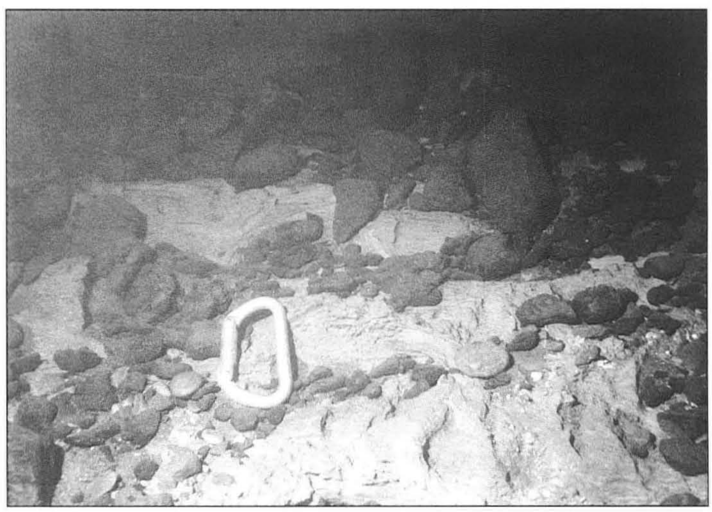

Figure 4. Pale-coloured clay-grade material exposed beneath cemented cobble armour. Joint Hole sump 1.

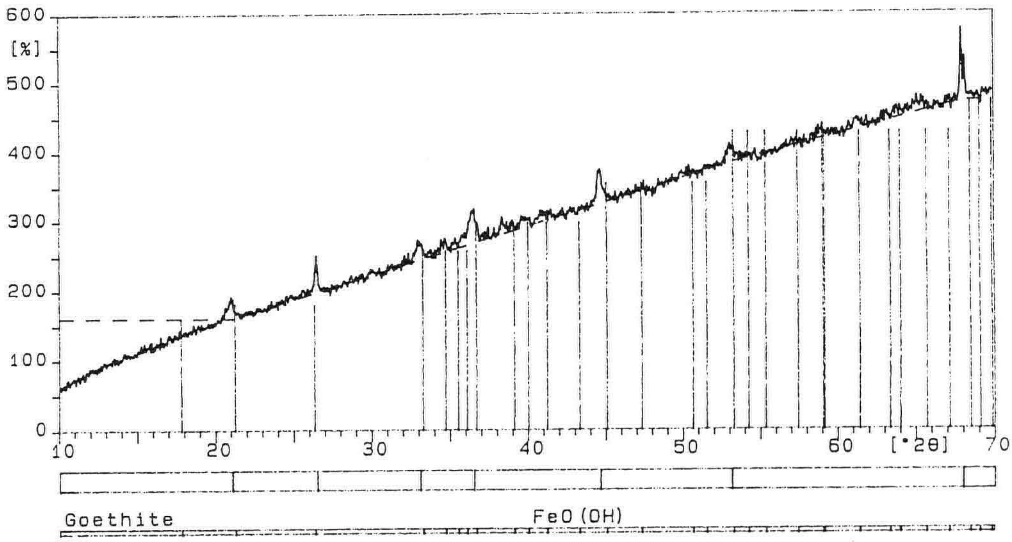

Figure 5. X-ray diffraction analysis of material forming the brownish black crust around and between the gravel clasts. Analysis was completed on a Phillips PW 1840 diffractometer. The sample was ground using a mortar and pestle to less than -100 mesh and packed into a cell plate.

Underlying the crust is a deposit of yellowish grey (5 Y 7/2) and pale yellowish brown (5 Y 7/2 and 10 YR 6/2) clay grade material (Fig.4). X-ray diffraction analysis reveals it consists almost entirely of quartz and calcite (Fig.6), with calcite making up between 9.7 and 18.6 percent by weight (Table 1). Augering has proved a depth of 100 to 500mm across the width of the passage near the sampling points. No layering of the sediment such as that recorded in fine-grained material from Agen Allwedd in Wales by Bull (1981) has been observed by the author, though a two layer colour difference has been seen elsewhere in the cave passage (J. Cordingley, personal communication).

The clay grade material is not being deposited at the present day, nor being transported actively through the cave, as it is protected beneath the cemented gravel armour. The clay grade material is only exposed where the gravel armour has been broken and moved by the passage of divers (Fig.7). Active sediment movement in Joint Hole occurs only during periods of extreme flooding, and is limited to isolated dune and bar forms of sand and fine gravel occurring on top of the cemented gravel armour, commonly in the lee of isolated boulders and slabs (Fig.8). The position of the uncemented sand and gravel bed forms is seen to change only following flood events.

ORIGINS OF THE SEDIMENTS

In terms of colour, lack of visible layering, and carbonate content, the clay grade deposits from Joint Hole are very similar to deposits described from the caves of Assynt in Scotland by Lawson (1995), though being mainly clay rather than silt grade particles. The Assynt deposits are called relict fine deposits by Lawson, and are found in abandoned phreatic passages away from the active streamways. The mineralogy of the Assynt deposits is dominated by quartz and carbonate, though clay minerals and feldspars are present in small quantities. No such minerals were recorded from the Joint Hole samples. Lawson (1995) interpreted the Assynt deposits as glacial rock flour washed into the cave systems through fissures while the systems were beneath an ice sheet and flooded with sub-glacial melt water. An origin as glacial rock flour is proposed for the clay grade material in Joint Hole. Glacial systems are very effective at producing large numbers of very small particles, due to grinding and polishing of material a the sole of the glacier. The lack of exotic minerals in the material suggests a mechanical origin for the deposit. Observations made elsewhere in the cave, by the author and other divers, indicate a large volume of the clay grade material is present within the system. So, any proposed origin must include a mechanism to generate large volumes of fine-grained material.

Sediments interpreted as reworked glacial rock flour have been recorded from caves in extra-glacial regions (Ford and Williams, 1985), though usually such deposits are laminated (Schroeder and Ford, 1983; Quinif and Maire, 1998). These deposits were deposited in flooded cave passages directly beneath temperate glacier ice (Quinif and Maire, 1988; Schroeder and Ford, 1983) or due to lateral back flooding of a cave system as the usual outlets were blocked by ice or till (Ford and Williams, 1985). No such laminations have been seen in Joint Hole, where vertical sections through the sediment are rare. Lawson (1995) reported very little evidence of layering, and the possibility of layering having been destroyed during the period of drying out was suggested to explain this. The lack of visible layering in

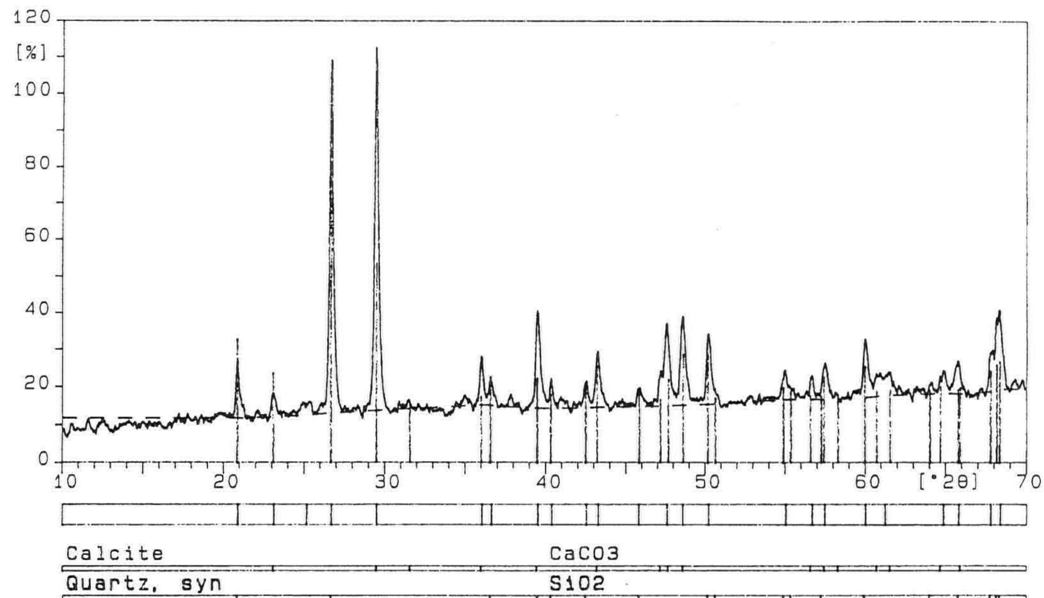

Figure 6. X-ray diffraction analysis of the clay grade material. Analysis was completed on a Phillips PW 1840 diffractometer. The sample was ground using a mortar and pestle to less than -100 mesh and packed into a cell plate.

Sample No.	Weight % carbonate
1	17.6
2	12.5
3	9.8
4	18.6

Table 1. Percent calcium carbonate equivalent as determined using the gravimetric method of Gale and Hoare (1991).

Joint Hole suggests that this explanation is unlikely, as the cave has remained flooded. Thus, the lack of layering may be a primary depositional feature.

It is likely that the gravel was washed into the cave at times of elevated flow related to melt water from the wasting of the ice sheet. Sandstone clasts could be derived from Wensleydale Group sediments or the Millstone Grit, and the shale from the Wensleydale Group, whereas the metaquartzite pebbles are typical of the Millstone Grit. Non-calcareous clay and silt clasts may be eroded from elsewhere within the cave system. The friable nature of the material means that it is unlikely to have been transported very far. Once emplaced, further transport has been minimal.

CONCLUSIONS

Sediments covering the floor of the Joint Hole main passage are not related to the present flow regime in the cave. Pale-coloured clay grade deposits are interpreted as glacial rock flour, washed into the cave and deposited under still water conditions. By analogy with deposits described from the Assynt area, deposition may have occurred when Chapel-le-Dale contained an active ice stream.

Overlying gravel deposits were deposited at times of increased water flow, possibly related to the wasting of ice cover at the end of the Late Devensian glaciation. A deposit of hydrated iron oxide cement has prevented erosion of the sediment.

No evidence of material derived from outside the Chapel-le-Dale catchment area has been found in the sediments analysed.

The fine-grained material has much in common with the material from the Assynt area of northwest Scotland, described as 'relict cave silts' by Lawson (1995). In Assynt the material is found in abandoned phreatic passages, whereas the main passage of Joint Hole is clearly of great age but is still flooded due to having been protected behind a ridge of resistant Ingleton Group rocks. The more complex mineralogy of the Assynt deposits probably reflects the more complex geology of the sediment source area. Similar material has been recorded in Beck Head, Cumbria (Cordingley, 1998), Malham Cove risings (Cordingley, 1999) and Dale Barn Cave, Chapel-le-Dale (Murphy *et al.*, in press).

ACKNOWLEDGEMENTS

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Figure 7. Clay grade material exposed where the passage of divers has disrupted the overlying cobble armour. Joint Hole sump 1.

Figure 8. Uncemented coarse sand and fine gravel deposited in the lee of a breakdown slab, overlying the cemented cobble armour. Current flow is from top left to bottom right. Joint Hole sump 1.

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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.

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MEETING REVIEW

7TH INTERNATIONAL KARSTOLOGICAL SCHOOL: "Classical karst"

Background

Held in Postojna, Slovenia, from 28 to 30 June 1999, the 7th International Karstological School ("Classical Karst") was organised by a team of staff members from the Karst Research Institute (KRI) at Postojna. It was attended by up to 66 delegates from Austria, Croatia, the Czech Republic, Great Britain, Hungary, Italy, the Netherlands, Norway, Russia, Slovenia and Switzerland. The official language of the School was English.

Topic

The central theme of the School was "denuded", "roofless" or "unroofed" caves, features that have long been known to exist, but with a significance that has only relatively recently become more fully appreciated. Presentations included some describing these phenomena and features within them, some discussing their organisation and place within wider karst models, and others covering a range of closely or more distantly related topics.

Papers presented

18 short papers were presented during two morning sessions:

Monday, June 28, 1999

A Mihevc: Unroofed caves- speleological and geomorphological features.
K Mais: Roofless caves, a polygenetic status of cave development with references to cave regions in the eastern limestone Alps of Salzburg, Austria.
D J Lowe: Why and how are caves "organised": does the past offer a key to the present?
F Šušteršič: Vertical formation of the karst.
J Móga: The reconstruction of the development history of karstic water network on the southern part of the Gömör-Torna karst on the bases of ruined caves and surface forms.
M Garašić: Roofless cave Crveno jezero in Croatia.
S Šušteršič and **U Stepišnik**: The "unroofed" cave near the Bunker (Laški ravnik).

Tuesday, June 29, 1999

J Čalić-Ljubojević and **V Ljubojević**: Natural bridges on the Vratna River as the last remnants of a former cave.
D Lacković: Slovačka jama (-1,258m) in Velebit mountain, Croatia.
P Bosak, J Bruthans, M Filippi, T Svoboda and **J Šmid**: Karst and caves in salt diapirs, SE Zagros Mountains, Iran.
S Faivre: Influence of tectonic forces on doline development; Velebit mountain range, Croatia.
A Zseni: Research of the soils on karst areas in Hungary (Bükk Mountains).
R Calligaris: Pocala Cave, Karst of Trieste, execution of 2 mechanical corings in the sediment.
S-E Lauritzen, D Karp and **S Eikeset**: Unroofed caves of the Tindall Karst Plain, Katherine, NT, Australia: Implications for Quaternary denudation history.
P Bosak, P Pruner and **A Mihevc**: Palaeomagnetic studies in the Černotiči Quarry (Crni Kal, Slovenia).
E Hoyk: Geoecological studies on the karstic territories of the planned Protected Area in Western Mecsek, South Hungary.
S Šebela: Morphological and geological characteristics of two denuded caves in SW Slovenia.
M Knez and **T Slabe**: Unroofed caves and their identification within the karst terrain (Kozina, Slovenia).

Available abstracts [edited]

[Full versions of these papers will appear in Acta Carsologica later in 1999.]

Karst and caves in salt diapirs, SE Zagros Mountains, Iran

Pavel Bosák [1], Jiøí Bruthans [2], Michal Filippi [2], Tomáš Svoboda [2], Jakub Šmíd [2]
[1] Institute of Geology, Academy of Sciences of the Czech Republic, Rozvojová 135, CZ-165 02 Praha 2, Czech Republic. [e-mail: bosak@gli.cas.cz]
[2] Faculty of Sciences, Charles University, Albertov 6, CZ-128 43 Praha 2, Czech Republic. [e-mail: mbundaf@hotmail.com]

About 200 salt diapirs (plugs) have been recorded in the Persian Gulf region. They penetrate through Phanerozoic sediments up to 12km thick within the Folded Belt of the Zagros Mountains. Many salt diapirs are still active, forming morphologically dominant peaks. Their annual uplift is estimated at 100 to 200mm, from which about 110 to 170mm can be dissolved by rainfall (which averages about 280mm per year). Most lie on faults or within fold plunges. Buoyant activity of the salt transports large blocks of "exotic", non-evaporitic, rocks, so the dominantly evaporite plugs also contain carbonate, siliciclastic and volcanic rocks of the Hormoz Complex (Upper Proterozoic to Middle Cambrian).

Salt plugs can be sub-divided by size into "small" (up to 6km in diameter) and "large" (up to 17km in diameter). By shape they can be divided into "circular", "linear" (veins) and "combined". On the basis of activity they are "active", "passive" or "ruined". Karstic rocks are represented by rock salt of the Hormoz Complex, less commonly by gypsum and anhydrite (also of the Hormoz Complex), by cap rock and by brownish gypcrete, which is a product of salt dissolution. The gypcrete is more or less indurated and reaches 10m in thickness.

Karst forms are especially well developed in passive salt plugs, where activity ceased some time ago. In active plugs karst forms are small and scattered, and some forms of karst are missing. Karst forms are mostly absent in ruined salt plugs, as salt and other evaporites have already been dissolved. The forms are completely comparable with those in classical carbonate rocks. Karren, cylindrical solution pipes, solution dolines, solution-collapse dolines (some with water at the bottom), uvala-like to polje-like depressions, blind valleys and canyon-like erosion forms, ponors and karst springs and caves can all be distinguished.

Long caves have developed especially in the form of "ideal watertable caves", sometimes on 2 or 3 levels. They are associated with near-coastal plugs, where a groundwater table can form. Commonly they connect polje-like closed depressions within the plug to outlets at the plug margins, at or near the coastline. Other caves at the bottoms of collapse-solution dolines or swallow holes are sub-vertical or inclined, and exploring them is difficult.

The *Tøí naháèù Cave* (with a total surveyed length of 3,160m, the World's third longest cave in salt) opens from the southeast margin of the Namakdan salt plug (on Qeshm Island), with an 8 by 3m entrance partly flooded by a lake. It comprises tunnel-shaped passages with large chambers, collapses and lakes. In one place the cave branches into two corridors, one with an active stream and another large passage with chambers. The largest chamber (Hangar) is 35 by 20 by 10m, and the end of the huge passage (the Namakdan Highway) was not completely explored. There are several deep shafts (40m) connecting the cave with the surface.

The *Namaktunel Cave* (about 400m long) is entered via a huge opening (about 15 by 15m) in the south slope of the Namakdan plug (Qeshm Island). The entrance leads to a huge meandering tunnel with abundant collapses. After several hundred metres, the tunnel terminates in very narrow passages. This cave is also nicely decorated, containing abundant curved stalactites. The *Ghár-e Daneshyu Cave* (total surveyed length 1,909m, the World's fourth longest cave in salt) is situated in the northwest part of Hormoz Island. The entrance opens into a small canyon that is formed by a broad but not high, irregularly meandering passage. In one place, there is a fossil cave level at +6m. The cave is richly decorated by salt speleothems (curved and branching stalactites more than 2m long, and cubic salt crystals).

These karst features, and the processes that formed them, are related dominantly to the dissolution of salt, less frequently to gypsum dissolution, and a major role is played by the process of halite subrosion under gypcretes. Deep circulation of meteoric waters was proved in some plugs, commonly supporting deep porous collectors in the surrounding non-evaporitic Phanerozoic rocks.

Geo-ecological studies on the karstic territories of the planned Protected Area in western Mecsek, South Hungary

Edit Hoyk
University of Szeged, Department of Physical Geography, Egyetem u 2, P. O. Box 653, HU-6722 Szeged, Hungary.

Earlier studies of the karst in Western Mecsek showed that this area is worthy of being protected, due to it surviving in a near natural state. In consequence, consideration is being given to declaring the karstic territory, with its wider environment, a protected area in the Danube-Drava Natural Park.

A good starting point to prove the almost untouched natural state of an area is examination of its soil and flora. Soil studies focus on determining the pH (and the related tendency for "souring", with a shift towards lower pH values), and on examining the calcium content. Measurements to check the heavy metal content (especially suitable for showing levels of anthropogenic contamination) will complement the above mentioned studies in the future. Investigations of the flora, based on examination of water balance, soil reactions and determination of rank, according to their categories of nature conservation value, can offer support to a claim for protection.

Results show that indirect anthropogenic effects can be detected by recognition of a pH shift towards lower values. This tendency for soil to become sour, or acidic, is less well marked in dolines, which are the most sensitive points within karstic fields. The relatively high calcium content provides a natural resistance against the lowering of pH values.

When examining the vegetation, special attention is paid to the ranking species into nature conservation categories. A significantly high ratio of association-forming and accompanying species, and the presence of protected species in relatively high numbers, can be seen, proving the nature conserving character of the territory.

On the basis of the investigations carried out, maintenance of the present state of the territory can be shown to be a desirable objective and, in order to realise this, the future protection of the area is completely justified.

Why and how are caves "organised": Does the Past offer a key to the Present?

David J Lowe
Limestone Research Group, University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, United Kingdom.

Many caves within carbonate (and perhaps other) rock sequences display marked spatial organisation, particularly a tendency to group within vertical clusters. Most past explanations of clustering involve "recent" effects and interactions. New ideas, based on study of "denuded" or "roofless" caves, acknowledge but re-interpret features and relationships that were observed long ago and commonly dismissed as "atypical", "irrelevant" or "impossible". Traditional explanations of vertical clustering must now be re-assessed.

Assumptions that any stratigraphical (bedding plane) or joint/fault fissure in carbonate rock provides (or provided) a *de facto* route for fluid transfer, and hence a focus for void development, are not confirmed by observation. Primitive pre-cave, but potentially cavernous, carbonate masses are not inevitably active hydrologically; nor are they geologically homogeneous. New evidence, and re-evaluation of earlier observations, implies that dissolutional void "inception" is related to a minor subset of all stratigraphical partings, which dominate initially, imprinting incipient guidance for later cave development. Recognition of this fundamental role provides a possible key to understanding the organisation of cave systems and necessitates acceptance of an expansion of speleogenetic timescales back to the time of diagenesis.

Roofless caves, a polygenetic status of cave development with reference to cave regions in the eastern limestone Alps of Salzburg, Austria

Karl Mais
Naturhistorisches Museum Wien, Karst- und Höhlenkunde Abteilung, Messeplatz 1/Stiege 10/1, AT-1070 Wien, Austria.

The phenomenon of roofless caves was reported early by Dawkins, as the breakdown of cave passages up to valleys in Devonian formations of England. Also, Franz Kraus found by fieldwork, that breakdown and roof collapse are the first steps from a normal subterranean cave to a doline-line with cave remnants, and subsequently to a gorge or valley, first with steep walls, then later with gentler slopes. Kraus considered the different valley parts and natural bridges of Rakov Škocjan to be an example of an old cave systems on its limits. He also pointed out that surface and sub-surface features make caves roofless. Localised surface denudation thins the roofs and than the roofs collapse, as at "Lončarevec Cave", near Great Otok in the Postojna region. The roof of this cave was thinned to 40 or 50cm, and then roof windows opened (Kraus, 1894, 73-75, 114). Consequently, he wrote that cave fillings on the karst surface, furrows and valleys are remnants of caves in regions with a high denudation rate (1894, 203). He described examples from the Postojna region.

Karst development in alpine regions is commonly dominated by glacial erosion. The effects of lateral and ground erosion by main or local ice streams form the typical valley morphology. Locally many caves are intersected and revealed in steep slopes. In plateau regions with gently inclined slopes, some caves became roofless due to sub-glacial erosion. Examples can be seen in the eastern alpine limestone massifs near Salzburg, especially the massifs of Steinernes Meer and Tennengebirge.

As the ice flow carved the plateau surfaces cave systems were opened like dots in inclined slopes. On plane surfaces many cave roofs were shaved down. Nowadays many mostly small caves are found locally, as cut parts of formerly extensive cave systems. This more or less characterises a "niveau", which has been called "Cave-Ruin-Niveau" (Höhlenruinen-Niveau). The name is not strictly correct, because in higher parts of the plateau, in undenuded mountains, long caves and not ruins are developed. It only looks like ruins on the surface. Nevertheless, karst massifs with a plateau character (especially Steinernes Meer, Hagengebirge, Tennengebirge) show many cave remnants at an altitude of 2,000-2,200m. Some of them are connected by roofless walled sections, some with cave wall morphology, cave sediments and speleothems, but in other cases cave wall morphology is absent. Typical surface forms with different kinds of karren are present, even in sinter layers.

Special reference is made to the Hennekopf and Rotwandl region in the Steinernes Meer massif, and to the region of Sandkar in the Tennengebirge.

Reconstruction of the development history of a karstic water network on the southern part of the Gömör-Torna karst, on the bases of ruined caves and surface forms

János Móga
Eötvös Loránd University, Geography Department, Markó u 29-31, HU-1055 Budapest, Hungary.

The lecture demonstrates the surface development of the Gömör-Torna karst (on the Hungarian-Slovakian border), from the Tertiary until the present day.

It follows the transitional process from covered karst conditions to open karst on the karst plateau, and its effect upon the surface forms and the karstic water network. The research included study of the evolution of surface and sub-surface water networks, and the regularity of the movements of underground rivers based on water indicating experiments. Ancient surface outflow directions of the covered karst were reconstructed from evidence of the scarce remains of epigenetic valleys inherited from cover deposits onto the limestone surface, from ruined swallow hole lines in valleys, and from the remains of water conducting tubes (caves) originating from earlier phases.

Typical "wall" flowstone preserved within the remains of an unroofed (denuded) cave, Laški Ravnik, Slovenia (photo: Dave Lowe).

Palaeomagnetic studies in the Černotiči Quarry (Črni Kal, Slovenia)

Petr Pruner [1], Pavel Bosák [1], Andrej Mihevc [2]
[1] Institute of Geology, Academy of Sciences of the Czech Republic, Rozvojová 135, CZ-165 02 Praha 6-Lysolaje, Czech Republic.
[2] Karst Research Institute, Slovenian Academy of Sciences and Arts, Titov trg. 2, SI- 6230 Postojna, Slovenia.

A unique profile of laminated speleothems was studied in the western wall of the Černotiči Quarry (Črni Kal, Karst Edge, SW Slovenia), in the remains of a palaeocave destroyed by blasting. The profile, which was only a few metres below the present levelled surface of the limestone plateau, comprised a c.1.6m-thick sequence of reddish brown, pale brown, brownish pale grey and ochreous, laminated to banded speleothems. It was deposited over a highly corroded surface of massive, greyish white, coarsely recrystallised speleothem (preserved thickness more than 2m), filling a probable side notch. The laminated sequence consisted of several layers separated by about 11 layers of red clay (most probably redeposited terra rossa soil) with thicknesses ranging from a thin film up to 10cm, and by some corrosional surfaces without clay. Some of the clay layers, contained small rounded clasts of slightly consolidated red clay. The speleothem included alternations from massive laminae to bands with detailed internal lamination in places, and of more porous, rather ochreous laminae, to bands. This feature indicates changing conditions of speleothem growth, alternating between slow (massive laminae) and more rapid (porous). This confirms variations in climatic conditions during carbonate precipitation.

Sampling for palaeomagnetic study was carried out in the laminated speleothem sequence (23 samples). Sampling of the white coarsely recrystallised speleothem below the laminated sequence was not carried out, as low preserved remanent magnetisation was expected, as is typical in such rock types.

Palaeomagnetic study detected a normal polarity magnetozone in the lower 1.2m of speleothem and one reversed polarity magnetozone, containing a not completely proved narrow normal polarity magnetozone, in the upper 0.4m of profile. Thus, the profile began its deposition in a normal polarity magnetozone and deposition was completed within a reverse polarity magnetozone. Calibration of these results to the commonly applied charts of geomagnetic polarity is highly problematical. The situation is made more complicated by the numerous breaks in speleothem deposition indicated by the clay interlayers and corrosional surfaces. Large thicknesses of speleothem deposited within the normal polarity and reverse polarity magnetozones indicate that deposition extended through long time-periods. Knowledge of the duration of the individual Neogene/Quaternary magnetozones therefore suggests that the *youngest possible age* of the boundary of normal/reverse polarity within this profile has to be correlated with Matuyama/Gauss boundary, i.e. 2.47/2.60 Ma.

Data obtained indicate a very ancient age of karstification (which is in agreement with the present position of the palaeocave just below the modern surface) and relatively stable carbonate precipitation conditions in the palaeocave environment. The cave itself must be much older, as the speleothems studied overlay a great thickness of older deeply corroded/eroded and highly recrystallised speleothem.

The "unroofed cave" near the Bunker (Laški Ravnik)

Simona Šušteršič and Uroš Stepišnik
University of Ljubljana, Department of Geography, Aškerčeva 2, SI-1000 Ljubljana, Slovenia.

Situated in the Laški Ravnik, about 4km east of Planinsko polje (Slovenia), this unroofed cave is the longest of many found in the area. More than 200m of denuded passage has been traced at the surface. The cave's general trend is north-south, and it continues southwards to an overhang, which appears to be the termination of a collapsed cave channel. Three main "passages" making up the unroofed cave have been recognised, and each has been transformed in its own way. Disintegration of parts of the former cave roof is apparent, forming "false solution dolines", between which the ceiling is partly preserved, either in-situ or as isolated blocks lying on cave sediment. In the down-dip direction, passage sides have disintegrated almost completely, and detached blocks have slid down into washed-out portions of the former cave passages. All three passages developed along bedding planes, but in different directions, such that two of them now "emerge" above the surface whereas the third plunges down and is completely choked by loam. The unroofed cave passes southwards into a "normal" underground route, where a barely accessible, very low and wide passage is accompanied by two "vertical" shafts, which are presumed to be former phreatic jumps. This part of the system is not considered in this paper.

Morphological and geological characteristics of two denuded caves in SW Slovenia

Stanka Šebela
Karst Research Institute ZRC SAZU, Titov trg 2, SI-6230 Postojna, Slovenia.

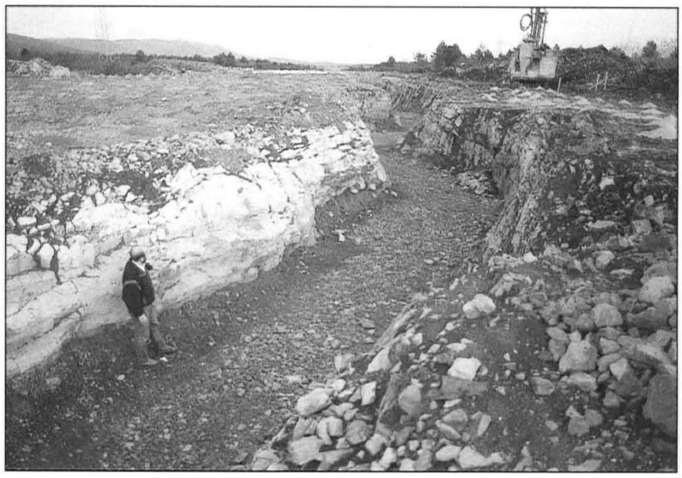
During early construction work on highways across the Slovenian Kras in 1994, the first so-called denuded (or roofless) cave was discovered near Povir, on the Divača-Dane highway. Because of the needs of highway construction, detailed topographical maps at 1:1,000 scale were compiled. Altitudes shown on such maps are determined to 1m intervals, and in some cases also to 0.5m. On the map an obvious morphological depression is shown, running from altitudes of 395.3 to 401m. The denuded cave is 320m long and up to 10m wide, running generally from NW to SE between cross sections 701 and 681 on the highway.

The cave is developed in rocks of the Liburnian Formation (K-Pc), which is bedded and contains platy limestone, marly limestone and limestone breccia (Jurkovšek et al, 1996). In the NW part of the cave the limestone dips towards the south at 20°, and in the central and SE parts it dips southwestwards at 20 to 30°. The limestone beds are 0.2 to 0.4m thick. According to the geological map of Jurkovšek et al (1996) there is a syncline with a general NW-SE trend between the denuded cave and the Divača Fault, but it dies out just in that area. Geological measurements in the cave confirm this failure of the syncline.

The denuded cave near Povir lies about 100m north of the NW-SE trending Divača Fault. In the cave a 50/70-90° fault is well exposed in the central to eastern part of the cave. Fractured zones on 70/80, 150 and 140° can also be followed. In the western doline there are fractured zones 70/30, 70, 60 and 340/80. The cave passage is mostly developed according to the direction of bedding planes.

During preliminary investigations before highway construction from Divača to Kozina, 4 denuded caves were recognised (Šebela, 1996), and 2 more denuded caves were found during highway construction. A cave between cross sections 139 and 149 on the highway was very well expressed morphologically, even before the highway construction. All together about 80m of the cave was observed, with a general W-E trend. The western part of the roofless cave was morphologically deepened for 0.5 to 1m. After about 30m the cave passage lost its identity in a doline (bottom of the doline 497.2m), which was probably a former cave chamber. The eastward continuation of the cave is not clearly determined, and it probably still has a roof. Part of the roofless cave could be followed about 20m eastwards from the old Divača-Kozina road, and this was also well illustrated by the morphology on the topographical map (1:1,000). The cave is lies between 497.2 and 505m a.s.l. and is filled with cave sediments. About 20m of the 80m-long cave still has a roof.

The cave developed in Eocene limestone on the SW limb of a syncline that runs in the Dinaric (NW-SE) direction between Dane pri Divači and Kačiče-Pared. Alveolinid-numulitid limestone dips towards the NE at 10 to 30°. The bedded alveolinid and numulitid limestone locally includes limestone with chert and limestone with lithothamnians, corals and hydrozoans (Jurkovšek et al, 1996). The direction of the principal fissured to broken zones is 290/70° or 110°. Fissures trending 40° and 190/80° are also present.



Andrej Mihevc of the Karst Research Institute, in part of an unroofed cave, encountered and cleared of much of its infill during motorway construction in Slovenia (photo: John Gunn).

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Vertical zonation of speleogenetic space

France Šušteršič
University of Ljubljana, Department of Geology, Aškerčeva 12, SI-1000 Ljubljana, Slovenia.

Recognition of "unroofed caves" has revealed not only the existence of a spatial domain where underground karst phenomena are being systematically transformed, but also that application of this knowledge allows the role of caves within geospeleological space/time to be described more consistently. Speleogenetic space is defined as those parts of the Earth's crust within which karst caverns may be formed. Accordingly, a karstified rock mass is defined as activated speleogenetic space. Due to the effects of denudation and water table lowering, a specific cave will appear to move upwards through speleogenetic space as time passes, until it reaches the surface. Because the denudational logic of the karst surface is vertical, the rock mass suffers disintegration through the full thickness of its outermost layers, and the same argument applies to in-rock features. Consequently, the concept of the speleothanatic zone is introduced. Within this zone the whole of the rock mass is attacked, on any possible surface, and the ultimate result is its complete annihilation. It may be deduced that all structures, of whatever origin, that expose rock surfaces to the effects of aggressive water will evolve via some form of speleothanatic progression, and three vertical zones of specific formative/de-formative processes can be demonstrated to exist within speleogenetic space.

Research of the soils on karst areas in Hungary (Bükk Mountains)

Aniko Zseni
Jozsef Attila University, Department of Physical Geography, HU-6722 Szeged, Hungary.

A study of the characteristics of the economy of the soil's nutrients on karst areas was carried out. During an examination of an $8km^2$ part of the Bükk plateau (Bükk National Park, Hungary) two soil samples (from different depths) were collected from every km^2. Different ecological conditions were sampled: beech forests, pine forests, beech with pine forest, woodland nursery and open field.

During the past ten years investigations of the soils that occur on the karst have gained prominence. The soil has an important role in the ecological system, because it can buffer harmful environmental effects that take affect quickly.

Various soil nutrients were measured, including total soil-nitrogen plus the quantity of plant-available phosphorus, potassium, calcium and magnesium. Although not actually a nutrient, the collective quantity of exchangeable and dissolved sodium was also measured. This enabled calculation of the S-value (exchangeable basis) of the soils.

Investigation of the soil cannot proceed without knowledge of its pH and the carbonate content. Therefore the investigation included determination of the pH (H2O) and pH (KCl) plus the carbonate content of soils. Soil moisture content - which is important to plant take-up of nutrients - was also part of the investigation.

Determination of pH and carbonate content of soils isn't only important because of the nutrients. In the case of karst areas it is important, to know these relationships, because the bedrock characteristics suggest that the soil should have a high carbonate content and, according to this, a neutral pH. Measurement showed that the soils of the Bukk plateau have a low carbonate content, which has a big influence on the presence of nutrients. In connection with this, the soil pH is also lower than expected. In the case of ΔpH (= pH(H2O) - pH(KCl)) the commonly high (around 1) values show that acidification is important in these soils.

Knowledge of the pH plus the N, P, K, Ca, Mg content of soils can be influential with regard to the protection of the environment, the upkeep of forestry and the management of meadows.

Fieldwork

Amid dire warnings about the potential unwanted attentions of ticks and their after-effects, field trips took place on the afternoons of the first two days and the whole of the third day. Unroofed cave sites on the levelled plains of Logaški ravnik and Slavenski ravnik, and those above Škocjanske jame and on the surface south of Sežana were visited. About 5km of the exposed remains of various unroofed galleries, displaying different types of transition from cavities to surface features, were seen, together with a variety of cave sediments.

Assessment

The 7th International Karstological School was both well organised and welcoming. If it was typical of the general standard of the annual event, future schools can safely be recommended. A spectrum of age, gender, nationality, experience and background was represented, with "vibrant" students rubbing shoulders with "venerable" professors. Not only that, but the younger delegates obviously felt quite comfortable in making their own presentations, discussing the ideas presented during the sessions, and generally enriching the debate. Much of the material covered in the lecture room and in the field was novel, but none of it was presented at so rarefied a level as to lose the interest or understanding of the cosmopolitan audience. Whereas the time-slots for some talks were very short, there was usually enough time for questions and discussion, either within or between the lecture sessions, or when travelling between field localities.

Various local dignitaries, as well as the delegates, attended an "end-of-School" dinner on the Wednesday evening. Judging by the reception of various *ad hoc* "votes of thanks", delivered in English with considerable style and humour, the Karstological School in general, and the meal, were enjoyed by all.

The Karstological Schools are not esoteric symposia for ivory-tower academics. They have something for everyone, and everyone is welcome. My only regrets are that I did not attend earlier schools in the series and that I may not be able to attend annually in the future. But, for an enjoyable few days of "not-too-heavy" karst science (weather permitting) and the chance to get to know some of the established and up-and-coming names in European karst science, the International Karstological School series comes well recommended. As a forcing ground, where new scientific talent can gain confidence before a knowledgeable but sympathetic audience, the schools may not be unique, but they are certainly invaluable.

Acknowledgements

Thanks to Tadej Slabe (Director) and the staff of the KRI, for their invitation to attend the Karstological School, and particularly Andrej Kranjc and Andrej Mihevc for providing factual information included above. Thanks also to Professor John Gunn (Limestone Research Group) for contributing travel support, Professor France Šušteršič and his family, for welcoming me into their home, and all others who made the short stay in Slovenia both possible and enjoyable.

Report by Dr D J Lowe, Limestone Research Group, University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, UK.

Tadej Slabe, the Director of the Karst Research Institute, provides an indication of the scale of part of an unroofed cave system, encountered and cleared of infill during motorway construction in Slovenia (photo: Dave Lowe).

THESIS ABSTRACTS

MICHIE, N J 1998

An Investigation of the Climate, CO_2 and Dust in Jenolan Caves, N.S.W.

PhD 1998, Macquarie University, New South Wales 2109 Australia.

Pressure of use of Jenolan Caves as a tourist spectacle has raised concerns about the well being of the caves, so three related physical subjects were reviewed and investigated; the cave microclimate, the CO_2 in the cave atmosphere and the dust fall in the caves. The microclimate has been shown to be dominated by several physical processes: in the absence of air movement, conduction and radiation dominate; in association with air movement, convective coupled heat and mass transfer tends to dominate energy flows. A new approach using boundary conditions and qualitative characteristics of transient fronts enables accurate measurement and analysis of energy, heat and mass transfer. This technique avoids the dimensionless number and transfer coefficient methods and is not geometrically sensitive. Conditions in caves are also determined by the capillary processes of water in cave walls. Air movement in caves depends on surface weather conditions and special problems of surface weather observation arise. A series of experiments were undertaken to evaluate the cave and surface processes. The physical processes that collect, transport and release dust were measured and described. Dust in the caves was shown to be carried from the surface, mainly by the visitors. The concept of the Personal Dust Cloud is developed, and experimental measurements and analysis show that this process is a major threat to the caves. New techniques of measurement are described. An accurate physiological model has been developed which predicts most of the CO_2 measured in Jenolan Caves, derived mainly from visitors on cave tours. This model, developed from previously published human physiological information also predicts the production of heat and water vapour by cave tourists. The effects of CO_2 on cave conditions has also been investigated. Details of a two year program of measurements in the caves are given. The generalised approach and methods are applicable to other caves, mines and buildings.

GULLEN, T 1999

Non-invasive investigation of polygonal karst features: Yorkshire Dales National Park.

MSc Dissertation, Exploration Geophysics, University of Leeds, Department of Earth Sciences, Leeds, LS2 9JT, UK.

Resistivity, refraction and resistivity tomography methods were used to ascertain the dimensions of any sediment body present within solution dolines. Fieldwork was undertaken at two sites within the Yorkshire Dales National Park: High Mark [SD920 679] northeast of Malham Tarn, and on Ingleborough, northeast of Clapham Bottoms [SD765 722].

Results of previous studies of doline fill have been inconclusive. It has been hypothesised (Howard, unpublished) that if dolines do contain significant amounts of sediment, the fill could provide a complete palaeoenvironmental record of the Quaternary.

Resistivity studies undertaken at High Mark used an Offset Wenner array, and field data were inverted to produce a 1-D image of the subsurface. The profiles were located at the base of the doline, in the area believed to contain the greatest sediment thickness. Results suggest that the fill comprises two layers. An upper layer approximately 1m thick is composed of poorly consolidated clayey sand with an apparent resistivity of 166Ωm. The second layer reaches a depth of 5.6m and is more clay-rich, with an apparent resistivity of 60Ωm. These interpretations are supported by evidence from augering. The upper 10m of limestone below the sediment has been altered during doline formation, weathering and fracturing, and has a resistivity of 220Ωm compared to 440Ωm for the unaltered bedrock.

Refraction profiles were undertaken at High Mark, using the hammer and plate method with a 2m geophone spacing. Profiles were located on the base, flanks and interfluves of the doline. Ground conditions prevented the acquisition of very long offset shots (>10m), and lack of these data hindered interpretation. Profiles undertaken at Ingleborough used an explosive shot placed in a 45cm-deep hole, and a 5m geophone spacing was used. Profiles were located at the base of the dolines.

Results at High Mark suggest that the limestone is overlain by 4m of sediment. The upper layer has a velocity of approximately 0.50m/ms, whereas that of the second layer is 1.19m/ms. Alteration of the upper 6m of the bedrock is indicated by a velocity of 2.00m/ms, compared to 2.99m/ms for the unaltered limestone. The bedrock surface is undulatory, possibly indicating the effects of preferential dissolution or glacial activity.

Results of the refraction surveys at Ingleborough indicate that the limestone is overlain by a single 4m-thick layer of sediment with a velocity of 0.52m/ms. Beneath this, the upper 13m of limestone is altered, with a velocity of 2.45m/ms, which increases to 3.75m/ms in the unaltered limestone below. Velocities obtained are lower than expected, but reliable imaging of the limestone was ensured by siting the profiles close to observed rock exposures. Refraction interpretations indicate that the centre of the doline is not coincident with the position predicted from observation of the surface morphology.

Resistivity tomography profiles were undertaken at the base of the dolines at both sites. A fully automated system employing a Wenner array with 25 electrodes at 5m spacings was used, and six levels were recorded. The field data were inverted and the results suggest that there are about 12.5m of sediment in the High Mark doline. The sediment is underlain by 2m of altered limestone and the bedrock base of the doline is relatively smooth.

In contrast, the thickness of sediment fill in the Ingleborough dolines is ≤7.5m, but the depressions are bounded by a greater thickness of altered limestone (≤10m). In places the limestone imaged appears to reach the surface, but is not observed in the field, indicating that minimal sediment cover is not imaged. The surface of the limestone is pitted by smaller sediment-filled depressions, possibly a feature of glacial scour.

Two profiles were forward modelled to test the reliability of the inversion model. The models were similar, but features were displaced to the right of the true section. Synthetic models were constructed to test geological hypotheses concerning the composition of the dolines. The models suggested that the dolines are relatively shallow (<12m) and are underlain by significant thicknesses of altered limestone (~10m).

The combination of results obtained suggests that dolines are not filled by significant quantities of sediment and, consequently, they cannot be used as palaeoenvironmental indicators of the Quaternary.

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 that 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 that 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 are available from the Honorary Secretary (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, Malvern, Worcs., WR13 6LF, UK. Closing dates for applications: 31st August and 31st January.

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 AND 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, UK and Professor J. Gunn, Limestone Research Group, Dept. of Geographical and Environmental Sciences, University of Huddersfield, Huddersfield HD1 3DH, UK.

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, UK.

CAVE STUDIES SERIES - occasional series of booklets on various speleological or karst subjects.
No. 1 *Caves and 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 and 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.
No. 7 *Caves and Karst of the Brecon Beacons National Park;* by Mike Simms, 1998.
No.8 *Walks around the Caves and Karst of the Mendip Hills;* by Andy Farrant, 1999.

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

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.

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 BCRA publications are obtainable from: Ernie Shield, Publication Sales, Village Farm, Great Thirkleby, Thirsk, North Yorkshire, YO7 2AT, UK.
BCRA Research Fund application forms and information about BCRA Special Interest Groups can be obtained from the Honorary Secretary: John Wilcock, 22 Kingsley Close, Stafford, ST17 9BT, UK.